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The role of price incentives in enhancing carbon sequestration in the forestry sector of Hungary

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ABSTRACT

This paper investigates the carbon sequestration potential of forests in Hungary through the introduction of a carbon price incentive, assuming an integrative national climate policy. We have developed a bio-economic mathematical optimisation model to represent the area and species distribution of Hungarian forests and we are optimising harvesting cycles without and with carbon payments. We assess the cost and volume of potentially available carbon removal by forests in the context of the national climate policy. To align our results with other climate policy instruments, we integrate the estimated carbon removal potential of the forests with the marginal carbon abatement cost curve of the energy sector in Hungary. We find that enhanced forest carbon sequestration can be more cost-effective than most other climate policy instruments. We find that forests could intervene at the lower end of the combined cost curve and shift it significantly to the right, resulting in much lower marginal and total costs of achieving the net zero target for Hungary.

1. Introduction

The role of forests in the global carbon cycle has been increasingly recognised, prompting climate policymakers to consider the vast potential of forest carbon sequestration in their plans to achieve net zero carbon emissions by mid-century, in line with their commitments under the Paris Agreement. There is a growing demand for the economic underpinning of a climate policy that considers the trade-offs between using forests for enhanced carbon sequestration versus enhanced timber production for material and biomass energy.

Currently, in most countries, forests contribute to climate policy through three main factors. First, forests produce biomass fuels (firewood, wood chips, pellets, etc.) that are consumed by end-users and energy producers, who are rewarded with a zero-emission factor because of the claimed climate neutrality of forest biomass. Second, forests produce timber for harvested wood products from pulp and fibre to sawlogs, construction materials and furniture, with varying capacities to store carbon before it is released back into the atmosphere. And third, forests contribute to climate policy through their 'natural' carbon sequestration, i.e., the removal and storage of atmospheric carbon without any price incentive.

Incentives are present for the first two factors. Much of the materials industry, such as cement, ceramics, glass, iron, steel, and chemicals, is constrained in their carbon emissions by some form of regulatory instrument targeting large polluters - e.g., a carbon tax or a mandatory emissions trading scheme (The World Bank, 2022). This provides an indirect support for less carbon intensive material alternatives, such as wood products.

Direct support is often provided for forest biomass fuels. Government support schemes for renewable energy usually still include biomass energy, paying direct subsidies to those who burn wood fuels. Amidst all the debate about whether biomass fuel is truly climate neutral (Ter-Mikaelian et al., 2015), (Brack, 2017)) and whether it should be considered renewable, (EASAC, 2017) we see growing demand for it in the short, medium and long term.

In the short term, the 2021–22 energy crisis has prompted markets and governments alike to demand more fuelwood, mainly to replace fossil gas and oil for heating buildings. (Romano, 2022) In the medium term, renewable energy targets are expected to increase further. And in the long-term, many hope that industrial-scale biomass energy with

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carbon capture technology will enter the commercial phase, with the promise of producing energy and removing atmospheric carbon at the same time. All of this increases the intensity of forest harvesting for energy products.

Governments, therefore, need to consider the socially optimal balance between carbon removal and storage and the production of wood for materials and energy. To make an informed and efficient choice in their pursuit of the policy mix with the lowest social cost, governments should consider the non-timber benefits of forests and integrate forest sink optimisation into national carbon mitigation plans. To this end, forest sink optimisation needs to be done in carbon cost terms that are comparable to other mitigation options. In a socially optimal climate policy regime, regulatory instruments should be designed and implemented in such a way that the cost of incremental carbon abatement in one sector does not differ significantly from that in another.

We have developed our Forest Carbon Sink Optimisation Model (FOX) to enable such an integrated climate economic approach. Our FOX model is a bio-economic mathematical optimisation model in which the production of forest wood is driven by biologically determined growth functions, while harvesting decisions are resolved by an economic profit maximisation objective function. In addition to the benefits of harvesting timber, we have incorporated the potential benefit of removing carbon from the atmosphere, by offering a certain payment for incremental carbon sequestration if harvesting is delayed by another period. Likewise, the model accounts for a carbon release cost when the final harvest is realised. This introduces the potential of forest wood as a carbon instrument in addition to forest wood as a commodity.

We calibrated our model with country-specific datasets collected from the forestry administrations of Hungary, Romania, Bulgaria, and Bosnia-Herzegovina. In this paper, we present our results for Hungary, a country with relatively low forest cover (20%) and low ecological status of its forests: high rate of clear cutting (90%), high share of non-native species cover (36%), and a low ratio of semi-forests (12%).[1]

As our work is policy oriented, we have configured the FOX Model to construct forest carbon sequestration supply curves for different time horizons. To align our results with other climate policy instruments, we integrate our estimated forest carbon removal potential into a combined marginal carbon abatement cost curve of the Hungarian energy and forestry sectors.

2. Literature

In terms of economic theory, we build on the neoclassical literature. (Bowes and Krutilla, 1985) wrote a seminal text on multiple-use management of public forests. We follow the conceptual approach of those who integrate carbon benefits into the Hartman framework of multiple-use forest optimisation models (van Kooten et al., 1995) (Amacher et al., 2009).

In our view, forests are currently being exploited for climate benefits by those who burn firewood for energy, thanks to the zero-emission factor applied to biomass by regulators. Thus, we emphasize the significance of the influential work of (van Kooten et al., 1995). who show that when timber has medium or low commercial value and forests are managed for carbon sequestration, the optimal age of rotation depends on the rate of carbon release at the time of timber harvest. If there is full immediate carbon release (e.g., firewood) it is optimal never to harvest the trees. A very similar optimum is found even if half of the timber carbon is preserved in permanent storage (harvested wood products, landfills). Optimal rotation ages revert to levels like the observed financial Faustmann ages only if all the carbon stored can be permanently preserved following harvest.

We developed our model based on the work of (Guo and Gong, 2017), (Guo et al., 2019)and (Ekholm, 2020). (Guo and Gong, 2017) model the potential and costs of promoting forest carbon sequestration through a tax/subsidy to forest owners for reducing/increasing carbon storage and show that a higher carbon price would lead to higher forest carbon stocks.

In a later paper (Guo et al., 2019) they apply a partial equilibrium model of the Swedish forest sector to assess the impact of increased bioenergy production on timber harvest and forest growing stock. Their results suggest that increased bioenergy production will lead to significantly higher harvests and a net loss of carbon storage in forests.

Using the production possibility frontier between harvesting and carbon storage, (Ekholm, 2020) it is shown that significantly higher forest carbon stocks can be achieved with lower levels of harvesting. The optimal position is determined by the interplay and changes in relative prices between timber, carbon, and other land-use dependent commodities.

In the extensive literature on modelling multiple-use forest management, several models apply exogenous timber and carbon prices. Samuelson, for instance, incorporates timber sold at a competitive market price when formulating his optimal forest rotation model (Samuelson, 2012). Assmuth & Tahvonen also use inelastic demand in their work to show that optimal carbon storage leads to longer rotations and increased standing volume, as well as a shift from clearcutting to continuous cover harvesting (Assmuth and Tahvonen, 2018). Goetz et al. also use exogenous timber market prices to model optimal forest management under carbon storage incentives and find that, for a given timber market price, rising carbon prices lead to a remarkable increase in the number of trees. (Goetz et al., 2010) West et al. show with their extended Faustmann model, also using exogenous timber prices, that a well-designed and calibrated carbon payment scheme can significantly increase forest carbon stocks, but biodiversity may suffer if the incentive is too strong as fast-growing plantations are favoured by landowners over slow-growing native species despite regulatory efforts. (West et al., 2019).

For international modelling experience, EFISCEN (European Forest Institute, 2021) was consulted for methods to estimate growth beyond the typical felling age. For Hungarian modelling experience, the CASMOFOR model (Somogyi, 2019) was closely consulted.

From a policy perspective, we consider it important that the forest sector can be seriously exploited for climate benefits by other sectors of the economy (e.g., energy producers enjoying a zero-emission factor for wood fuel) or by other regions (where carbon release from forests is effectively constrained by policy instruments). The latter phenomenon, often referred to as carbon leakage, is estimated by (Pan et al., 2020) to be much higher in the forest sector than in the energy sector. Others argue that harvest leakage between countries that promote forest sinking and those that do not could seriously compromise the overall climate benefits of such policies. (Päivinen et al., 2022), (Kallio et al., 2018)).

In recent literature, many have questioned whether climate policy should focus on the carbon removal capacity of forests (Ojha et al., 2019), (Wernick and Kauppi, 2022), (Iversen et al., 2021)). It is argued that, instead of rapidly increasing forest carbon stocks in the short term, forest policies should promote biodiversity and forest resilience in the long term. (Hoogstra-Klein et al., 2017) show how carbon sequestration is perceived by forest owners as the least actively managed and mostly unintended forest function.

Several authors argue for finding the socially efficient combination of increasing forest carbon sinks and replacing fossil materials and products with wood-based alternatives. They also propose linking mitigation and adaptation measures to improve the long-term resilience of forests. (Verkerk et al., 2020) In their meta-analysis, (Valatin, 2014) conclude that, when compared to several alternatives, forestry options for carbon mitigation are generally cost-effective.

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[1] All Hungarian forestry data used in this article was collected from the Hungarian Agricultural Ministry website (Ministry of Agriculture of Hungary, 2021)) and from the websites of the National Land Centre which manages both the National Forest Database (National Land Centre, 2022a) and the National Forest Inventory (National Land Centre, 2023).

Several publications compared the cost-efficiency of forest carbon sequestration to decarbonization measures in the energy sector. In an early work by (Baral and Guha, 2004) they find that significant carbon benefits arise if fossil fuels are substituted by biomass harvested from short rotation woody plantations, the mitigation efficiency of which surpasses that of forests. In more recent literature, (Liu et al., 2022) conduct a comparative cost analysis of various carbon reduction options and find that afforestation is the second most cost-efficient alternative, right after the reduction of coal-fired power. It is also a substantially more cost-efficient option in removing carbon than renewable energy investments. (Münnich Vass, 2017) also finds that forest carbon sequestration is more cost-efficient than renewable energy sources in mitigating carbon emissions, even when considering technological improvements for renewables.

Integration of forestry models with partial equilibrium energy models aims at finding the optimal allocation of resources between these two sectors. (Jåstad et al., 2021) integrated the Nordic Forest Sector Model (NFSM) and Balmorel, the Nordic heat and electricity market model to better understand the efficient allocation of scarce biomass resources between the forestry and energy sectors. They analyse how decarbonization goals influence the interaction of the two sectors. They find that integrated modelling gives substantially different results in terms of biomass prices and energy volume projections compared to stand-alone modelling. The authors recommend studying spillover effects between the two sectors by means of integrated modelling when long term policy scenarios are analyzed, carbon pricing included.

3. Description of the FOX model

The FOX model determines the optimal harvesting time of forests at the national level, based on exogenous forest growth functions and timber and carbon prices. It is a dynamic, linear mathematical optimisation model. The FOX model is a direct application of the multiple-benefit forestry models by (van Kooten et al., 1995) and (Guo and Gong, 2017) to the case of Hungarian forestry under carbon price incentives. Our model assumes even-age forest management, in which the optimal rotation is static because the timber and carbon prices, the costs and the interest rate is assumed to be constant over the entire time horizon. (Montgomery and Adams, 1995) See Appendix for the detailed definition and analytical solution of the model.

In the FOX model, alternative scenarios of timber and carbon prices and discount rates can be set, and the model determines the optimal time of harvesting. Harvesting includes both felling and thinning of forests, with thinning being a mandatory activity determined as an exogenous function of the standing stock in each age group and the availability of the main stock. This is so to reflect the dominant management approach, which applies thinning to enhance the growth of the remaining standing stock and to provide a constant flow of revenues. Therefore, in our model thinning is not a control variable. The model allows for the coexistence of multiple forest age classes. Timber prices are defined for three main demand segments: 'sawlogs' for the timber industry, 'pulpwood' for the fibreboard and paper industry and 'firewood' for all energy purposes. The model is written in GAMS with an Excel interface.

In the context of exogenous parameters, the model finds the optimal cutting age for each stratum of the species and age matrix of the standing stock. The following model outputs are calculated for all modelled time periods: forest stock changes and harvesting (both by species and age), and changes in CO_2 sequestration. Finally, the model constructs forest carbon sink supply curves for different time periods.

The non-negative decision variables of the FOX model are the demanded volume of timber and the area for final felling and area for reforestation in both existing and new forests.

FOX modelling results are to be interpreted with the following assumptions and limitations.

(i) FOX currently calculates sequestration only for the stem wood. All other carbon pools of the forest land category (below-ground biomass, soil, litter, deadwood) are disregarded.
(ii) All harvested wood is assumed to be fully oxidised within the harvest period (instantaneous release to the atmosphere), i.e., the forest manager is required to make a carbon release payment for the full amount in the period they chose to harvest.
(iii) FOX assumes that all the three distinct demand segments have perfectly elastic demand, i.e. markets absorb any amount of output at the competitive market price. In the case of a small economy located in Central Europe, such as Hungary, this assumption may hold in the short run but not necessarily in the longer run.

4. Data

The Hungarian Forest Carbon Sink Optimisation Model (FOX-HU) is mainly based on data provided by the Hungarian National Forest Accounting Plan (NFAP-HU), the National Forest Database (at the Hungarian Ministry of Agriculture) and the National Forest Inventory (at NFK, the National Land Centre of Hungary). The FOX-HU model consists of 10 groups of tree species based on the most widely used categorisation of species in Hungary.

4.1. Land distribution of existing forest stock

The distribution of existing forest areas is detailed in Table 1, categorized by species group and age classes. As the area distribution is divided into 10-year age classes, the length of the modelling period is also measured in 10-year periods. As age classes are not differentiated beyond 100 years, 11 age classes are used in the model to represent existing forest stock.

We use the average of 2017–2021 median cutting ages for each species to calibrate the yield of the three assortments in each age group.[2] We identified the existence of standing stocks older than the median cutting age. The sum of forest area with overage stands is roughly 235,000 ha in our modelling database. We assume that about 100,000 ha of this is managed primarily for timber benefits, implying that there have been some factors in the last 5 years that have made it rational to leave these stands longer than the historical average. Several such factors have emerged in the context of managing Hungarian forests, including low interest rates, a surge in wood market supply from sanitary cuttings in the neighbouring countries as a result of the bark beetle calamity, and the government price regulation of residential natural gas supply, which nominally fixed household gas tariffs, leaving firewood the more costly fuel for space heating. For the remaining 135,000 ha, we assume multiple-use forestry, optimising for timber and non-timber benefits, such as biodiversity, landscape, recreation, water resources, etc. Therefore, we exclude it from optimisation as "protected forests". The wood in these forests continues to grow and sequester carbon, which is considered in the model. Their area is kept constant at around 135,000 ha, corresponding to the protected status definitions of the Hungarian forest statistics.[3]

4.2. Increments of the standing and thinning stock

In addition to the area distribution of the existing forests and the

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[2] The median cutting age for the analyzed species are the following: Oaks 101 years, Turkey oak 90 years, Beech 117 years, Hornbeam 89 years, Black locust 36 years, Other hardwood 75 years, Hybrid poplar 26 years, Poplars 43 years, Other softwood 65 years, Conifers 67 years. (National Land Centre, 2022c).

[3] NFAP-HU: 270–280,000 ha (Somogyi et al., 2019), NFK: 134,000 ha (National Land Centre, 2022a).

Table 1
Area distribution of existing forests in Hungary by species and age classes, year 2019 (in 1000 ha).

Age / species	Oaks	Turkey oak	Beech	Horn-beam	Black locust	Other hardwood	Hybrid poplar	Poplars	Other softwood	Conifers
1–10	22.7	9.5	3.5	2.0	81.3	6.1	20.3	22.1	3.6	4.6
11–20	59.7	25.1	14.5	8.1	133.6	18.6	44.1	23.4	8.0	9.4
21–30	32.4	16.8	9.0	7.9	123.9	17.9	30.2	14.7	10.9	19.4
31–40	31.5	17.7	5.2	11.1	73.8	15.8	9.3*	11.5	20.2	41.7
41–50	27.8	19.3	4.6	10.4	21.1*	12.8	3.1*	6.7	19.3	52.2
51–60	31.0	17.5	5.3	7.8	12.9*	11.1	1.9*	4.7*	16.3	27.6
61-70	38.7	17.9	6.9	8.4	6.4*	11.2	0.5*	2.9*	8.6	20.1*
71-80	35.6	28.7	11.5	13.3	1.4*	7.8	0.1*	1.2*	5.1*	6.1*
81-90	37.4	24.4	12.7	11.6	0.3*	5.7*	0.0*	0.4*	2.6*	4.9*
91-100	26.0	15.8*	11.8	7.8*	0.1*	4.0*	0.0*	0.1*	1.4*	2.6*
101+	45.7*	19.4*	27.1	8.7*	0.1*	6.7*	0.0*	0.0*	2.0*	2.9*

Source: (National Land Centre, 2022a).

[*] Areas for protected stock (stock with an age above the median cutting age).

median cutting age, another key input is the volume increment of the main standing stock and of the thinning stock, both measured in m^3/ha/10-year period. The volume increment of the main standing and thinning stock is determined by the biological growth of species based on the Sopp dendrometric database (Sopp, 1974). However, this dataset only covers forests up to 110 years of age, so input parameters for age classes above 110 years needed to be extrapolated. The extrapolation is based on a regression analysis presented in the EFISCEN model of the European Forest Institute (EFI) by (Pussinen et al., 2001).

4.3. *Demand segments*

The FOX model can distinguish between different forest product demand segments. In the FOX-HU settings, three demand segments are identified: firewood, pulpwood and sawlog.

The demand segment ratios for final felling apply to mature forests at least as old as the median felling age shown in italics in Table 2. Harvesting of younger forests produces a lower proportion of sawlogs and a higher proportion of pulpwood and firewood, and below a certain age (specified independently for each species group), no sawlogs can be harvested.

4.4. *Carbon content*

The carbon fraction of the stand is calculated as the tonnes of carbon stored in a cubic metre of wood. This measure varies between species because of their carbon content – tonnes of carbon stored in a tonne of wood – and their wood density (or weighted average wood density in the case of grouped species), the mass of a cubic metre of wood.[4] We use the weighted average of the carbon fraction to calculate the mass of carbon sequestered in the forest. The input data for carbon content and weighted average wood density are based on reference values from (Somogyi, 2008), (Kis-Kovács et al., 2022) and (IPCC, 2006).

4.5. *Costs, prices, discount rate*

Cost and price input parameters are assumed to be constant over the modelling horizon. Harvesting costs and regeneration (reforestation) costs were collected from official statistics. (Ministry of Agriculture of Hungary, 2021) The prices for products in each demand segment were determined based on price statistics (Ministry of Agriculture of Hungary, 2021). Weighted averages were calculated with the most 'typical' products on the market (products with the highest marketed volumes within each product category). Table 3 shows the cost, price, and discount rate parameters used in the model runs presented.

Given the input data and the associated assumptions, the FOX-HU model is run for 18 periods (180 years), but only the first 13 periods (130 years) are evaluated.[5] Period-1 is the base period 2019 with the most recent data available.

5. Modelling results

We present our results from the scenario analysis of the FOX-HU model to discover the possible role of price incentives in enhancing carbon sequestration by the forest sector in Hungary. In the reference scenario no carbon price is introduced, while in the alternative cases we apply different (carbon) price incentives. In this section, we first present the harvest cycles and production volumes for the reference scenario without carbon price incentives. Then we present the results for 10 alternative scenarios with gradually increasing carbon prices for sequestration and release.

5.1. *Reference scenario*

In the FOX-HU Reference Scenario no carbon payments are made, net sequestration is not rewarded, and net emissions are not penalised. The Reference Scenario thus reflects the current policy landscape, where forest harvesting decisions are not influenced by carbon prices. Forests are harvested when they generate the highest net present value of timber benefits minus costs. Fig. 1 shows the level of the main standing stocks, including both optimised and protected forests, which show a net decline in timber stocks over the first five periods. This is in line with the latest government projections in strategic documents (Somogyi et al., 2019), where stocks are declining due to high share of ageing stocks, increased harvesting intensity and a slowdown in afforestation. The rebound in timber stocks between periods 5 and 7 is a result of the extensive reforestation following the harvests of the first few periods. Between periods 1 and 5, beech and other hardwood species show the largest declines in both percentage and absolute terms. Among the short rotation species, hybrid poplar declines the most due to the timing of the harvest, followed by conifers and black locust.

5.2. *Alternative carbon pricing scenarios*

The following section presents the results of alternative scenarios in which we introduce a carbon pricing instrument into the FOX-HU model. This is a linear carbon tax-and-subsidy scheme that rewards each additional tonne of carbon sequestered in any period with a flat

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[4] The carbon fraction is calculated as the product of carbon content and weighted average wood density.

[5] As it has been introduced in the previous section, the FOX model aims to maximize the net present value of net benefit from forestry over a limited time horizon, between 0 and T. The current model cannot assign a residual value to the forest after the end of the horizon (e.g. in $T+1$), thus the last periods of the extended time horizon are impacted by this limitation. Therefore, the first 13 modelling time periods are considered out of the 18 periods.

Table 2
Share of harvested timber by demand segment, species group and harvest type, Hungary.

Demand segment	Oak	Turkey oak	Beech	Horn-beam	Black locust	Other hard-wood	Hybrid poplar	Poplars	Other soft-wood	Conifers
Thinning										
Sawlog	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Pulpwood	4.8%	3.5%	16.4%	7.9%	3.9%	4.3%	70.2%	66.6%	27.4%	80.1%
Firewood	95.2%	96.5%	83.6%	92.1%	96.1%	95.7%	29.8%	33.4%	72.6%	19.9%
Final felling of mature forest										
starting at years of age	*110*	*90*	*120*	*90*	*50*	*90*	*30*	*40*	*70*	*70*
Sawlog	46.3%	5.8%	38.0%	12.4%	19.9%	25.9%	88.3%	54.4%	33.6%	43.7%
Pulpwood	2.6%	3.3%	10.2%	6.9%	3.1%	3.5%	8.2%	30.3%	19.2%	45.1%
Firewood	51.2%	90.9%	51.8%	80.7%	77.0%	70.6%	3.5%	15.2%	47.2%	11.2%

Source of data: (National Land Centre, 2022c).

Table 3
Input parameters for the FOX-HU model.

	Planting costs for all species (EUR/ha)	Cutting costs for all species (EUR/m^3)	Market prices by demand segments (EUR/m^3)			Discount rate (%)
			Firewood	Pulp	Sawlog	
Input data	2597	26	43	34	104	3%

Source of data: (Ministry of Agriculture of Hungary, 2021).

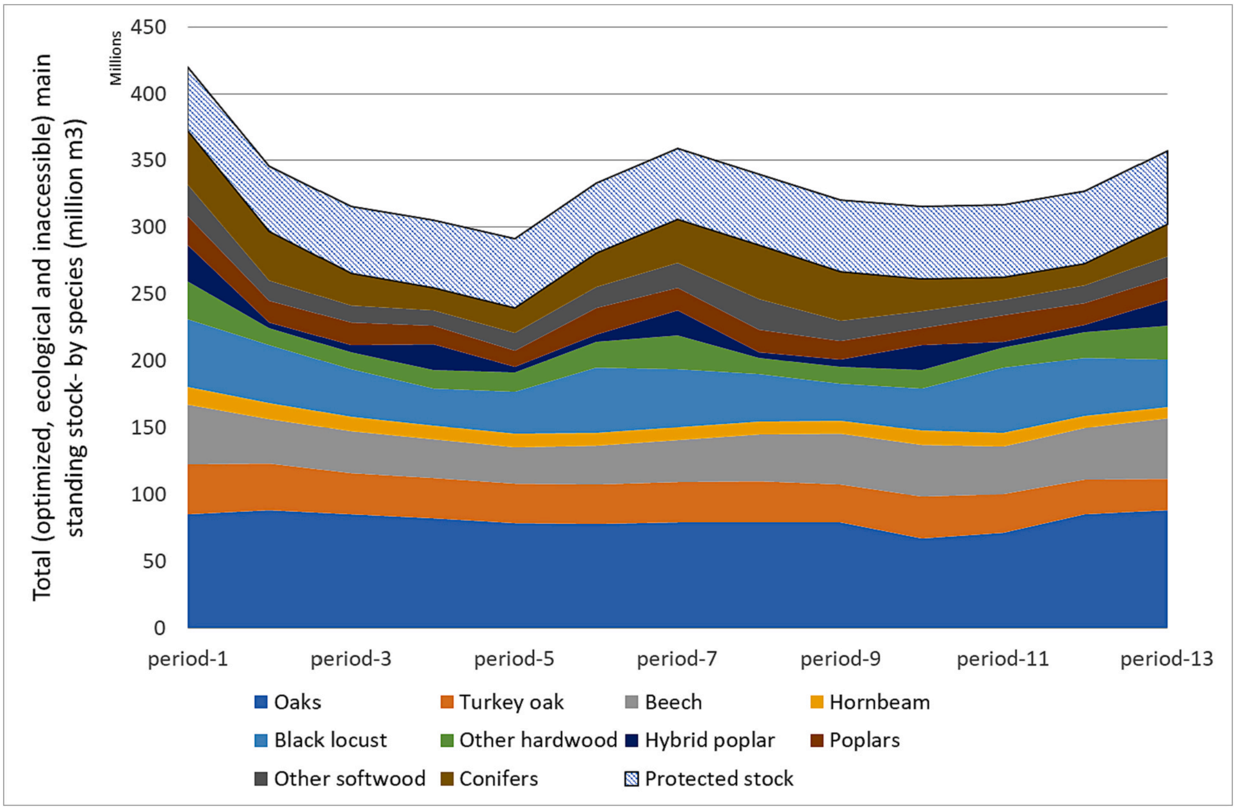

Fig. 1. Main standing forest stock throughout the modelling horizon in Hungary, Reference Scenario, million m^3.

rate subsidy payment and penalises each tonne of carbon released through harvesting with the same level of flat rate tax payable after the released carbon.

This instrument has the potential to significantly change the cost-benefit dynamics over the time horizon of the model. Note that the direction of the carbon payments is the reverse of the timber payments: carbon subsidies are only paid if timber harvesting is delayed by another period, and similarly, if timber is produced and sold, the carbon tax is paid at the same time, after the assumed immediate release of carbon.

Fig. 2 compares the growth of sequestered carbon at different prices. While a payment of 10 EUR/t of CO_2 induces little change in forest management, 20–30 EUR/t leads to net sequestration of 34 million tonnes of CO_2 by 2050. As the price of CO_2 increases through the scenarios, sequestration increases significantly. At 50 EUR/t, 164 million tonnes more CO_2 are sequestered by 2050 than without carbon payments, and a price of 100 EUR/t leads to 247 million tonnes more sequestration than in the Reference Scenario.

The largest gain is observed as the price jumps from 20 to 60 EUR/t:

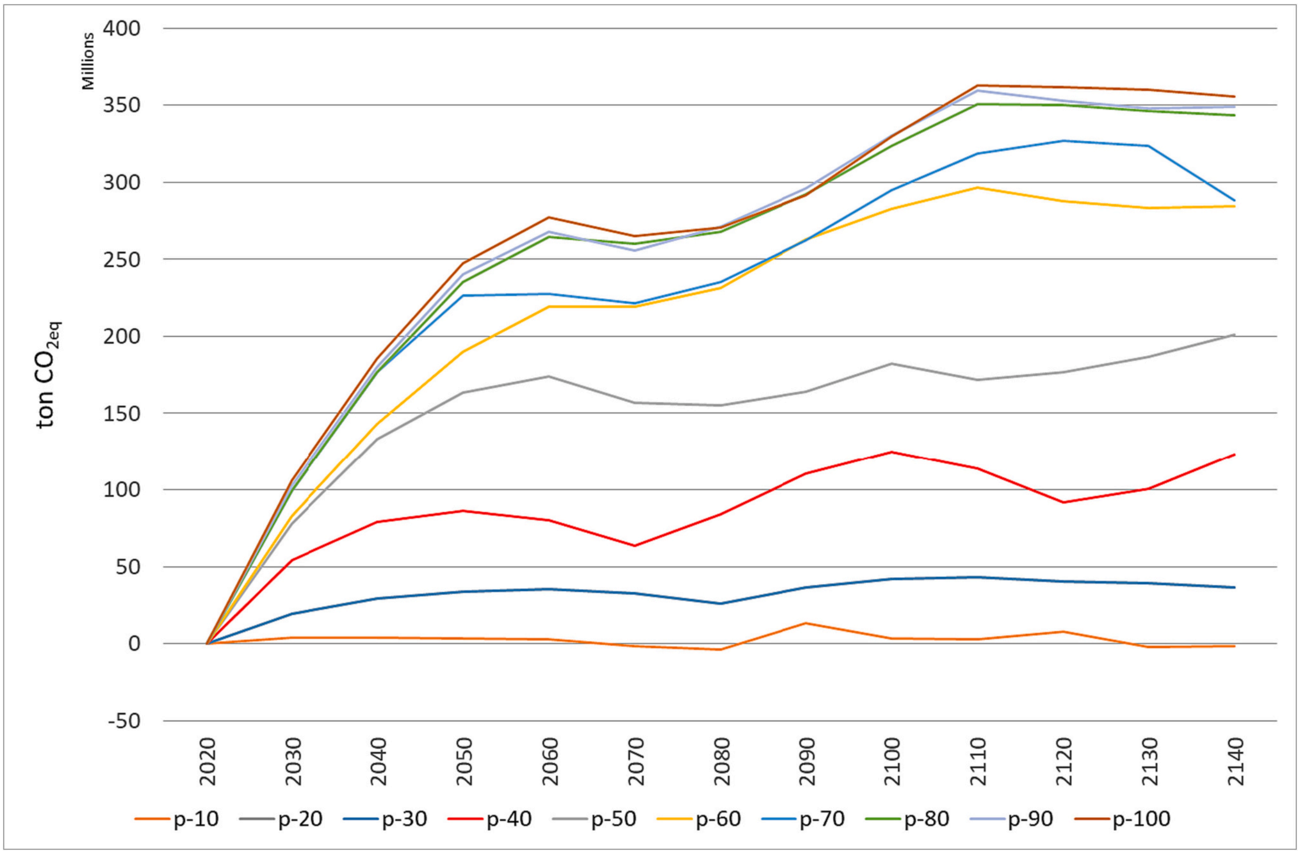

Fig. 2. Changes in sequestered CO_2 stocks under different carbon prices, compared to the Reference Scenario in Hungary, million tonnes of CO_2.

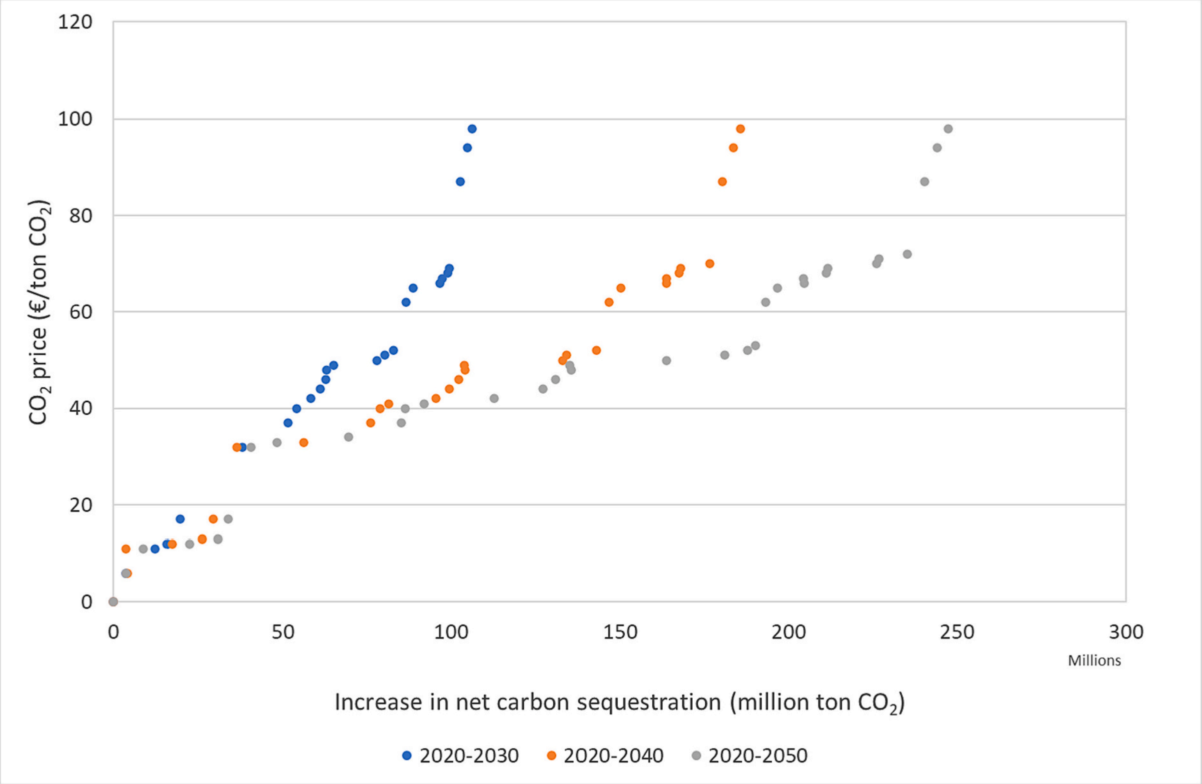

Fig. 3. Carbon sequestration supply curves of the forest sector in Hungary in three different time horizons, 1 to 3 decades.

the carbon price becomes a game changer at 20–30 EUR/t and induces a huge amount of additional sequestration as it gradually rises to 40, 50 and 60 EUR/t, triggering 86, 164 and 190 million tonnes of additional sequestration respectively by 2050. Above 60–70 EUR/t, the carbon sequestration potential of the forest appears to be saturated. We further raised the carbon price in FOX-HU to 80–90-100 EUR/t in subsequent model runs but only marginal additional sequestration could be induced.

Fig. 3 translates our results into economic terms. We present carbon sequestration supply curves for forests in Hungary for the first half of the century. These are inverse supply curves, which represent prices in terms of quantities. Inverse sequestration supply curves can be interpreted either as how much CO_2 is sequestered at a given CO_2 price, or as the price to be paid for an additional tonne of CO_2 sequestration. The X axis is the cumulative sequestration for one, two and three decades at certain fixed prices from 2020 to 2030, 2040 and 2050 respectively, assuming constant carbon price incentives throughout the modelling horizon.

These ‘short-run’ supply curves are useful for understanding the consistency of our results. A carbon price of 40 EUR/tCO_2 applied over the entire modelling horizon, leads to a cumulative additional removal of 54 million tCO_2 from 2020 to 2030 (i.e. an additional 5.4 mt/yr annual sequestration on average over 10 years) compared to the Reference Scenario. In the next decade, the cumulative removal increases to 79 million tonnes, and the total additional removal induced by this price signal is 86 million tonnes by 2050.

The total additional sequestration is not evenly distributed across the decades. As we have shown in Fig. 1, there is a gradually declining but very pronounced trend in the Reference Scenario for harvesting an ageing stock over the first three decades, with the slope of the decline gradually decreasing from the first to the third decade. This means that any carbon price has the largest impact on the slope in the first decade (e.g. at 40 EUR/t it is 5.4 mt/yr on average), with a smaller impact over two decades (3.9 mt/yr on average) and an even smaller impact over three decades (2.9 mt/yr on average).

Fig. 4 shows the modelling results in the form of Marginal Abatement Cost (MAC) curves. These conceptually represent the cost of avoiding one additional unit of emissions at each emission level and are widely used by policy makers to develop optimised, least-cost decarbonisation strategies.

The positive correlation between CO_2 prices and forest sequestration, as demonstrated above, is consistent with national abatement cost curves, that delineate annual emission reductions. Notably, this concept may be misleading in that forest-based carbon sequestration cannot be switched on and off like a wind turbine. Not only is the ability of forests to sequester additional carbon a slow, long-term option, but the cumulative growth of forests is a prerequisite for additional carbon sequestration in any given year. Therefore, as useful as they may appear, annual forest carbon MAC curves need to be interpreted carefully, considering the more realistic cumulative supply curves shown in Fig. 3.

In Fig. 4, we present only the milestone years to make the marginal cost of forest carbon sequestration comparable to other abatement options. The benefits of carbon pricing for forest sequestration are greatest in the earliest period up to 2030 declining towards 2040 and 2050. Recall that in the Reference Scenario intensive harvesting also increases until 2030 before decreasing in the later decades. Therefore, a given surplus sequestration target can be achieved at a lower marginal cost in 2030 than in 2050. For example, if the regulator were to target 6 million tons of additional sequestration in each of the milestone years, the carbon price would need to increase from 40 to 70 EUR/t by 2050 – but this target is achievable only if the price incentive is maintained over the entire modelling horizon, allowing the additional forest stock to accumulate before each milestone year.

6. Discussion

Based on our scenario analysis, we have estimated the marginal carbon abatement cost curve for the forest sector in Hungary up to 2050. The results indicate that the annual net carbon sequestration can be

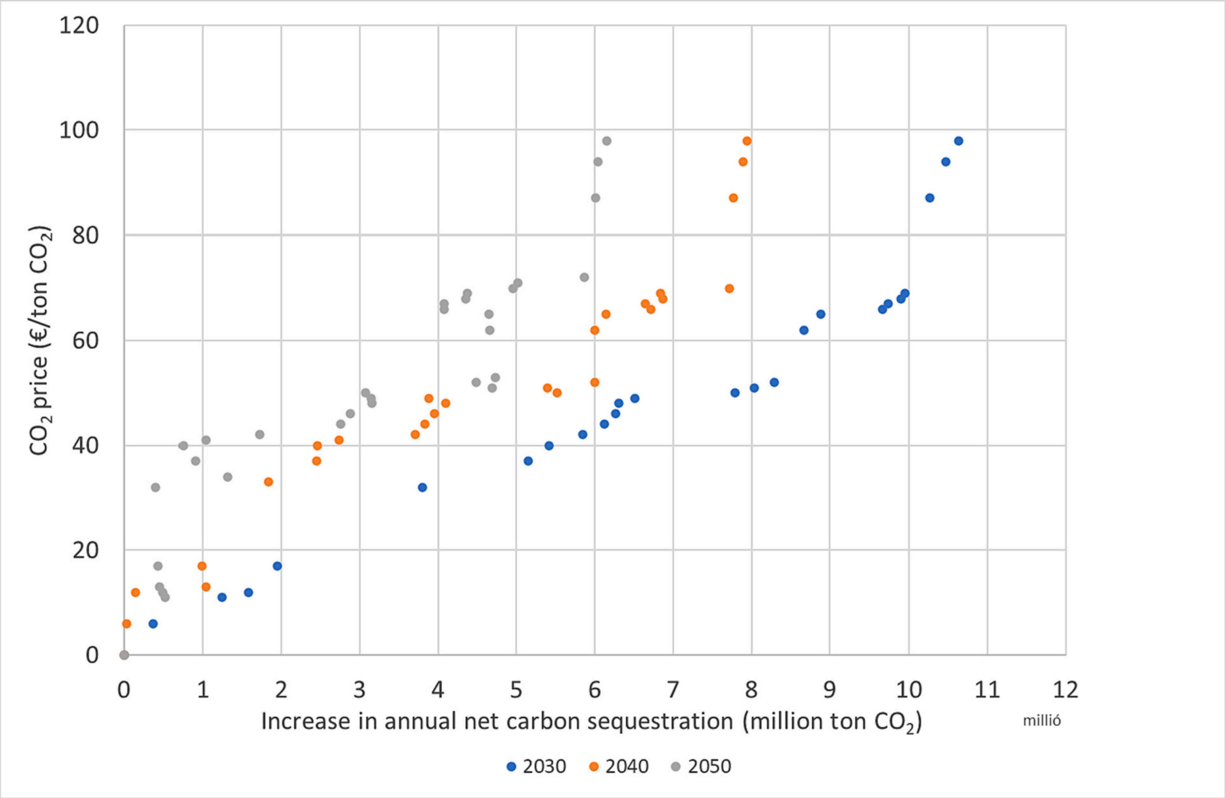

Fig. 4. Marginal carbon abatement costs of the forest sector at different CO2 prices in different milestone years in Hungary.

significantly increased by a regulatory incentive. This substantial carbon sequestration potential of forests raises the question of their role in national climate policy.

As we highlighted in our literature review, many authors argue for the integration or comparative assessment of the forestry and the energy sectors in terms of their carbon mitigation efficiency. In the following section, we discuss our forest carbon sink optimization results in the context of another carbon mitigation modelling exercise for Hungary, the Hungarian TIMES (HU-TIMES) model. The HU-TIMES model and its most recent results were published by (Mezősi and Rácz, 2023).The TIMES model is one of the many partial equilibrium energy sector models. Energy sector models are diverse in their build-up and conceptualization (econometric or technological top-down models versus statistical or engineering bottom-up models) (Swan and Ismet Ugursal, 2009). Bottom-up and hybrid models are further distinguished by their methodology (simulation, optimalization and accounting models) (Fleiter et al., 2011).

The HU-TIMES model is an optimization model of hybrid bottom-up and top-down construction, aiming to satisfy exogeneous demands at the lowest cost, subject to predefined constraints. Energy demand is defined by subsectors for the base year, and then projected for time horizons up to 2050 by econometric models with explanatory variables like GDP, population, and crude oil price. Energy demand can be supplied by a pool of energy technologies, existing and new, available at various capital expenditures and variable costs, and, with various specific carbon emissions.

One of the predefined constraints is total greenhouse gas emissions. The model can be run with any carbon emission limit, so among others, the scenario of net zero GHG emissions by 2050 was run for the Hungarian energy sector.

The HU-TIMES model will find the most socially cost-efficient allocation of carbon mitigation efforts among the subsectors of the energy sector. The social cost of the full decarbonization of the energy sector is captured by the sector specific marginal abatement cost curve, widely used in the literature with a well-established methodology. (Misconel et al., 2022)review the literature that defines carbon abatement cost curves by similar models. These approaches share the feature that they identify the least-cost response to the emission constraint, identifying the sectors and technologies where abatement happens.

(Mezősi and Rácz, 2023) investigated the marginal costs of greenhouse gas (GHG) abatement in the Hungarian energy sector for the period 2016–2050 using the HU-TIMES model.[6] They have found that in a reference case – if no additional policy instruments are introduced – the total GHG emissions of the energy sector would decrease to 29.5 million tonnes of CO_2eq by 2050. In addition, their results show that the marginal abatement costs increase exponentially from a few EUR/t CO_2eq to as much as 2500 EUR/t CO_2eq as the targeted abatement levels are approached. Even with these extremely high marginal abatement costs, the Hungarian energy sector alone cannot achieve net zero emissions by 2050.

The importance of using a policy instrument to increase carbon sequestration in the Hungarian forest sector can be captured by constructing an integrated MAC for the forest and energy sectors (see Fig. 5 below). As displayed, the marginal abatement costs of forest sequestration (blue lines) appear at the lower end of the integrated MAC curve, while the rest of the curve is shifted to the right. Integrating the relatively low-cost abatement potential of the forest sector would make it possible to achieve net zero GHG emissions from the combined forest and energy sectors in Hungary by 2050. Furthermore, the additional net carbon sequestration realised in the forest sector significantly reduces the marginal abatement cost of the Hungarian energy sector. Based on our calculations, the marginal abatement cost in the Hungarian energy sector could be reduced by more than 66%, from 2500 to 800 EUR/t CO_{2eq} of Hungary by 2050, if appropriate price incentives were applied in the forest sector.

Although the integration of the marginal abatement cost curves of different sectors is necessary to find the most socially (cost) efficient way to achieve net zero emissions by 2050, it is important to note the assumptions of the above example for Hungary. The analysis assumes that any price incentive will last for a hundred years, so that it can stimulate the growth of additional forest stock, which is a prerequisite for any milestone year carbon abatement. In this study, we do not consider the possibility of forest area expansion.

On the other hand, the above example for Hungary shows that enhanced forest carbon sequestration can be more cost-effective than some other climate policy instruments in other (e.g. energy) sectors. Therefore, the authors of this study recommend including optimised forest sector carbon sequestration in long-term national energy and climate plans. This can be done in an explicit or implicit way.

An explicit method to induce optimal carbon sequestration within an integrated climate policy is by establishing a carbon payment scheme. This scheme would give a carbon benefit to forest managers when they delay logging to a later period and impose a carbon penalty in the period when an area is harvested. Social welfare optimality of such a scheme would require the marginal abatement costs to equalise across the emitting sectors. Consequently, the first best carbon price applied to the forestry sector should closely align with the long-term equilibrium carbon price resulting from the abatement by the rest of the economy.

(Manley, 2023) presents an analysis of how carbon pricing impacts the relative profitability of two forest management approaches in New Zealand plantations. Under the current New Zealand carbon payment system, which closely aligns with our analysis, involving the allocation of carbon units for sequestration and the obligation to surrender carbon units when carbon stocks decline, at a carbon price of 50 NZD/ton CO2 (equivalent to 28 €/ton CO2), permanent forestry becomes more profitable than production or rotation forestry across 26–71% of the plantation area, depending on the specific carbon accounting framework in use. At a carbon price of 100 NZD/ton CO2 (equivalent to 56 €/ton CO2), permanent forestry surpasses production forestry in terms of profitability across all plantation areas. The widespread application of permanent forestry, on the other hand, puts the wood processing sector into a difficult position.

Yet, the practical implementation of an explicit carbon pricing scheme for the forestry sector might not be feasible in many countries. Therefore, implicit carbon pricing should be considered, involving a combination of policy instruments aimed at extending harvesting cycles and transitioning from rotational to permanent forestry, e.g., effective harvesting limits, mandated changes to management regulations, etc., eventually resulting in enhanced carbon sequestration as if triggered by a carbon shadow price. An implicit carbon pricing policy should be planned along carbon shadow prices in order to justify the cost of the policy in terms of the social cost of carbon.

7. Conclusion

This study presents a bio-economic model of Forest Carbon Sink Optimisation (FOX) and the results of its calibration and application for the case of Hungary.

We use our FOX model to assess the extent to which hypothetical carbon payments influence forest management decisions and affect the annual volume of carbon sequestration and total carbon stock in Hungary. We estimate the range of carbon price incentives necessary to achieve net-zero climate targets including induced forest carbon sequestration. In the case of Hungary, we find that relatively low carbon

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[6] The Hungarian TIMES model is an application of the mathematical optimization model TIMES (The Integrated MARKAL-EFOM System) for Hungary. The TIMES model was developed by the International Energy Agency's Energy Technology Systems Analysis Program (IEA-ETSAP). The HU-TIMES model supported the development of the Hungarian National Energy and Climate Plan and the Hungarian Long-term Strategy.

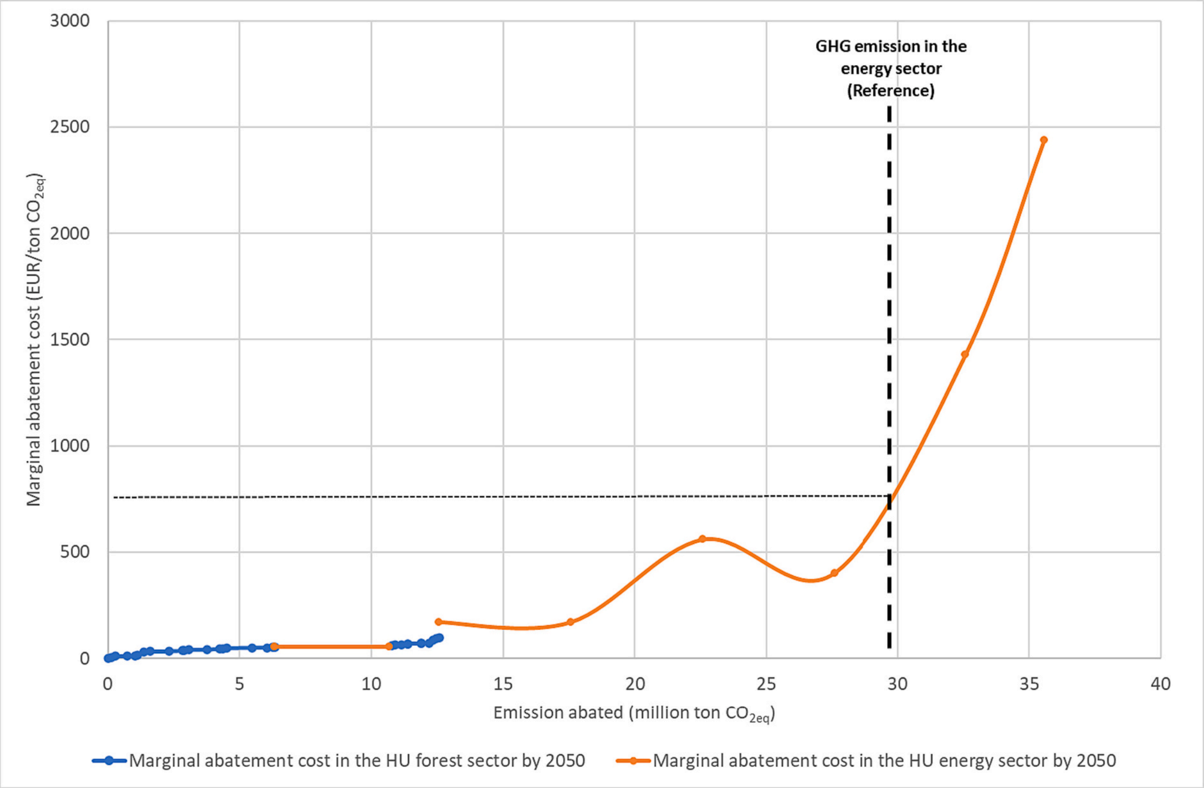

Fig. 5. The integrated marginal carbon abatement cost curve for the forest and energy sectors and the reference GHG emission level of the energy sector in Hungary in 2050, EUR/t of CO2eq and thousand tonnes of CO_{2eq}.

prices would be sufficient to reduce intensive harvesting and make the forest sector contribute significantly to the national of CO_2 mitigation over the next three decades at a relatively low cost.

Our study has identified the economically efficient sequestration potential in the Hungarian forest sector. With the application of current EU ETS prices in the forest sector, Hungarian forests could sequester 5–8 million tonnes more CO_2 than the approx. 4 million tonnes sequestered annually without price incentive in the Reference Scenario. Overall, the forest sector could remove 9–13 million tonnes of CO_2 annually. The real magnitude of these figures becomes comprehensible in the context of Hungary's total GHG emissions, as they represent 14% - 20% of the 62.8 million tonnes of total net GHG emissions in 2020 without Memo Items and LULUCF for Hungary.

Finally, to align our results with other climate policy instruments, we integrated our estimated carbon removal potential of the forests with the marginal cost curve of carbon abatement in Hungary's energy sector. Our main finding is that forests could contribute to the lower end of the combined cost curve, significantly shifting the curve to the right, resulting in much lower marginal and total costs of achieving the net zero target for Hungary.

We plan to further develop our FOX model in two main ways. We are considering introducing demand elasticity to enable FOX to analyse the impact of induced carbon sequestration on product markets. We will develop the FOX model to facilitate afforestation based on land-use change from agriculture to forestry, hoping to understand why Hungary's ambitious afforestation policy has recently failed and whether carbon pricing could be an effective instrument to initiate it.

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CRediT authorship contribution statement

Gabriella Szajkó: Conceptualization, Methodology, Investigation, Resources, Writing – original draft. **Viktor József Rácz:** Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing – review & editing. **András Kis:** Conceptualization, Methodology, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Gabriella Szajko reports financial support was provided by European Climate Initiative (EUKI).

Data availability

In our manuscript, we have shared the url links to the public data sources we used in our research.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2023.103097.

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