Applying REKK's Forest Carbon Sink Optimization (FOX) Model for Bosnia-Herzegovina

Authors:

András Kis, REKK

Marijana Kapovic-Solomun, Faculty of Forestry, University of Banja Luka

Viktor Rácz, REKK

Gabriella Szajkó, REKK

The research project leading to this report was funded by the European Climate Foundation (https://europeanclimate.org/)

Grant Agreement # G-2211-65116

Table of Contents

1 Executive summary 3
2 Introduction 5
3 The forestry sector of Bosnia-Herzegovina 6
3.1 Forest coverage 6
3.2 Modelled forest areas 8
4 The FOX model 10
4.1 General description 10
4.2 Use of FOX for continuous cover forestry 14
5 Model inputs 15
5.1 Land coverage of existing forests 15
5.2 Timber yield 16
5.3 Wood assortments and harvesting age 19
5.4 Costs of forest management 21
5.5 Sales price of assortments 21
5.6 Carbon content 22
6 Modelling results 23
6.1 Plantations 23
6.2 Coppice forests 25
6.3 High forests 28
6.3.1 80% LIMIT scenario 28
6.3.2 100% LIMIT scenario 30
6.3.3 NO LIMIT scenario 32
6.3.4 Introduction of carbon payments 34
6.4 Transformation of coppice to high forest 38
7 Conclusions, policy recommendations 41
7.1 Conclusions 41
7.2 Policy recommendations 42
8 References 43

1 Executive summary

This report provides an overview of the application of REKK's Forest Carbon Sink Optimization Model (FOX) to analyze the future trajectory of forests in Bosnia and Herzegovina (BiH) and understand how carbon payments and forest management policies may influence the long-term sustainability of harvests and carbon storage.

BiH has a complex forest structure, characterized by a combination of state and private ownership, forests of varying quality, and different management techniques. The decentralized administration based on entities results in differences in regulation, data availability, and data transparency, posing challenges in establishing a consistent and uniform forestry database covering all forest areas. Consequently, our analysis primarily focused on state-owned "economic" forests.

The most valuable forests in BiH are the uneven-aged, mixed-species "high forests" with a high share of tall, old trees. These forests account for over half of the total forest area in BiH and contain more than three-quarters of the standing stock. They hold significant ecological and economic value. High forests are under continuous cover forest management, with selective cutting that is limited to 80% (as maximum) of the annual growth of the main stand.

Coppice forests are the second most common forest type in BiH. Traditionally, coppice forests regrow from the stumps or roots of cut trees, but their management in BiH is currently limited. The economic value of a hectare of coppice forest is lower compared to high forests, but this also depends on the quality of the coppice forests, which can vary. Although there is government intention to transform coppice forests into high forests, practical progress has been limited as there is little economic rationality in support of this transformation.

Plantations have the least importance among the forest categories in BiH, with relatively low land coverage and mediocre quality. While they were established for economic purposes in the 1960s and 70s, they currently hold low economic value and are often left unmanaged. Some plantations undergo thinning, but clear-cutting and reforestation are rare.

The most common tree species in BiH forests are beech, followed by (sessile) oak, Norway spruce, fir and pines. Forests produce various timber categories, with sawlogs being the most valuable, while firewood and pulpwood fetch lower prices. The majority of sawlogs come from mature high forests, particularly coniferous species.

The FOX Model relies on forestry and forest management data structured for rotation forestry in other Central and Southeast European countries. As the data format in BiH differs, specific transformations were required to adapt the data for input into FOX. These transformations involved converting diameter classes to volume per hectare, adjusting yield curves, and creating numerous small "virtual forests" with uniform species and age classes to represent the mixed nature of high forests and coppice forests.

After populating the model with data, various test scenarios were run in FOX to align the results with practical experience. When necessary, data was calibrated to ensure consistency. Subsequently, scenarios were developed and analyzed to gain insights into the development pathways of different forest types in BiH and how specific policies would incentivize changes in forest management.

In the case of plantations, modeling results confirmed field observations that large-scale harvests are absent due to the higher cost of reforestation after clear-cutting compared to revenues from harvest. Significant increases in timber prices would be necessary to stimulate active forest management. While plantations continue to grow, there is a slow but steady accumulation of sequestered carbon.

Similar results were obtained for coppice forests, where current conditions make active management economically unviable. However, if selective cutting and subsequent natural regeneration are feasible, coppice forests could be utilized for increased harvests compared to the present situation. Furthermore, this approach could facilitate the transformation of some coppice forests into high forests. Alternatively, assuming current timber prices to prevail in real terms throughout the modelling horizon, a subsidy of 1,000-1,600 KM/ha would be required to incentivize this conversion, leading to significantly increased carbon sequestration in the coming decades as well as enhanced timber benefits.

High forests in BiH are of paramount importance, covering the majority of forested areas, timber volume, and carbon sequestration. They are also the most actively managed forest type in the country. Under the current practice of limiting final felling to max. 80% of current annual increment, modelling results indicate that the main stock of high forests continues to grow steadily. Simultaneously, the volume of final felling remains relatively stable, averaging around 50 million m^3 per decade throughout the modelled time frame. The species and assortment composition of the harvests also remain balanced over time.

As a hypothetical scenario, if final felling were limited to 100% of annual growth, the main stock of high forests would experience a slow decline over time, accompanied by increased volatility in harvested volume. The fact that the stock declines, instead of staying constant, is the consequence of a changing forest structure due to harvests taking place for older trees. Although this scenario can still be considered sustainable forest management, it is important to note that timber reserves slowly shrink, resulting in a decrease in CO_2 stored in high forests.

In another counterfactual scenario, we assumed the absence of any regulatory limits on harvests, granting forest managers unrestricted freedom to cut trees solely based on business considerations without taking into account sustainability, soil health, biodiversity, and other environmental factors. According to modelling results, all trees that have reached harvesting age would be cut within the next 10 years. This initial intensive harvest would be followed by several decades of minimal cuts, during which the forest stock gradually recovers to some extent but never reaches the initial stock again. Carbon reserves would also be severely impacted.

The introduction of carbon payments would primarily make sense for a scenario in which regulatory limits on harvests are absent. Our modelling results confirm that higher carbon payments per ton of sequestered CO_2 would incentivize forest owners to delay harvesting. A carbon payment of 50 EUR/ton CO_2 has minimal impact, while around 90-100 EUR/ton CO_2, substantial carbon sequestration would be triggered. At this level carbon payments become more attractive than timber revenues, leading to a cessation of all harvests in both beech and oak high forests. As the carbon price approaches 200 EUR/ton CO_2, carbon storage would further increase, resulting in a complete halt to harvesting in all high forests.

From a carbon storage perspective, the current practice of an 80% harvesting limit is comparable to a scenario without prescribed regulatory limits on harvests but accompanied by a carbon payment of approximately 100 EUR/ton CO_2.

Based on our analysis, several conclusions emerge for the forestry sector in BiH:

- Coppice forests, and potentially plantations, are underutilized resources. Modest initial investments can facilitate the transformation of these forests into higher-yield timber forests with increased carbon storage. International climate financing may play a role in supporting such endeavours, and further detailed, location-specific analysis is necessary to fully understand their potential.
- Maintaining the enforcement of felling limits constitutes superior climate policy. The management of high forests in BiH serves as a commendable example of sustainable forestry practices and carbon sequestration that can be shared with other countries.
- Currently, carbon payments to promote additional carbon storage are not justified for BiH. However, this could change if timber prices rise significantly or if the national marginal cost of carbon abatement increases, creating demand and economic rationale for increased forest-based carbon storage.

2 Introduction

REKK developed the Forest Carbon Sink Optimization Model (FOX) in response to the increasing demand pressure on forestry products, particularly firewood, and the lack of a coherent approach to integrating the carbon sinking potential of forests into a socially cost-efficient national climate policy. After successful applications of the FOX Model in Hungary and Romania in 2021-2022, the current report focuses on its application to the forestry sector of Bosnia and Herzegovina (BiH), while the Bulgarian application is still in progress.

BiH is a country rich in natural forestry resources, boasting a forest coverage rate of 63% (including forest-like areas), surpassing both the European average (39%) and other countries in the Balkans region. The country possesses a significant number of mature and highly valuable forests, which could be financially attractive for large-scale harvesting, posing a risk to carbon sinks. Additionally, BiH has extensive areas of less valuable forests that offer potential for additional carbon sequestration. In this context, understanding the carbon sinking potential of BiH's forestry sector, the potential for increased sequestration through appropriate price signals that reflect the social cost of carbon, and the applicability of related carbon policies are crucial.

Modeling the forestry sector of BiH required collecting and validating forest-related data (Chapter 3) and developing a comprehensive database as input for the FOX Model, which is introduced in Chapter 4. Due to data availability, the model's forest coverage was limited to state-owned "economic" forests, excluding privately owned, often degraded forests or nature protection areas. Although only half of BiH's forest land is included in the FOX Model, it contributes the majority of the country's timber harvest. Many of the conclusions of the report may be valid for the rest of the forestry sector as well.

Since a significant portion of BiH's forest area is managed as continuous cover forests, the available data had to undergo substantial transformation to align with the structure required by the FOX Model, as described in Chapter 5. FOX itself was further developed to account for specific forest management regulations in BiH. The modeling results are presented in Chapter 6, separately for each

main type of forest. Finally, Chapter 7 offers conclusions and policy recommendations based on the research findings.

Draft final results of this research were shared during an online workshop on June 13, 2023, with academic experts, practitioners, NGO representatives, and government officials from BiH. The feedback received from participants was incorporated to finalize the results and conclusions.

It is important to note that the financial figures presented in this report are primarily denominated in the local currency of BiH, the convertible mark (KM), with a conversion rate of 1 euro equal to 1.95583 KM.

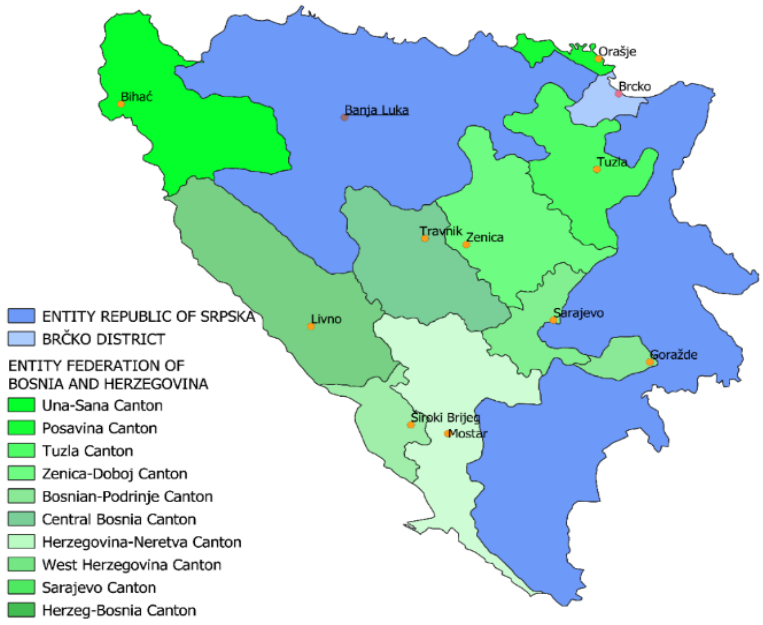
We express our sincere gratitude to the European Climate Foundation (ECF) for their generous funding, which made this research project possible. For more information about ECF, please visit their website at https://europeanclimate.org/.

3 The forestry sector of Bosnia-Herzegovina

3.1 Forest coverage

The most recent comprehensive, publicly available data on the forestry sector in Bosnia and Herzegovina (BiH) was published by FAO (2015). This publication is not officially endorsed by the governments of both Entities (Republic of Srpska and Federation of BiH entity), which have jurisdiction over the forestry sector at the entity level. Decision-making at the state level does not directly cover the forestry sector. The FAO assessment relies on two types of data: 1) Statistical Information based on the data from public Forest Enterprises on the entity level and Agencies for Statistics on the entity and State level and 2) the National Forest Inventory of 2009 which has not been officially adopted as a data source and it has not been made publicly available.

Figure 1 The administrative structure of BiH (entities and cantons)



According to the FAO (2015) report around 3.2 million hectares, or 63% of the country is covered by forests or forest-like areas. Of this, 3.04 million hectares qualify as forest according to FAO methodology. The composition of forests is displayed by Table 1.

Table 1 The structure of forests in Bosnia and Herzegovina (hectares)

Forest land	Economic	Non-Economic	Protected	Special purpose	Protective	Total
High forest	1,329,500	46,300	5,200	8,800	262,600	1,652,400
Coppice	843,200	158,700	1,600	2,400	246,300	1,252,200
Total forest	**2,172,700**	**205,000**	**6,800**	**11,200**	**508,900**	**2,904,600**
Shrubbery	52,700	41,100	0	100	36,700	130,600
Other forest area	3,300	3,100	0	100	2,600	9,100
Total FAO forest	**2,228,700**	**249,200**	**6,800**	**11,400**	**548,200**	**3,044,300**
Barren land	55,700	88,400	800	3,400	38,900	187,200
All forest and forest land	2,284,400	337,600	7,600	14,800	587,100	3,231,500

Source: FAO (2015)

Forests can serve several purposes, as evident from the table (economic, non-economic, protective etc.), while from the perspective of forest management, most forests fall into one of three categories: high forest, coppice and plantation. Forests of the Republika Srpska entity have FSC certificate, as well as some cantonal forests in Federation of BiH.

The high forests of BiH are typically of natural origin (not planted), they consist of mixed age trees, and frequently of mixed species. The older, tall trees of the high forests sometimes form a closed

canopy. These forests are not only the most common in the country, representing almost half of all BiH forests, they are also the most valuable both ecologically and economically.

Coppice forests are the second most common type of forest in BiH. Traditionally coppice grows from the stumps or roots of cut trees, but coppice forests in BiH are only moderately managed. The economic value of a hectare of coppice forest is much below that of high forest, but also depends on the quality of coppice forests which can differ.

While plantations do not appear among the above FAO categories, there is about 100 thousand hectares of plantations of economic purpose, planted during the 1960s and 70s. These forests are also of lower quality and value than high forests.

Most of the economic forests are owned by the state, as shown in Table 2. The 1 million hectares of state owned high forest are the best quality forest area in the country. Coppice forests are of secondary economic importance and this is especially the case for privately owned coppice.

Table 2 Ownership of economic forests in Bosnia and Herzegovina (hectares)

	State	Private	Total
High forest	1,063,400	266,100	1,329,500
Coppice	408,700	434,500	843,200
Total	1,472,100	700,600	2,172,700

Source: FAO (2015)

As Table 3 shows, high forests have considerably more stock per hectare than coppice, and state owned (and managed) high forests have about 40% more wood per hectare than private high forests. According to recent data (Agency of Statistics RS and FBiH, 2021) the volume of state owned high forests, 302.6 million m^3, is still at around the same level as in 2009.

Table 3 Volume of wood in economic forests in Bosnia and Herzegovina

	Volume of forest stock (1000 m^3)		Average volume (m^3/ha)	
	state	**private**	**state**	**private**
High forest	299,630	53,968	282	202
Coppice	35,710	46,412	87	107
Total	335,340	100,380		

Source: FAO (2015) and own calculations

3.2 Modelled forest areas

Data with sufficient detail for modelling purposes is available for state owned economic forests only (Table 4). Only the major species are included, but excluded species make up only a few percentage points of state forest areas. The modelled area is equivalent to about half of all forests, and over 70% of all managed forests. While not all forest areas are covered by the analysis, the ecological and economic importance of the modelled areas give it a high weight.

Table 4 Modelled forests

Forest category		Area (ha)	Approximate annual harvest (thousand m^3)
Plantations	Norway spruce	23,540	negligible
	Pines	58,241	
	Fir	17,771	
High forest	Beech	485,356	1,900
	Norway spruce	174,629	900
	Silver fir	178,466	1,200
	Austrian pine	71,764	80
	Sessile oak	92,236	200
Coppice	Beech	221,945	moderate
	Oak	197,526	
	Other hardwood	26,944	
Total		1,548,418	4,500-5,000

Plantations are in principle managed as rotation forests, with clear cut followed by reforestation, and significant thinning taking place during the growth of the forest. Plantations produce both sawlogs and pulpwood, but no firewood, as the modelled plantations are all coniferous, less suitable for energy generation. The quality and value of timber in plantations is below average. As a result there is only moderate harvesting, markedly below the volume of annual timber growth. Norway spruce and Fir often appear together in mixed forests, the area from the table reflects the share of the two species.

In case of high forests, harvesting is at around sustainable levels, with annual harvests of about 4.5-5 million m^3 and annual growth of high forest main stands estimated to exceed 5 million m^3/year. In case of high forest sessile oak, much of which is viewed as degraded forest, harvest is significantly below its potential. High forests in Bosnia-Herzegovina are continuous cover forests with mixed species and age groups. The high forest areas in Table 1 refer to the total area occupied by each tree species within mixed species forests, and not actual forests of only one species. For instance, 485 thousand hectares of beech means that within the close to 1 million hectares of state owned mixed species high forests, this is the approximate total area occupied by beech trees. In high forests there is selective cutting in accordance with 10-year management plans, mainly targeting individual trees, sometimes small groups of trees. Based on the requirements of the Law on Forestry of the Republic of Srpska (Official gazette 75/08 i 60/13), fellings are limited to 80% of the annual volume increase spelled out by the respective forest management plan (Law on Forestry; Matić, V. 1984, p. 339). In the space of the cut trees, seedlings and young trees fill the niche naturally. When natural regeneration does not happen as expected, then planting may become necessary. Thinning is negligible. High forests in Bosnia and Herzegovina represent prominent ecological value. Afforestation is a regular activity, implemented according to Forest management plans every year.

Due to below-average habitats, high utilization costs, and subsequently low profits, forest management of coppice has been somewhat neglected. As a result, many coppice forests have

become degraded and offer limited economic prospects. Consequently, there is limited harvesting and most timber is used as firewood or pulpwood. There is government intention to develop coppice forests into high forests, either through 1) direct conversion involving a clear cut and reforestation or 2) indirect conversion which requires selective cutting, removing low quality trees and replacing them with the seedling of desired species (Detailed in the Forest management plans for each Forest management economy). Neither plan is implemented on any meaningful scale since they do not make economic sense and external financial support is not available. A third option is lack of any management, anticipating that coppice will eventually turn into high forest, while delivering important ecosystem services (e.g. soil protection, water retention, carbon sequestration). The time need of this natural conversion is likely to be many decades, maybe a century. Because of the long time need, there is an absence of empirical evidence that this can indeed happen.

4 The FOX model

4.1 General description

The FOX model determines the optimal harvesting 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 harvesting process includes both felling and thinning of forests. The model allows the coexistence of several forest age classes. Timber and carbon prices are set exogenously for the model. 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 can handle up to 10 species/species groups in 10-year age classes and can be run for up to 220 years (with 10-year time periods). All characteristics can be extended based on the input data. The model is written in GAMS with an Excel interface.

In the context of dynamic exogenous factors, model outputs can be calculated for all modelled time periods: forest stock changes (by species and age), final forest harvesting (by species and age), forest thinning as a function of the available forest (by species and age), CO_2 sequestration and the impact of the carbon price on forest stock, harvesting, thinning and CO_2 sequestration. Finally, the model constructs forest carbon sink supply curves for different time periods.

The model determines the optimal timing of harvesting for each species and age group through dynamic linear optimisation based on the different end-use prices and costs associated with forest harvesting and planting, as well as the implicit forest growth functions.

The objective function maximises the net present value of the net benefits from timber production and the stream of net benefits from incremental carbon sequestration:

$$max\ PHI = \sum_{t} DF * \left(\sum_{c} pd_{c,t} * x_{c,t} - muc_{t} * \sum_{c} r_{c,t} - mup_{t} * \sum_{s,th} v_{s,tp,th} + PCAREX_{t} + PCARNEW_{t} \right) \quad 1)$$

Where the objective function is subject to

$$\sum_{t} w_{s,u,t} \leq land_{s,u} \qquad \forall s,u \qquad 2)$$

$$\sum_{u,c}\left(w_{s,u,t} * yw_{s,c,u,t}\right) \leq gamma_t * \sum_{u,c}\left(\left(land_{s,u} - \sum_{1}^{t-1} w_{s,u,t}\right) * \left(yw_{s,c,u,t} - yw_{s,c,u,t-1}\right)\right) \qquad \forall s,t \qquad 3)$$

$$\sum_{th} v_{s,t,th} \leq \sum_{u} w_{s,u,t} + \sum_{tp} v_{s,tp,t} \qquad \forall s,t \qquad 4)$$

$$r_{c,t} = \sum_{s,u} w_{s,u,t} * yw_{s,c,u,t} + \sum_{s,tp} v_{s,tp,t} * yv_{s,c,tp,t} \qquad \forall c,t \qquad 5)$$

$$thnew_{t,c} = \sum_{t}^{T}\sum_{s}\sum_{tp} v_{s,tp,t} * ytv_{s,tp,t,c} \qquad \forall c,t \qquad 6)$$

$$thex_{t,c} = \sum_{s,u}\left(land_{s,u} - pl * \sum_{t=1}^{t-1} w_{s,u,t}\right) * ytw_{s,u,t,c} \qquad \forall c,t \qquad 7)$$

$$x_{c,t} \leq r_{c,t} + thex_{t,c} + thnew_{t,c} \qquad \forall c,t \qquad 8)$$

$$PCAREX_t = \frac{\sum_s\{[(\sum_u(land_{s,u} - pl * \sum_{t=1}^{t} w_{s,u,t}) * yw_{s,c,u,t}) - (\sum_{s,u}(land_{s,u} - pl * \sum_{t=1}^{t-1} w_{s,u,t}) * yw_{s,c,u,t})] * nu_s\} * pc_t}{pl} \qquad \forall t \qquad 9)$$

$$PCARNEW_t = \sum_{s,tp}\left\{\left[\left(\sum_{t+1}^{T} v_{s,tp,t} * yv_{s,c,tp,t}\right) - \left(\sum_{t}^{T} v_{s,tp,t} * yv_{s,c,tp,t-1}\right)\right] * nu_s\right\} * pc_t \qquad \forall t \qquad 10)$$

$$DF = \frac{1}{(1+rho)^{10(t-1)}} \qquad 11)$$

Indices

c	commodity
s	species
u	tree age of „existing" forest
t	modelling period
th	period of final harvesting for „new" forest (th is part of the modelling period t)
tp	reforestation period (tp is part of the modelling period t)

Parameters

$pd_{c,t}$	commodity-specific price
muc_t	time dependent harvest cost
mup_t	marginal plantation cost
$land_{s,u}$	available land area
$yv_{s,c,tp,t}$	standing volume of new forest
$ytv_{s,tp,t,c}$	exogenous increment of thinning for new forest
$ytw_{s,u,t,c}$	exogenous increment of thinning for new forest

$yw_{s,c,u,t}$	standing volume of existing forest
nu_s	species-specific carbon content coefficient
pc_t	carbon price
rho	discount rate
DF	Discount factor
$gamma_t$	maximum share of the annual volume increase to be felled

Variables

PHI	net present value of benefit from timber production and carbon sequestration
	DF
	$pd_{c,t}$
$x_{c,t}$	quantity supplied
$muc_t r_{c,t}$	harvested quantity
$mup_t PCAREX_t$	net benefits from incremental carbon sequestration in case of "existing" forest
$PCARNEW_t$	net benefits from incremental carbon sequestration in case of "new" forest
$w_{s,u,t}$	area for final felling in existing forest
$v_{s,t,th}$	area for final felling for new forest
$v_{s,tp,t}$	area of new forest for reforestation
$thex_{t,c}$	thinning of existing forest
$thnew_{t,c}$	thinning of new forest

$$ytw_{s,u,t,c} yw_{s,c,u,t} nu_s pc_t rho$$

The objective function (Eq. 1) consists of the following four terms: the benefits from timber, as a perfectly elastic, linear demand "function" where the commodity specific it's the prices ($pd_{c,t}$) are exogenously determined for each period (t) and measured in € per m^3 timber demanded. The quantity supplied for each commodity ($x_{c,t}$) in each period (t) variable is measured in m^3 and determined by the model.

The objective function consists of the costs associated with harvest and plantation. The cost of harvest is calculated with exogenous and time dependent harvest costs (muc_t) measured in € per m^3 timber harvested and by the endogenously determined harvested timber quantity ($r_{c,t}$), given in m^3. The plantation cost is determined by the exogenous marginal plantation cost measured in € per hectare and the area of reforestation in period (tp). The last two terms of Eq. 1) describe the stream of net benefits from incremental carbon sequestration, discussed in detail in Eq. 10).

The supply of timber is determined endogenously and driven by the area for reforestation ($v_{s,tp,t}$) and area for final felling ($w_{s,u,t}$) and ($v_{s,t,th}$). The model distinguishes between "existing" forests from the beginning of the modelled time horizon, represented by w, and "new" forests from reforestation activities during the modelled time horizon, represented by v. The final felling of existing forest ($w_{s,u,t}$) is a matrix which describes the area for final felling for species (s) for tree ages (u) and for each year within the modelling period (t) measured in 1000 hectares. Similarly, variable ($v_{s,tp,th}$) includes the area of new forest for reforestation for species (s) for tree ages (tp) and the area of forest for final cut for each year within the modelling period (th) measured in 1000 hectares. Here tp and th are elements of t. Both ($w_{s,u,t}$) and ($v_{s,tp,th}$) are nonnegative variables.

The above-mentioned objective function is subject to the following constraints (introduced by Eq. 2)-10)). Constraints (Eq. 2) - 4)) describe the maximum amount of area that is available for final felling. Eq. 2) sets the maximum amount of area for final felling of "existing" forest for each species (s) and each forest age (u) over the entire modelled horizon, given the exogenously determined land area for each species and tree age ($land_{s,u}$). Eq. 3) describes the limitation on felling (left hand side) as a function of maximum share of the annual volume increase to be felled ($gamma_t$) and the annual volume increase (right hand side). Furthermore, Eq. 4) defines the maximum amount of area for reforestation $\sum_{th} v_{s,tp,th}$ (left hand side, LHS) as a function of the sum of the area for final felling of „existing" $\sum_u w_{s,u,t}$ and „new" forest $\sum_{tp} v_{s,tp,th}$ (right hand side, RHS of Eq. 4).
The constraint introduced by Eq. 5) describes the supply of timber from final felling by demand segment (c) for the modelled period (t) which is the product of the variable area available for final felling ($\sum_{s,u} w_{s,u,t}$) and ($\sum_{s,tp} v_{s,tp,th}$) and the main standing volume ($yw_{s,c,u,t}$) and ($yv_{s,c,tp,t}$) for „existing" and „new" forest, respectively. The main standing volume is determined for each species (s), each tree age (u and tp), each demand segment (c) and each period (t).

Constraints (Eq. 6)) and (Eq. 7) define the timber available from thinning for "new" and "existing" forests respectively. For thinning, the model takes into consideration all afforested land, meaning forest areas still available for final felling, $\sum_t^T \sum_s \sum_{tp} v_{s,tp,t}$ and $\left(land_{s,u} - pl * \sum_{t=1}^{t} w_{s,u,t}\right)$ for "new" and for "existing" forests respectively, where (T) indicates the end of the modelling time horizon. Eq. 6) and Eq. 7) also include the exogeneous increment of thinning ($ytv_{s,tp,t,c}$) and ($ytw_{s,u,t,c}$) for "new" and "existing" forest. Thus, the thinning is calculated based on the land available in period (t) for each species and tree age and the associated yield of side stocks, and it is automatically harvested and supplied in each period.

Constraint Eq. 8) sets the market equilibrium correlation where the demand side (LHS) is constrained by the supply side (RHS). The supply side consists of the timber production from final felling ($r_{c,t}$) and thinning of "existing" ($thex_{t,c}$) and "new" forest ($thnew_{t,c}$). The demand of timber ($x_{c,t}$) is determined for each time period (t) and each demand segment (c) ensuring that the perfectly elastic demand does not exceed supply at any time period and demand segment.

Equation 9) and 10) constraints describe the net benefits from incremental carbon sequestration for "existing" forest ($PCAREX_t$) and "new" forest ($PCARNEW_t$). Note that, from the forest manager's perspective, incremental carbon sequestration generates carbon benefits and loss of sequestration, i.e. forest harvest incurs carbon costs on growing stock. Thinning wood is produced and cut within the same time period, generating zero carbon benefit or loss. The RHS of these constraints consists of the following three main parts: the changes in the forest stock between period ($t-1$) and (t), the species-specific carbon fraction coefficient (nu_s) and the – time dependent – carbon price (pc_t) in CO_2 equivalent. The changes in forest stock includes the changes in area available between period ($t-1$) and (t) and the wood volume yield of side stocks for "existing" and "new" forests.

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

(i) FOX currently only accounts for stem-wood. This is only one of the carbon pools in forestry – albeit the most important one.

(ii) All harvested wood is assumed to be fully oxidised within the harvest period (instantaneous release to the atmosphere), i.e. all the carbon from the harvest is assumed to be lost to the

atmosphere and the forest manager is required to make a carbon release payment for the full amount.

(iii) FOX assumes that all the three distinct demand segments have perfectly inelastic demand, i.e. markets absorb any amount of output at the competitive market price. In the case of a small economy located in Central and Eastern Europe, such as Bosnia-Herzegovina, this assumption may hold in the short run but not necessarily in the longer run.

4.2 Use of FOX for continuous cover forestry

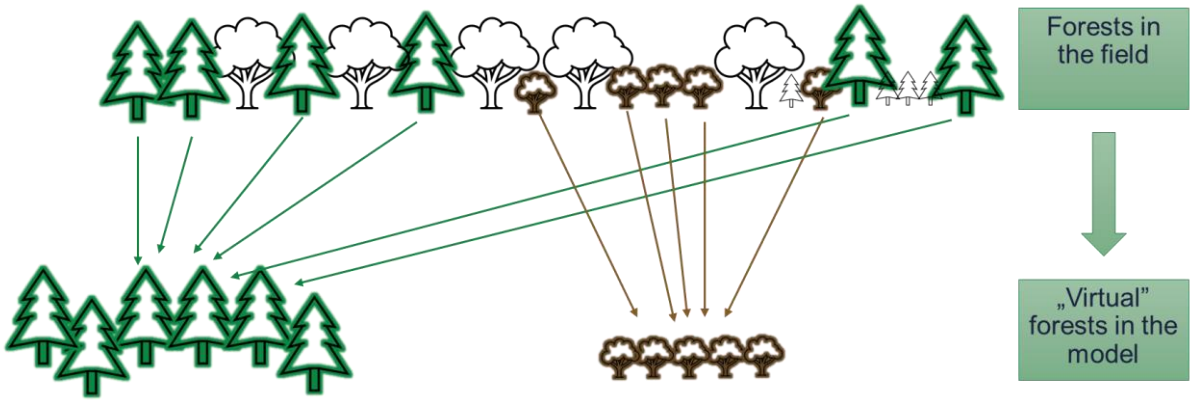
One limitation of using FOX is that it has been developed for modelling single-species, even-aged rotation forestry, so not directly suitable for continuous cover forestry (CCF) as the latter involves uneven-aged trees from multiple species. To address this limitation and become capable of modelling forests in BiH, particularly high forests, certain adjustments were made to align the characteristics of these forests with the structure of the FOX model.

To achieve this, the modelled forest units were virtually constructed by converting uneven-aged, mixed species forests into even-aged, single species forests, as illustrated by Table 1. A crucial step in this process involved the species-specific conversion of diameter to age and the number of trees to area. This conversion allowed for the creation of "virtual" forests, wherein an actual forest patch was segmented into numerous micro-units. Each micro-unit contained only one species and one age category. Subsequently, similar micro-units were aggregated at the country level.

This approach resulted in input tables that are compatible with FOX, where each cell represents the total countrywide area occupied by a particular species and age group within a given forest category. Although these forests are virtual representations, they provide the necessary data for FOX modelling and analysis in the context of BiH's forests.

We have confidence in the suitability of this methodology for analysing forest management policies at the country level. It is worth noting that according to Vanclay (2012), continuous cover forestry (CCF) can be effectively modelled using stand-based approaches, such as stand table projections. In the early stages of forest modelling, when computational capacity and data granularity were limited, this was the predominant methodology employed. However, it is also important to note that for individual forests with limited size and detailed data granularity, alternative approaches like cohort-based and single-tree models, in conjunction with economic optimization techniques, may be more appropriate. These alternative methods allow for a higher level of resolution and precision in modelling individual forests, taking into account specific characteristics and enabling more refined analysis.

Figure 2 The construction of even-aged, single species „virtual forests" for modelling purposes



5 Model inputs

In this chapter, we provide an introduction to the important characteristics of the forests in BiH that serve as inputs to FOX. We also briefly describe the data transformations when this helps to better interpret the data.

5.1 Land coverage of existing forests

The forest area utilized in the analysis (Table 1) has been disaggregated into specific age categories as required by the FOX Model. While the necessary data for plantations was readily available, significant data transformations were required for high forest and coppice. Forest inventories data in forest management plans in BiH primarily provide information on tree diameter rather than age classification. To derive the representation of each tree species within the forest area, we employed a calculation method based on the distribution of volume stocks per hectare by diameter class. This involved determining the percentage contribution of individual diameter classes to the total volume stock and multiplying it by the total area of the corresponding tree species[1].

The generated figures for coppice were deemed satisfactory. However, when applying this transformation to high forests, we observed that the resulting age distribution was disproportionately skewed towards older stocks, with a lack of younger forests. This did not align with the reality, namely that there is a substantial number of young trees in high forests due to the harvests of the last decades. Moreover, it was not suitable for modelling purposes as it could potentially lead to undesirable overharvesting.

To address this issue, we implemented an algorithm to allocate high forest areas to younger age groups while simultaneously satisfying several criteria. These criteria included ensuring that the area

[1] This exercise was done using the Tables of taxation elements of high and coppice forests in SR Bosnia and Herzegovina, i.e. the Table of thickness growth by tree species, pages 91 - 122, served to establish the connection between thickness growth-diameter-age

of young forests is in line with the harvested volumes and corresponding areas over the past two decades, maintaining consistency with statistical figures for total current stock (m^3) and total species-specific forest area (hectares), and achieving a more balanced distribution of age groups, without allowing for areas beyond the typical harvesting age. Modifying the yield curves of the main stocks was necessary to achieve this equilibrium, recognizing that the original yield curves were derived from even-aged forests rather than continuous cover forestry. Table 5 reviews the results of this exercise, offering an overview of the species and age composition of the modelled forests.

Table 5 Age and species specific area coverage of the modelled forests (thousand hectars)

	Plantation			High forest					Coppice		
Age (years)	Norway spruce	Pines	Fir	Beech	Norway spruce	Silver fir	Austrian pine	Sessile oak	Beech	Oak	Other hard-wood
0-10	0.0	0.0	0.0	38.5	20.3	23.1	2.5	5.0	0.0	0.0	0.0
11-20	0.0	0.0	0.0	38.5	20.3	23.1	2.5	5.0	0.0	0.0	0.0
21-30	0.0	0.0	0.0	45.4	14.3	13.2	7.4	7.5	0.0	0.0	0.0
31-40	0.0	0.0	0.0	45.4	14.3	13.2	7.4	7.5	3.1	0.0	9.5
41-50	11.8	23.3	8.9	45.4	14.3	13.2	7.4	7.5	19.2	24.3	11.8
51-60	11.8	34.9	8.9	45.4	14.3	13.2	7.4	7.5	47.1	30.7	5.6
61-70	0.0	0.0	0.0	45.4	14.3	13.2	7.4	7.5	70.5	50.6	0.0
71-80	0.0	0.0	0.0	45.4	14.3	13.2	7.4	7.5	79.0	83.0	0.0
81-90	0.0	0.0	0.0	45.4	14.3	13.2	7.4	7.5	3.1	9.0	0.0
91-100	0.0	0.0	0.0	45.4	14.3	13.2	7.4	7.5	0.0	0.0	0.0
101-110	0.0	0.0	0.0	45.4	14.3	13.2	7.4	7.5	0.0	0.0	0.0
111-120	0.0	0.0	0.0	0.0	0.0	13.2	0.0	7.5	0.0	0.0	0.0
121-130	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.5	0.0	0.0	0.0

Source: Data from forest management plans, statistical agencies and own calculations

5.2 Timber yield

Forest growth in FOX is quantified using yield curves, which are also referred to as growth curves or growth tables. These curves provide information on the volume of wood per hectare at different ages for both the main stand and thinning operations.

- The yield curves for the main stand indicate the age-specific volume of wood per hectare (measured in m^3/hectare). These curves allow us to assess the growth and development of the forest over time.
- Yield curves for thinning illustrate the volume of wood harvested during specific age categories (measured in m^3/hectare/period) without conducting a final cut. Even with thinning activities, the forest continues to grow, as evident from the increasing volume of the main stand.

In the case of BiH, FOX utilizes 10-year periods as the reference timeframe. Consequently, the yield curves for the main stand display the volume of wood for forests aged 10, 20, 30 years, and so on, while the yield curves for thinning represent the volume of wood harvested during the 1st, 2nd, 3rd, and subsequent 10-year periods.

The increment data for plantations and natural forests were derived from different sources. For plantations, the Widemann (1943) dataset was utilized. In the case of high forests and coppice, the data used for recalculations was obtained from the Tables of taxation elements of high and coppice forests in SR Bosnia and Herzegovina (Drinic et al., 1980). These tables provided information on thickness growth and the number of trees per hectare and were subsequently converted into volume increase tables.

The resulting yield tables encompassed age groups ranging from 30 to 110-130 years, depending on the species under consideration. However, since modelling required data beyond these age groups, extrapolation was performed to cover younger forests (below 30 years) and older forests (over 110 years). Additionally, some of the time series data required smoothing to eliminate outliers. To accomplish this, we used the regression analysis presented in the EFISCEN model documents of the European Forest Institute (EFI) by Pussinen et al. (2001):

The growth function is assumed to have a quadratic form, and the coefficients are calculated based on the following formula:

$$I_{Vf} = a_0 + \frac{a_1}{T} + \frac{a_2}{T^2} \qquad 12)$$

, where
I_{Vf} is the ten-year volume increment,
T is the age of the stand in years, and
a_0, a_1, a_2 are the coefficients,

Given these estimated coefficients, the extrapolation of the volume increment is calculated for the older stand age (up until 600 years). Since the estimated volume increment deviates from the observed values, some correction must be made, given the following formula of Pussinen et al (2001):

$$I_{Va} = I_{Vf} * \left(\frac{a_1}{T}\right)^{beta} \qquad \forall\, V_a \leq V_m \qquad 13)$$

$$I_{Va} = \frac{I_{Vf} * V_m}{V_a} \qquad \forall\, V_a > V_m \qquad 14)$$

where
I_{Va} is the ten-year volume increment for observed standing increment,
I_{Vf} is the ten-year volume increment for estimated standing increment,
V_a is the observed standing volume (measured in $^{m^3}/_{ha}$),
V_m is the estimated standing volume (measured in $^{m^3}/_{ha}$), and
$beta$ is the correction parameter, that is the relationship between the relative standing volume and the relative volume increment (Nilsson et al. 1992) [2].

[2] Nilsson, S., Sallnäs, O. and Duinker, P. 1992. Future forest resources of Western and Eastern Europe. International Institute for Applied Systems Analysis. A report on the IIASA forest study. Parthenon Publishing Group, UK. 496 p. Based on the discussion in Nilsson et al. (1992) and Pussinen et al. (2001), in our calculation a specie-independent 0.4 value is applied for beta parameter.

After the above EFISCEN estimation in the case of high forests the area coverage, registered volumes of wood and the yield curves of main stands had to be reconciled, as described in Chapter 5.1. This required the proportionate upward adjustment of the yield coefficients for high forest main stock.

Lastly, in the context of high forests, it was necessary to harmonize the area coverage, recorded wood volumes, and the yield curves of the main stands, as outlined in Chapter 4.1. This process entailed proportionate upward adjustments of the yield coefficients for the main stock of high forests, by multiplying all the coefficients with the same, species-specific value, ranging from 2.0 for sessile oak to 3.5 for norway spruce.

The yield curves for main stands and thinning are presented in Figure 3 and Figure 4, respectively. Among the different forest types, high forest species demonstrate the highest growth rates in the main stand, while coppice forests, particularly oak and other hardwood coppice forests, exhibit slow growth. Plantations demonstrate moderate growth in the main stand, with notable yields from thinning operations.

Figure 3 Yield of main stands (m^3/ha)

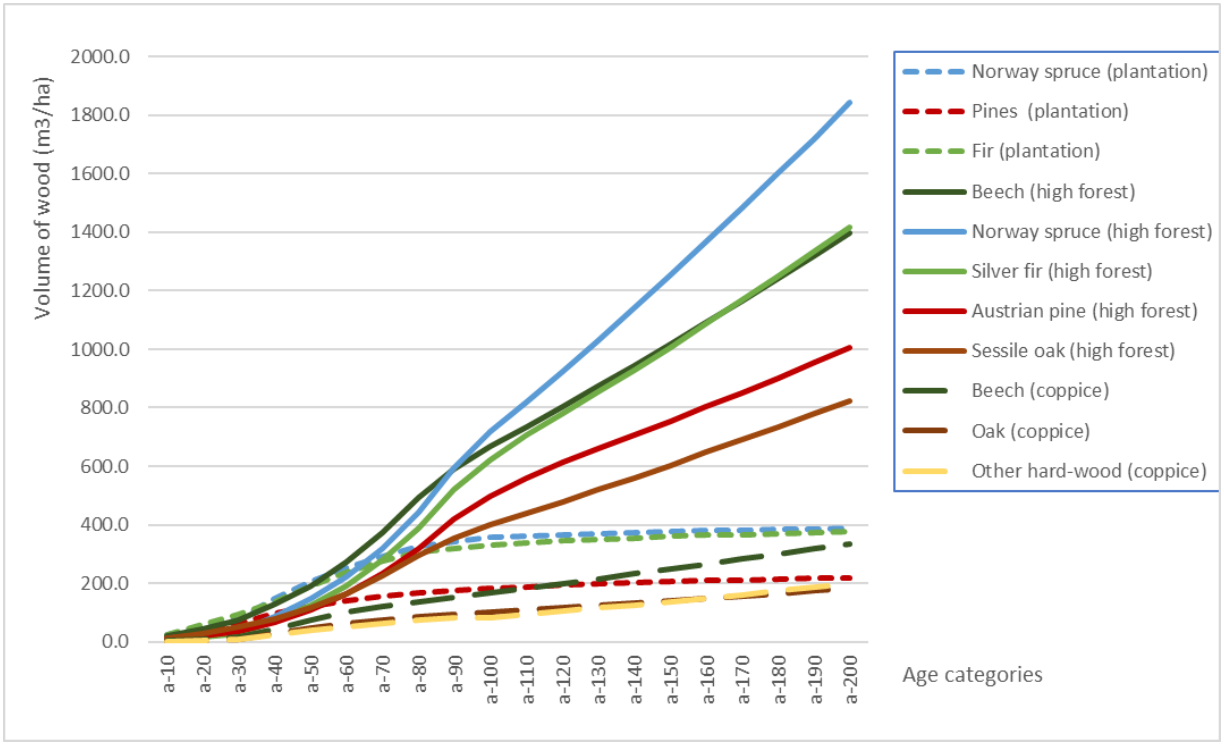
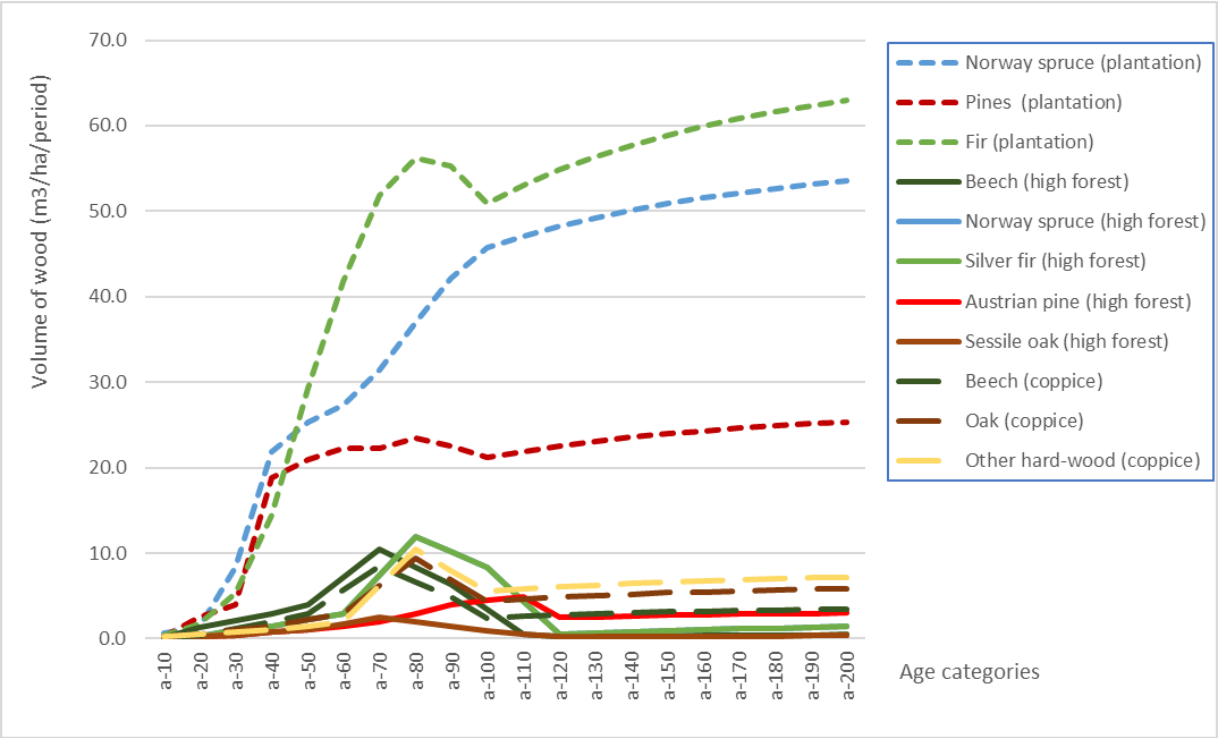


Figure 4 Yield of thinning (m^3/ha/period)



5.3 Wood assortments and harvesting age

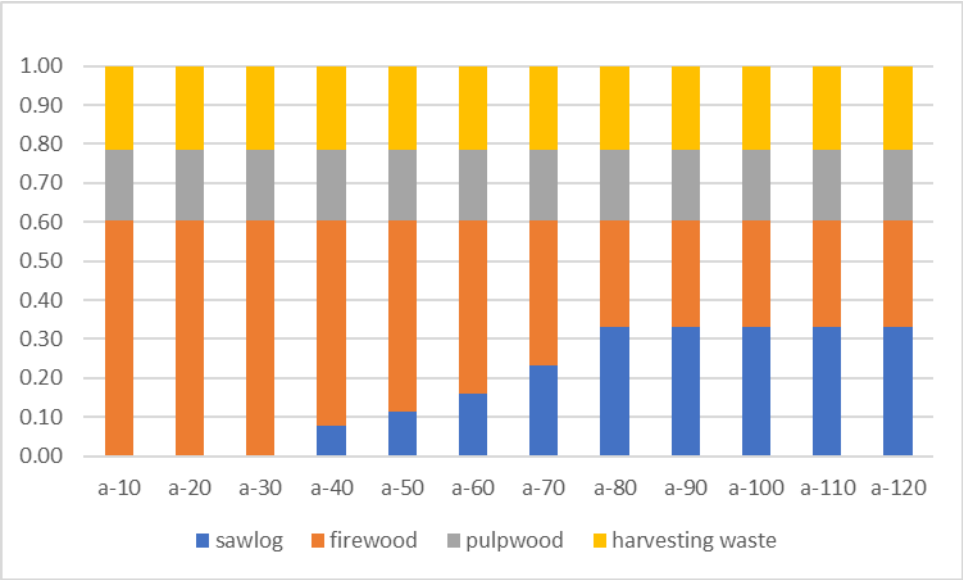
Timber production in FOX comprises three main types of assortment, along with harvesting waste. These assortments are sawlog, firewood, and pulpwood. The distribution of assortments varies depending on the species and the age of the trees.

To determine the age-specific ratios of the assortments for each species, field data from BiH was utilized[3]. Figure 5 presents an illustration specifically for beech high forests. In this case, the proportion of pulpwood and harvesting waste remains constant, while the ratio of sawlog increases at the expense of firewood. By the age of 80, sawlog constitutes approximately 33% of the total timber, maintaining that level thereafter.

[3] Sources:

- Implementation of the Production and Financial Plan of the JPŠ "Forests of the Republic of Srpska" a.d. Sokolac for 2021, and for FBiH 2021 for public owned forests.
- Tables of taxation elements of high forests and coppice forests in Bosnia and Herzegovina, Sarajevo 1980.
- Execution of Production and Financial Plans of PFE Forest of Republika Srpska, Existing Forest Management Plans, Tables of taxation elements of tall forests and coppice forests in Bosnia and Herzegovina, Sarajevo 1980.

Figure 5 The share of age-specific assortmentsand harvesting waste for high forest beech



The same pattern is applicable to other species as well, the share of sawlog within timber is increasing until the cutting age is reached, thereafter it stays constant. Table 6 showcases the composition of timber assortments at the age of harvesting for all forest types modelled in the study. It should be noted that coniferous timber is not ideal for firewood, but it can be effectively utilized for industrial purposes as pulpwood. The ratio of harvesting waste in cut timber is assumed to be constant for all age categories (Forest management plans of the RS and cantons in FBiH).

Table 6 Composition of timber at harvesting age

	sawlog	firewood	pulpwood	harvesting waste	harvesting age (years)
Norway spruce (plantation)	0.35	0.00	0.36	0.29	40
Pines (plantation)	0.35	0.00	0.36	0.29	40
Fir (plantation)	0.35	0.00	0.36	0.29	50
Beech (high forest)	0.33	0.27	0.18	0.22	80
Norway spruce (high forest)	0.62	0.00	0.10	0.28	80
Silver fir (high forest)	0.63	0.00	0.12	0.25	90
Austrian pine (high forest)	0.66	0.00	0.11	0.23	80
Sessile oak (high forest)	0.32	0.28	0.18	0.22	100
Beech (coppice)	0.06	0.46	0.22	0.26	50
Oak (coppice)	0.05	0.47	0.22	0.26	50
Other hard-wood (coppice)	0.00	0.48	0.26	0.26	50

Source: Execution of Production and Financial Plans of PFE Forest of Republika Srpska and cantons in FBiH

The harvesting age of a species also serves as a crucial calibration variable for the model. Considering the inherent uncertainties associated with certain model inputs, such as species-specific land

coverage across different age groups and yield curves for high forests, there exists some flexibility in setting the values for these variables. To validate the accuracy of the model, the results are compared against forest management plans, specifically by verifying if the model's predicted harvesting age aligns with the age at which harvesting typically occurs in practice.

5.4 Costs of forest management

FOX utilizes two types of costs: the cost of cutting and the cost of reforestation following clearcut.

The average cost of cutting, based on statistical data, is 31.05 KM/m^3. Actual, site-specific values depend on orographic conditions, the terrain, availability of roads, distance to main road, as well as the type and age of trees cut. The range of observed cutting costs is between about 27 and 38 KM/m^3. The unit cost applies to the gross harvested volume, including harvesting waste that stays in the forest. The cutting cost of timber in coppice forests may be higher than the cutting cost of high forests, since a m^3 of the latter requires less effort. For modelling purposes, we use the average value of 31.05 KM/m^3.

As for the cost of reforestation, it is estimated at 4,000 KM/ha. This is the figure applied for plantations and coppice. However, the actual cost can vary depending on site specific conditions and the success of the initial round of planting. In the case of selective felling, it is expected that the forest will naturally regenerate without additional costs for the forest manager. Selective felling practices are employed in all high forests, aiming to maintain sustainable forest management practices while minimizing reforestation expenses. Therefore 0 cost is applied to reforestation of high forests. There are some coppice forests that are also selectively cut as opposed to clear cuts, but there is no data on how widespread this practice is for coppice forests. Therefore in case of coppice, the full reforestation cost of 4,000 KM/ha is applied in FOX.

5.5 Sales price of assortments

The sales price of different assortments in the forestry sector is influenced by forest type and species, as outlined in Table 7. Typically, sawlog holds a higher value compared to firewood and pulpwood, while oak tends to command a premium over other species. To determine the average prices for each assortment and forest type, a weighted average approach is utilized, using the volume of the main stock as the weight in the calculation. Forest types are modelled separately, and in the current version of FOX a single price is applied to each assortment. By using weighted averages, the average values account for the varying volumes and characteristics of the different forest types, resulting in a more accurate representation of the overall pricing dynamics within the model.

Table 7 Sales price of wood assortments (KM/m^3)

	sawlog (KM/m3)	firewood (KM/m3)	pulpwood (KM/m3)	harvesting waste (KM/m3)	Current volume of main stock (1000 m3) *
Norway spruce (plantation)	160		52	0	5,395
Pines (plantation)	160		52	0	7,759
Fir (plantation)	160		52	0	3,818
Beech (high forest)	137	67	78	0	162,324
Norway spruce (high forest)	190		60	0	49,172
Silver fir (high forest)	177		60	0	49,672
Austrian pine (high forest)	150		60	0	17,884
Sessile oak (high forest)	280	78	78	0	23,512
Beech (coppice)	112	67	78	0	26,211
Oak (coppice)	250	67	70	0	14,588
Other hard-wood (coppice)		67	70	0	986
Average	**164**	**68**	**71**	**0**	
Average for plantation	160		52	0	
Average for high forest	164	68	71	0	
Average for coppice	161	67	75	0	

Source: Sale price list of PFE „Sume Republike Srpske" and statistical offices of the RS and FBiH, KM/m^3

* Estimated volume of main stock in each forest category using FOX input data. The current volume is used as the weight to calculate average prices for plantations, high forests and coppice.

5.6 Carbon content

The carbon content of the stand is calculated as the tons of carbon stored in a cubic meter of wood. This measure varies between species because of their varying carbon fraction (i.e., tons of carbon stored in a ton of wood) and basic wood density (i.e., the ratio between dry mass of stem-wood in tons and fresh stem-wood volume in cubic meters.) In the case of grouped species, we use the weighted average of carbon fraction and basic wood density. We apply the weighted average of the carbon content to calculate the mass of carbon sequestered in the forest (see equations 9) and 15)). The input data for carbon fraction and weighted average of basic wood density are based on reference values from IPCC 2006 Guidelines, Chapter 4, Volume 4, Tables 4.3 and 4.14., respectively.

Table 8 Carbon content of tree species in the FOX-BiH model

Species or species group	Basic wood density t/ m^3	carbon fraction, t/t	**carbon content t/m^3**
Oak	0.58	0.48	0.28
Sessile oak	0.58	0.48	0.28
Beech	0.58	0.48	0.28
Scots pine	0.42	0.51	0.21
Austrian pine	0.47	0.51	0.24
Norway spruce	0.4	0.51	0.20
Fir	0.4	0.51	0.20

source: IPCC 2006 Guidelines, Chapter 4, Volume 4, Tables 4.3 and 4.14.

Note that the carbon content is not equal to how much CO_2 is sequestered in a unit growth of tree volume. To get the CO_2 equivalent, the carbon content must be multiplied by the mass of the molecule, 44/12.

6 Modelling results

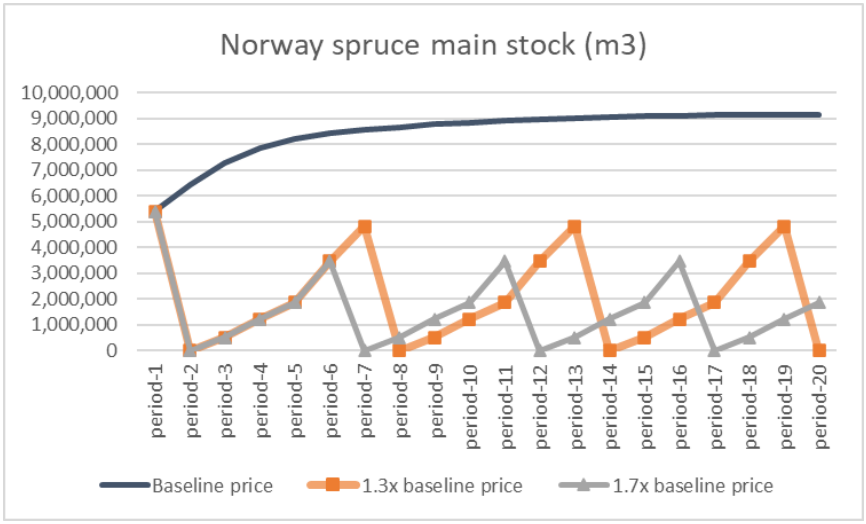
Results are presented based on forest types to account for their distinct features and enable a more customized analysis. The three forest types were modelled separately to ensure accurate and specific findings.

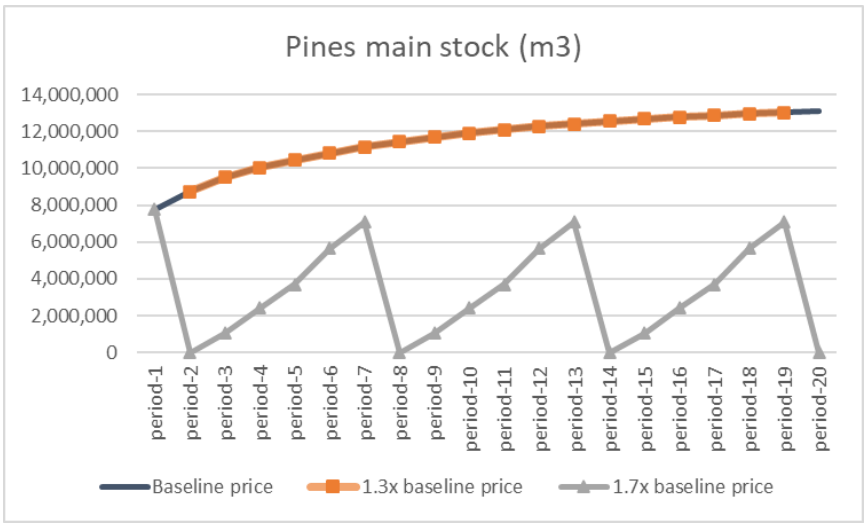
6.1 Plantations

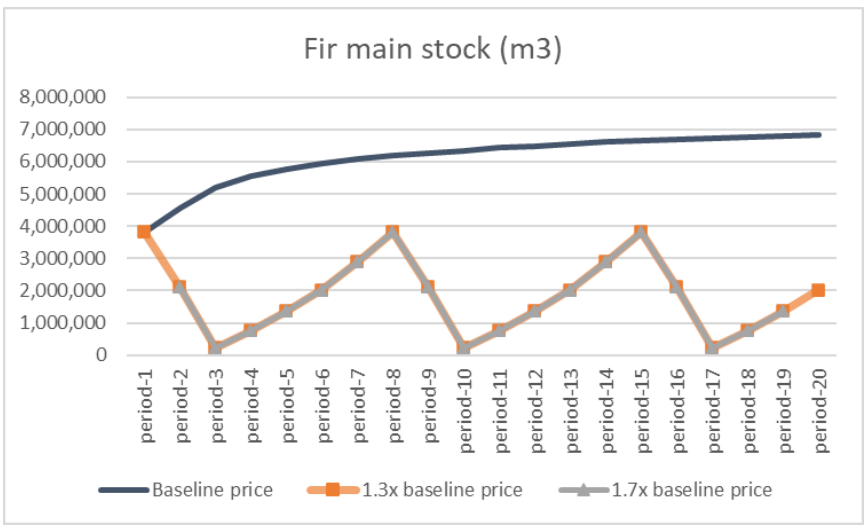
While in principle plantations should be under rotation forestry management, in practice they are seldom harvested as the costs of obligatory reforestation outweigh the net revenues from the harvest. Our modelling results align with this observation. Currently, there is no final cut in plantations, only thinning is conducted. As a result, plantations keep growing and sequestering CO_2 at a moderate pace. In this baseline scenario, implementing a carbon payment would have no impact since the forests already achieve the maximum feasible level of carbon accumulation.

To foster rotation forestry in plantations, an increase in timber prices for timber assortments is necessary. For Norway spruce and Fir plantations, a 30% higher timber price would prompt a 60- and 70-year harvesting cycle, respectively. In the case of pines, a 70% increase in timber assortment prices is required to incentivize active forest management. These findings are detailed in Figure 6.

Figure 6 Stock of Norway spruce, Pines and Fir plantations at baseline and increased assortment prices



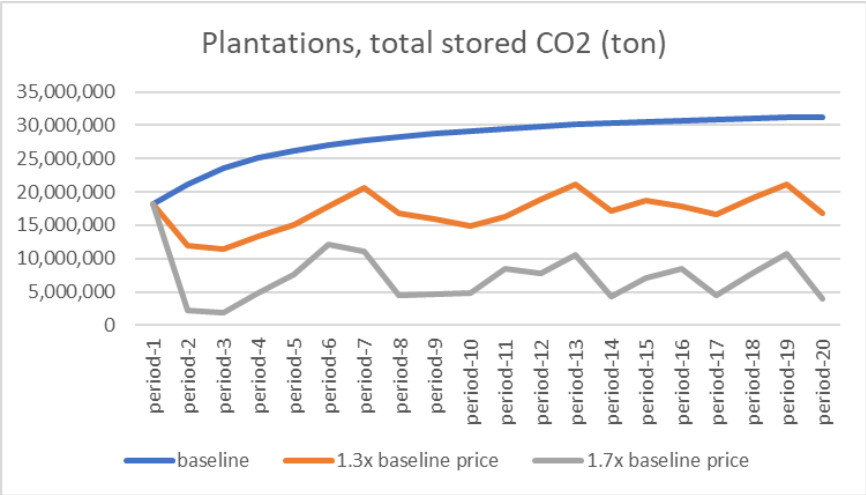




Note: The length of a period is 10 years.

While higher timber assortment prices would incentivize active forest management, they would also result in lower levels of carbon storage, as shown in Figure 7. Therefore, if prices were substantially higher than the current levels - a scenario that could occur over a multi-decade time horizon - the implementation of a carbon payment or other climate policy instrument may be necessary to discourage excessive harvesting and reestablish higher levels of carbon storage in forests.

Figure 7 Total stored CO_2 in plantations under different assortment price scenarios



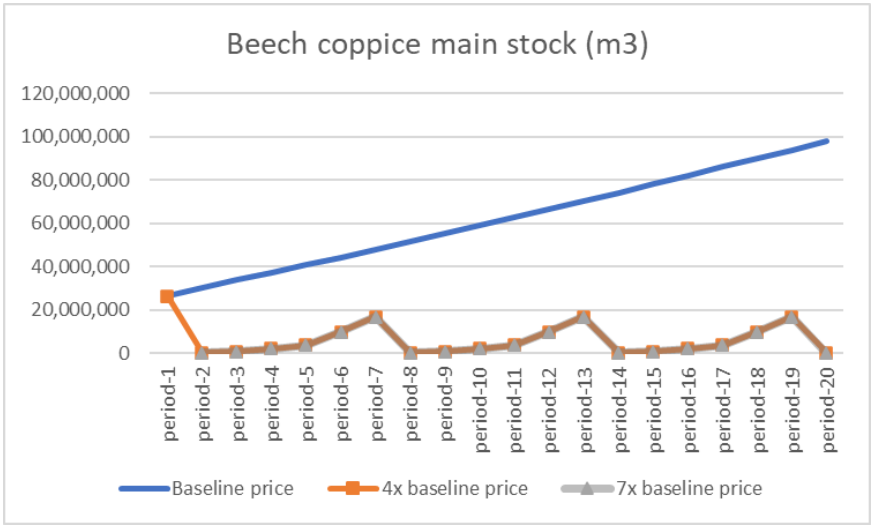
Note: The length of a period is 10 years.

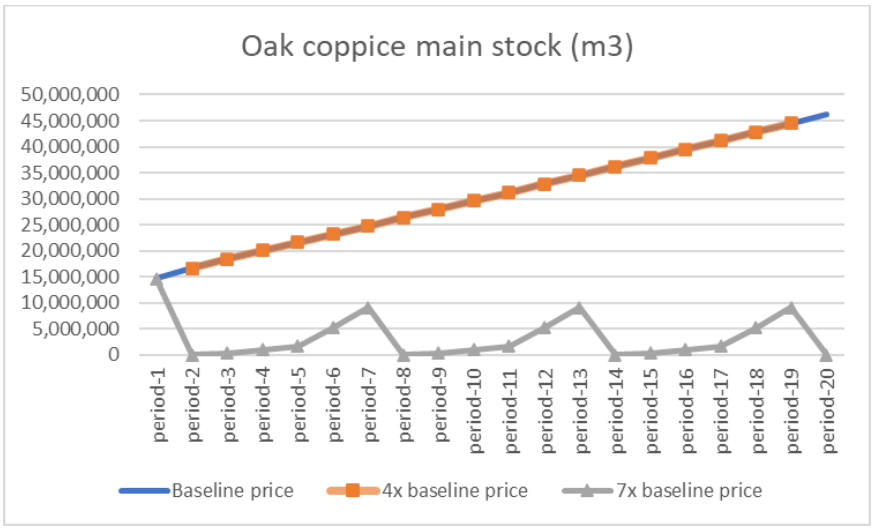
6.2 Coppice forests

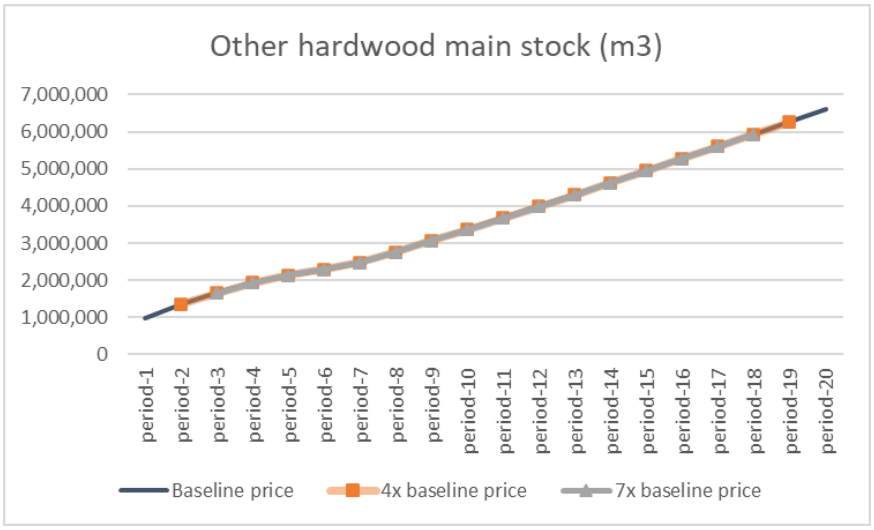
Similarly to plantations, coppice forests are not managed actively, as the potential revenues fail to offset the associated expenses. We examined the influence of assortment prices and reforestation costs to identify which price and cost level would incentivize active management.

Figure 8 shows the coppice stock at different price levels. For beech, prices four times higher than the baseline are needed to trigger active management. In the case of oak coppice, prices need to be increased to seven times the baseline to incentivize active management. For other hardwood species, the ratio would need to be approximately twelve times higher. The figure displays results for all species with baseline, 4x baseline, and 7x baseline prices.

Figure 8 Stock of beech, oak and other hardwood coppice forests at baseline and increased assortment prices



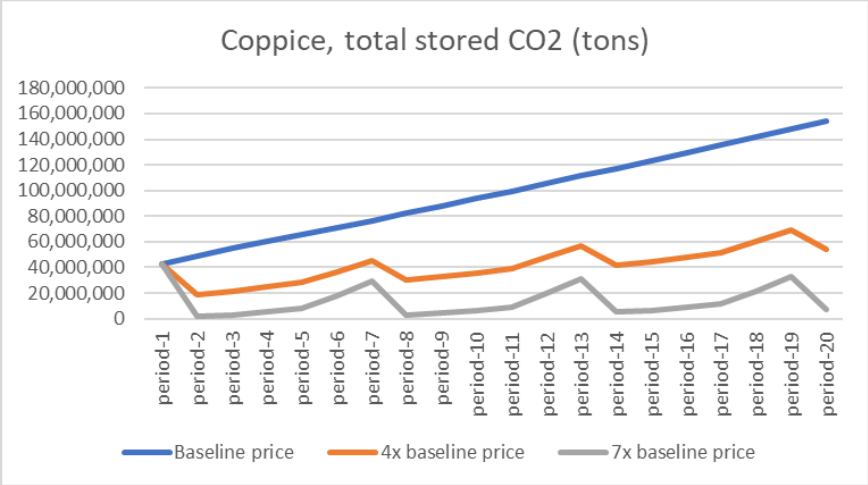




Note: The length of a period is 10 years.

The CO_2 stock under the three price scenarios is shown in Figure 9.

Figure 9 Total stored CO_2 in plantations under different assortment price scenarios



Note: The length of a period is 10 years.

Furthermore, we examined the impact of reforestation costs. Our modelling results revealed that the cost of reforestation has a more pronounced influence on coppice rotation forestry than assortment prices (Table 9). When the cost of reforestation is assumed to be zero, indicating the feasibility of natural regeneration, rotation forestry can commence even at current assortment prices. This finding can be attributed to the relatively modest average yearly growth of coppice, which necessitates significantly higher timber prices to offset the expenses associated with reforestation. In certain regions of BiH, there are coppice forests that can naturally regenerate after selective cutting of small sections. In these specific areas, the costs associated with reforestation can be presumed to be negligible, establishing rotation forestry as a viable economic option.

Table 9 Rotation forestry of coppice under selected assortment price and reforestation cost combinations

	Baseline prices (100%)	4x baseline prices	7x baseline prices
Baseline reforestation cost (4000 KM/ha)	none	Beech (60 years)	Beech (60 years) Oak (60 years)
Lower reforestation cost (2000 KM/ha)	none	Beech (60 years) Oak (60 years)	Beech (50 years) Oak (50 years) Other hardwood (50 years)
No reforestation cost (0 KM/ha)	Beech (60 years) Oak (50 years) Other hardwood (80 years)	Beech (50 years) Oak (50 years) Other hardwood (50 years)	Beech (50 years) Oak (50 years) Other hardwood (50 years)

Note: Only those species are listed in the cells where rotation forestry would be triggered. The length of the rotation cycle is displayed in brackets

6.3 High forests

High forests in BiH merit special attention as they constitute the majority of the country's forested areas, timber volume, and CO_2 sequestration. Furthermore, high forests are the most actively managed forest type in the country. Our analysis covers three lines of scenarios:

- Current forest management, wherein harvest is restricted to 80% of annual growth ("80% LIMIT" scenario).
- Increased harvest: Allowing for the harvesting of 100% of the annual growth ("100% LIMIT" scenario).
- Hypothetical scenario: Harvesting decisions driven solely by profit maximization, without any regulatory limitations ("NO LIMIT" scenario).

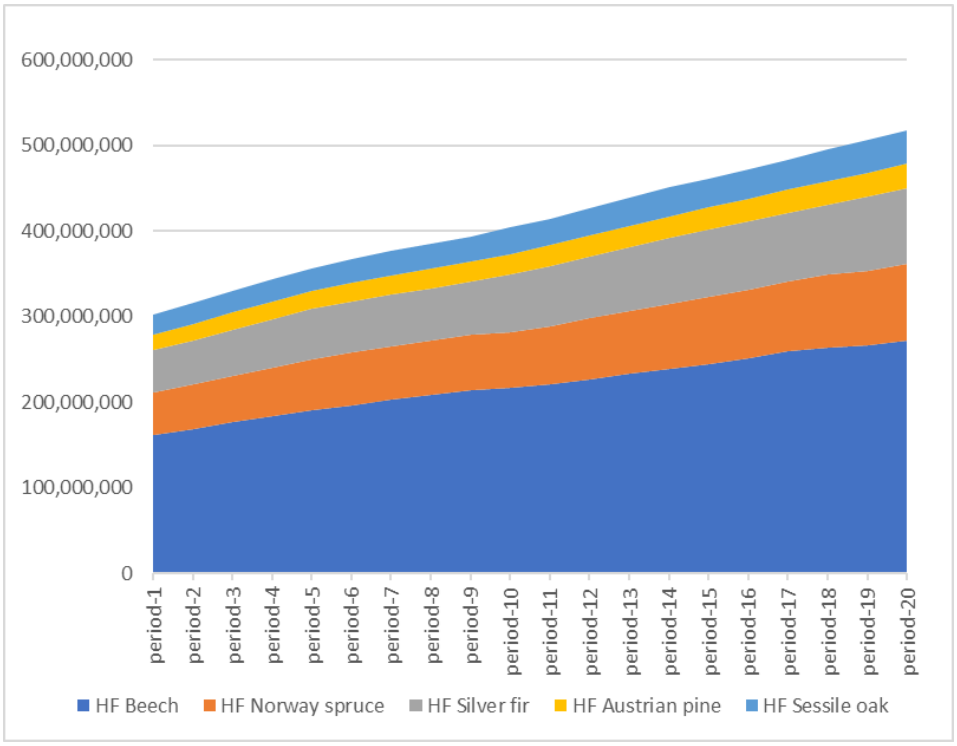
Additionally, we explore the influence of carbon payments on harvesting decisions. Unlike plantations and coppice forests, there is significant ongoing harvesting activity in BiH's high forests. In the absence of regulatory constraints, the volume of final felling would be even greater, therefore exploring the potential impact of carbon payments is reasonable.

6.3.1 80% LIMIT scenario

When final felling is limited to 80% of annual growth, it does not significantly harm the growth potential of forests. Our modelling, conducted over a 200-year time horizon, demonstrates that the main stock of high forests continues to grow steadily (Figure 10). Simultaneously, the volume of final felling remains relatively stable at around 50 million m^3 per 10 years throughout the modelled time frame (Figure 11 and Figure 12). A modest decrease can be observed after period 8, as the harvests from earlier periods result in an age structure that yields lower average outputs for several decades. Nevertheless, overall forest management appears to be sustainable, with a growing stock and

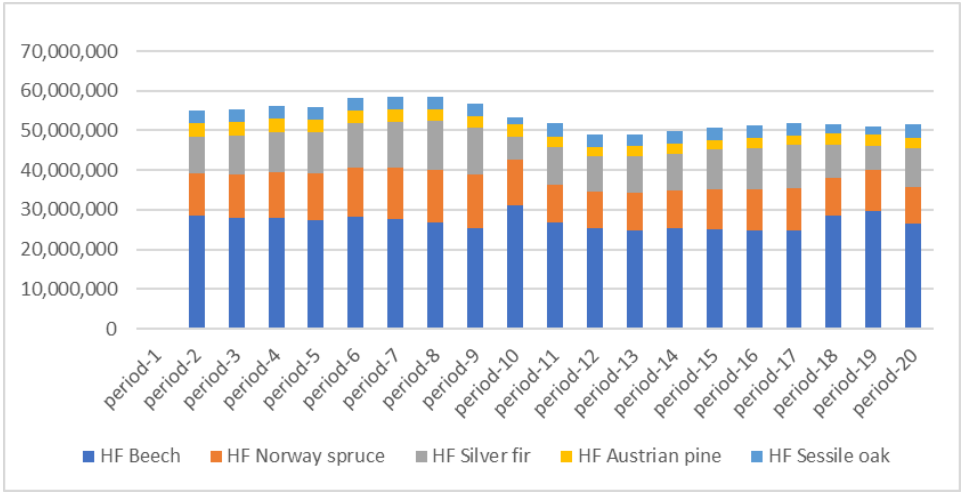
relatively consistent harvests. Additionally, the species and assortment composition of the harvests remain balanced over time.

Figure 10 Main stock of the analysed BiH high forests under the 80% LIMIT scenario (m^3)



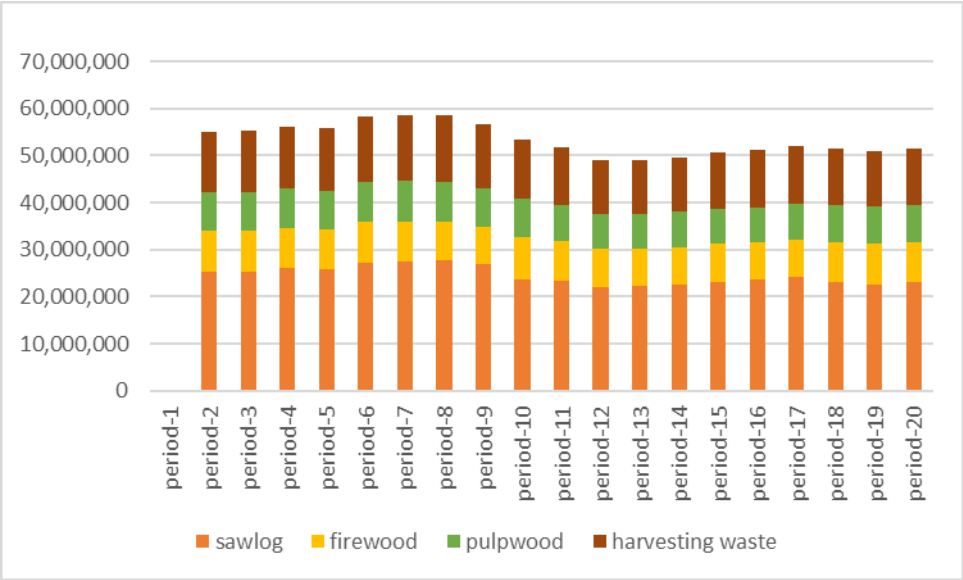
Note: The length of a period is 10 years.

Figure 11 Final cut by species under the 80% LIMIT scenario (m^3/10 year period)



Note: The length of a period is 10 years.

Figure 12 Final cut by assortments under the 80% LIMIT scenario (m^3/10 year period)

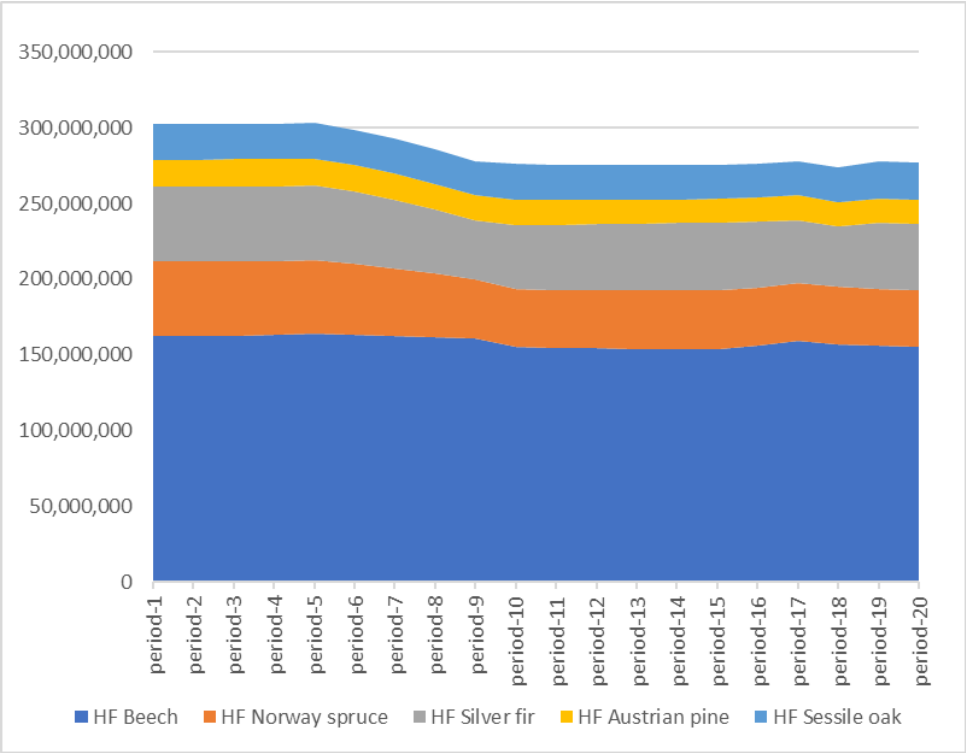


Note: The length of a period is 10 years.

6.3.2 100% LIMIT scenario

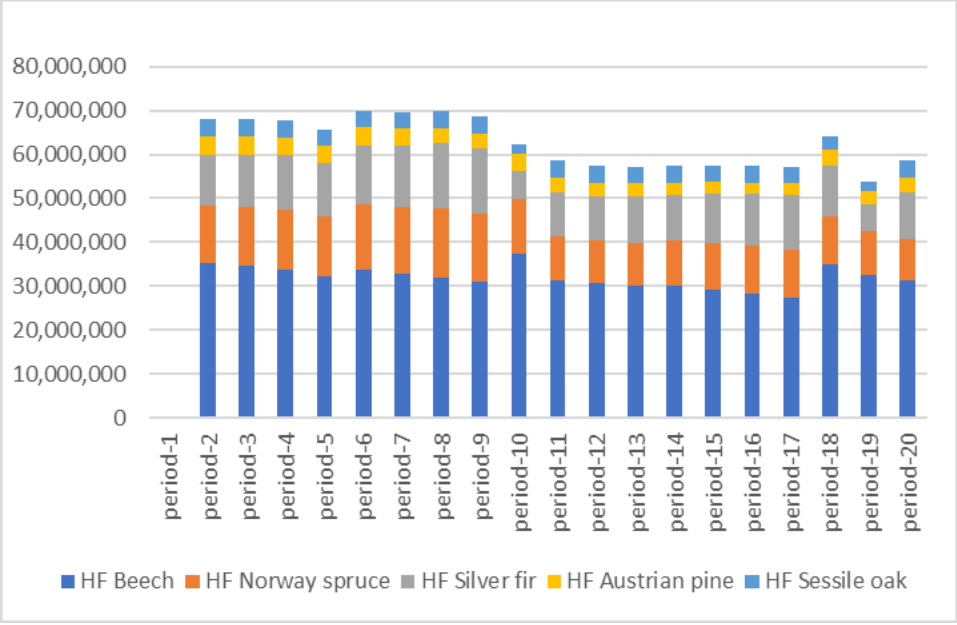
We have introduced an additional scenario with harvesting limits, where the harvest is set at 100% of annual growth. This scenario is not based on any policy or practice, it serves as a comparison to the other scenarios. As depicted in Figure 13, the main stock of high forests experiences a slow decline when the entirety of the annual growth is exploited (the fact that the stock declines, instead of staying constant, is the consequence of a changing forest structure due to harvests taking place for older trees) . Comparatively, this scenario yields a higher overall harvest (Figure 14, Figure 15) than the 80% LIMIT scenario, but it also demonstrates increased volatility in harvested volume. While this can still be considered as sustainable forest management, it should be of note that timber reserves dwindle, and the amount of CO_2 stored in high forests – which is proportional to the volume of the main stock – decreases, as opposed to the 80% LIMIT scenario.

Figure 13 Main stock of the analysed BiH high forests under the 100% LIMIT scenario (m^3)



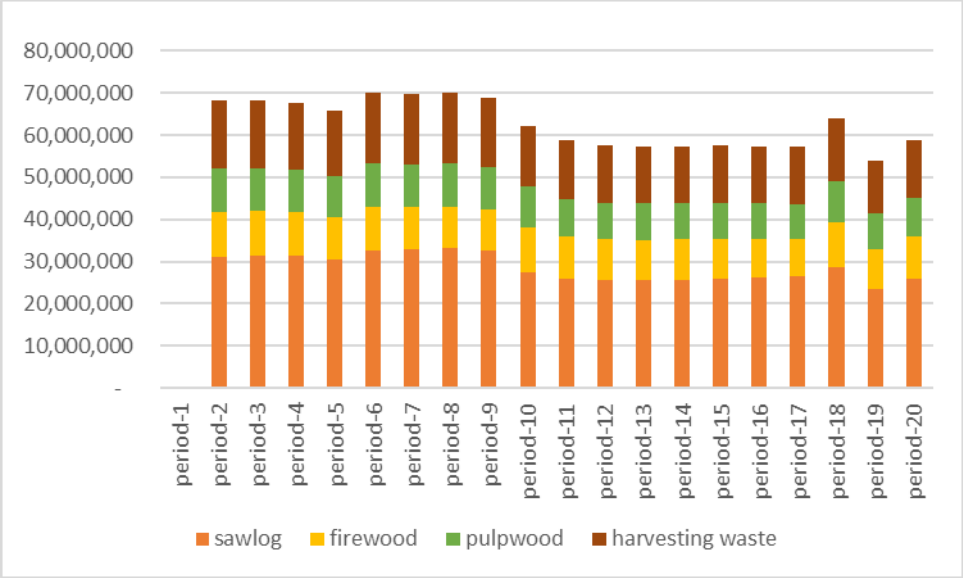
Note: The length of a period is 10 years.

Figure 14 Final cut by species under the 100% LIMIT scenario (m^3/10 year period)



Note: The length of a period is 10 years.

Figure 15 Final cut by assortments under the 100% LIMIT scenario (m^3/10 year period)



Note: The length of a period is 10 years.

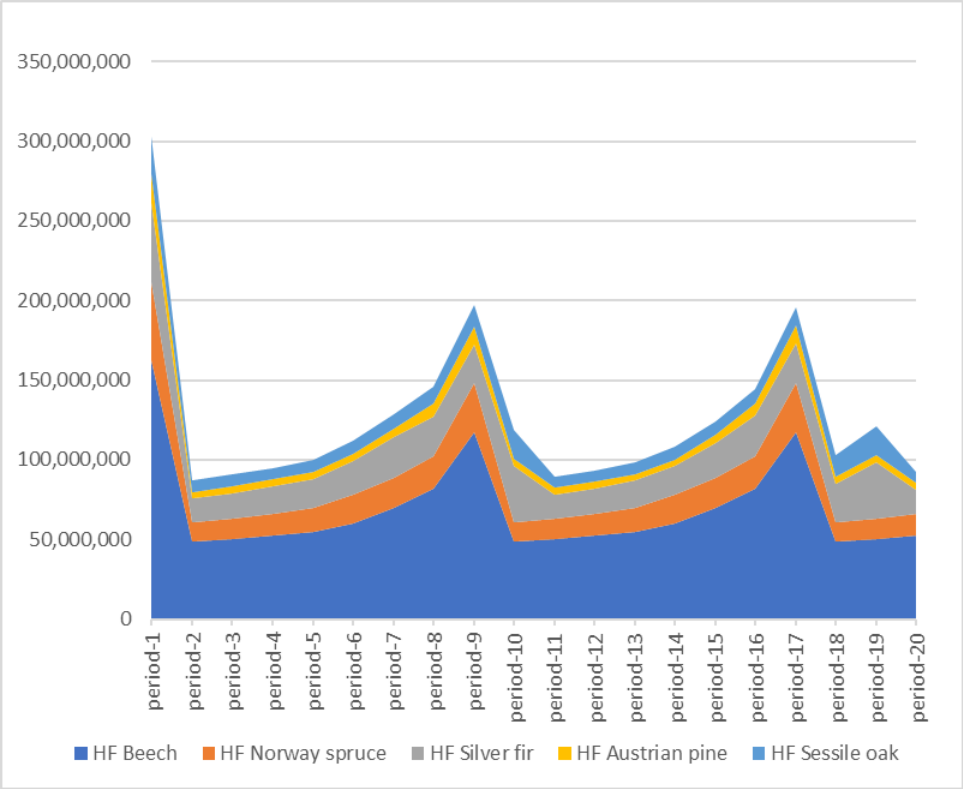
6.3.3 NO LIMIT scenario

In this scenario, we assume the absence of any regulatory limits on harvests, allowing forest managers unrestricted freedom to cut trees based solely on business considerations. Essentially, harvesting decisions are driven by profit maximization without regard for sustainability, soil health, biodiversity, and other environmental factors. This hypothetical scenario represents a situation where high forests are handed over to a large private corporation that is primarily focused on financial success. Also note that the NO LIMIT scenario is the theoretical representation of what could actually happen if authorities were unable to enforce any harvesting limit.

According to the modelling results, all trees that have reached their harvesting age would be cut within the next 10 years (Figure 16). This initial intensive harvest is followed by several decades of minimal cuts, during which the forest stock gradually recovers to some extent, but without ever reaching the initial stock again. Subsequently, a new round of harvesting becomes feasible as the forest regains its productivity (Figure 17, Figure 18).

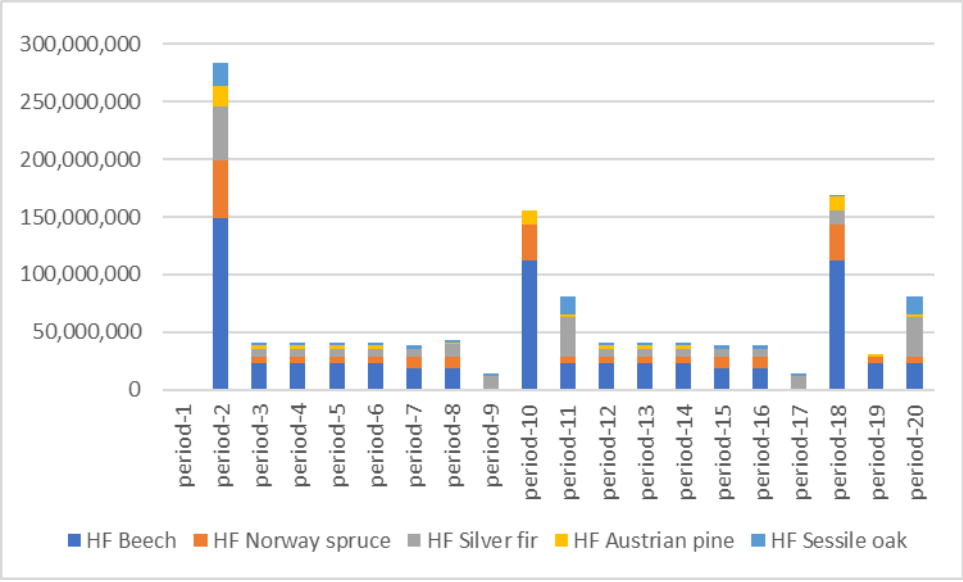
While the NO LIMIT scenario is unthinkable in the context of BiH, it has occurred in European history and continues to happen in lower-income countries where there are inadequate regulations or enforcement mechanisms to protect forests. It serves as an important contrast to the 80% LIMIT scenario, emphasizing the significant value that harvesting limits provide in terms of sustainable forest management.

Figure 16 Main stock of the analysed BiH high forests under the NO LIMIT scenario (m^3)



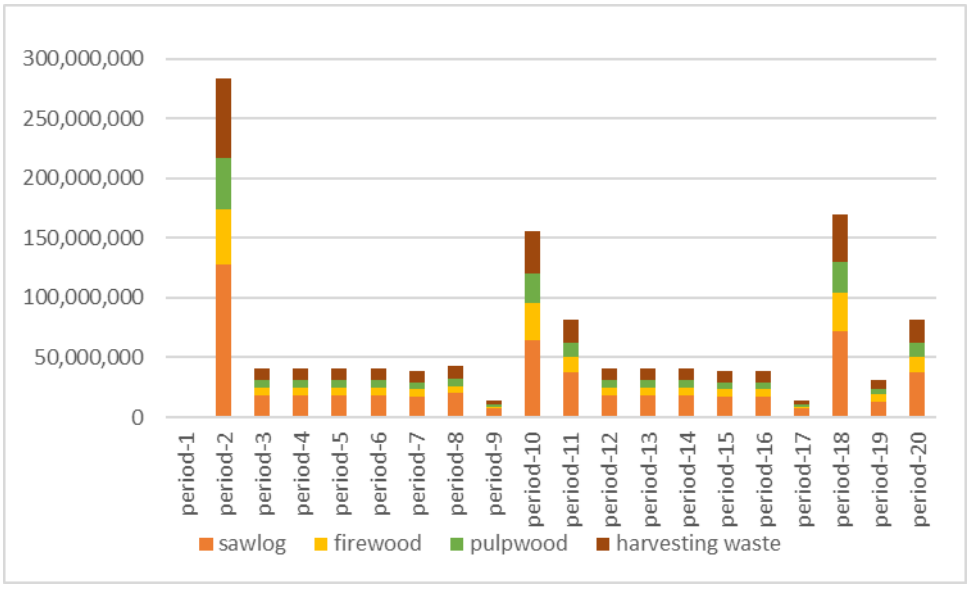
Note: The length of a period is 10 years.

Figure 17 Final cut by species under the NO LIMIT scenario (m^3/10 year period)



Note: The length of a period is 10 years.

Figure 18 Final cut by assortments under the NO LIMIT scenario (m^3/10 year period)

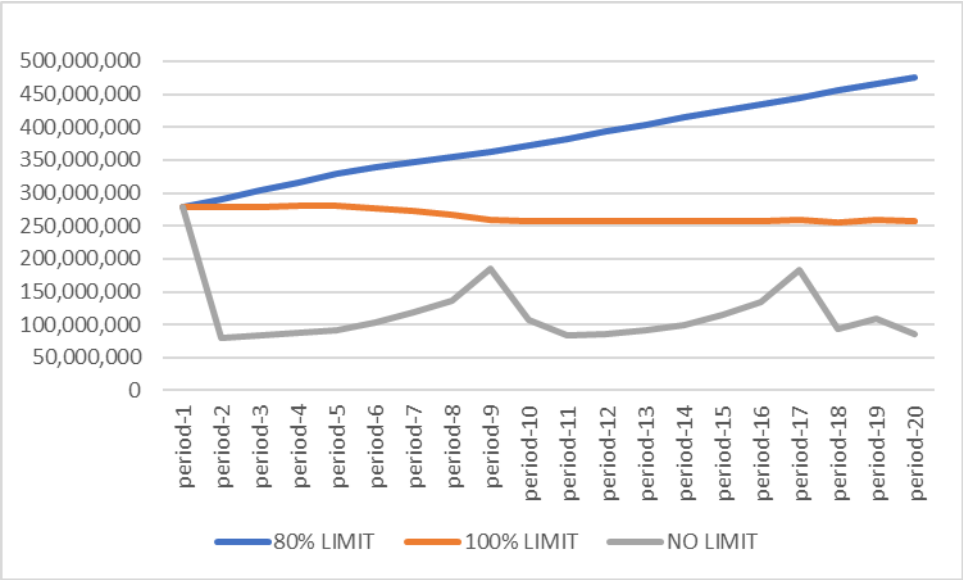


Note: The length of a period is 10 years.

6.3.4 Introduction of carbon payments

Figure 19 illustrates the carbon pathways of the three analysed high forest scenarios – still without any carbon payments involved. The 80% LIMIT scenario not only demonstrates sound forest management practices, but also emerges as an appealing climate policy. In contrast, the other two scenarios would lead to a net loss of stored carbon over the analysed 200-year period.

Figure 19 Carbon stock in high forest scenarios (tons of CO_2)



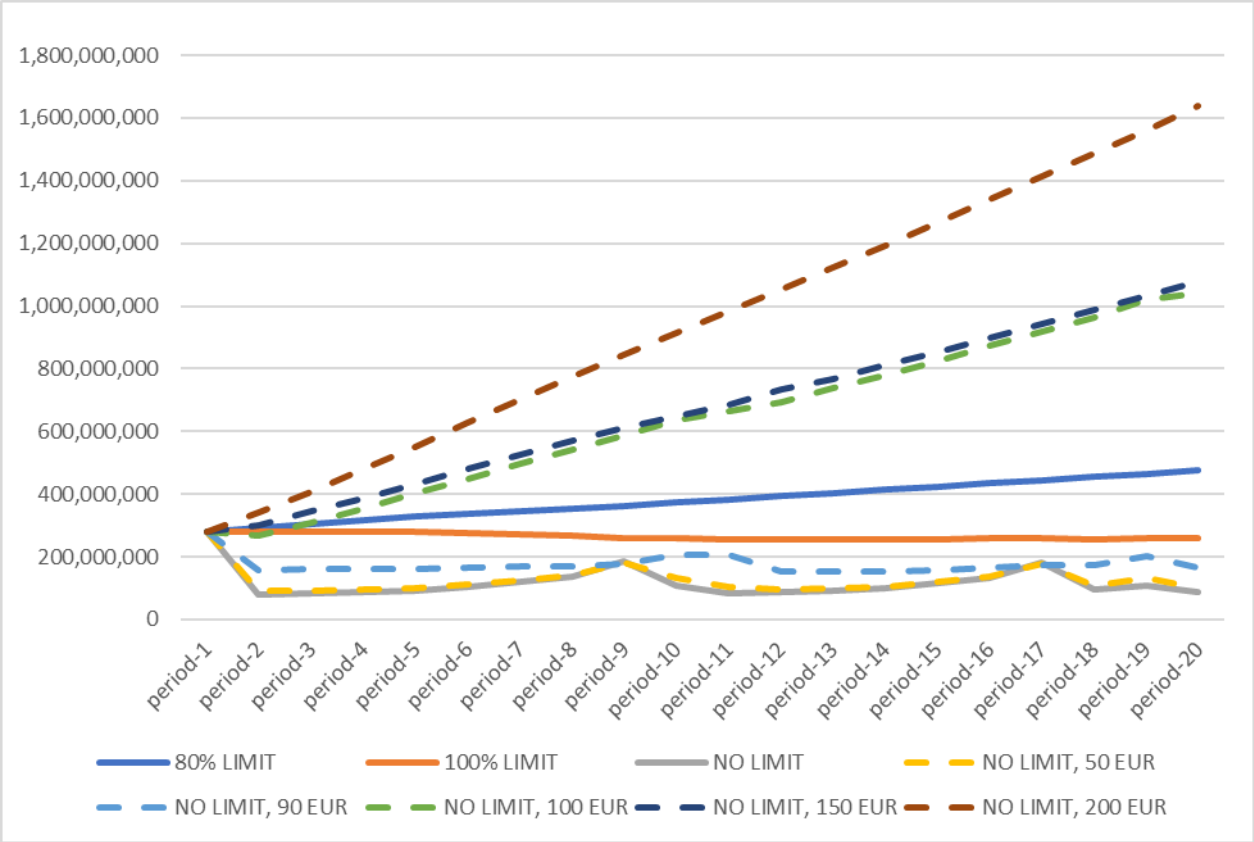
Note: The length of a period is 10 years.

The introduction of carbon payments serves as a powerful incentive to delay harvesting. Carbon payments take the form of a linear carbon tax-and-subsidy scheme rewarding every additional ton of carbon sequestered in any period by a flat rate subsidy payment and penalizing each ton of carbon released from harvesting by the same level of flat rate tax payable after the released carbon. This instrument has the potential to substantially change the cost – benefit dynamics over the time horizon of the model. Note that the direction of carbon payments is the inverse of timber payments: carbon subsidies are payable only if timber harvest is delayed by another period and, similarly, when timber is harvested and sold, the carbon tax is payable at the same time, after the assumed immediate release of carbon.

The higher the carbon payment per ton of sequestered CO_2, the more likely forest owners are to delay harvesting. Carbon payments were incorporated into the NO LIMIT scenario to explore which carbon incentives would yield carbon storage levels comparable to those in the 80% LIMIT and 100% LIMIT scenarios.

As shown in Figure 20, a carbon payment of 50 EUR/ton CO_2 has minimal impact, resulting in a carbon pathway and forest stock similar to the NO LIMIT scenario. With a payment of 90 EUR/ton CO_2, there is a moderate incentive to delay harvests, but the carbon stock remains lower than that of the 80% LIMIT and 100% LIMIT scenarios. However, at 100 EUR/ton CO_2, significant carbon sequestration occurs. This is the threshold at which all harvests would cease in both beech and oak high forests, as carbon payments become more attractive than timber revenues. A similar observation may be made at 150 EUR/ton CO_2. This implies that raising the carbon payment level from 100 to 150 EUR/ton CO_2 provides little additional benefit in terms of carbon sequestration. On the other hand, at 200 EUR/ton CO_2, carbon storage would significantly increase, resulting in a complete halt to harvesting in all high forests.

Figure 20 Carbon stock in high forest scenarios, with carbon payments added to the NO LIMIT scenario (tons of CO_2)



Note: The length of a period is 10 years.

The significant shift observed between 90 and 100 EUR/ton CO_2 payments may appear unexpected. However, it can be attributed to the homogeneous nature of beech and oak high forests in the model. In the analysis, active forest management abruptly ceases in nearly 600 thousand hectares of forests. The accuracy of our analysis could be enhanced if more detailed data was available on high forests, enabling us to segment them based on productivity. Without such data, we can conclude that, from a carbon storage perspective, the current 80% harvesting limit regime is comparable to a scenario without prescribed regulatory limits on harvests but accompanied by a carbon payment of approximately 100 EUR/ton CO_2.

Finally, we also examined carbon payments as an additional tool alongside harvesting limits, rather than as an alternative. In this analysis, we introduced carbon payments to the scenario with an 80% harvesting limit, starting at 10 EUR/ton CO_2 and gradually increasing the payment in increments of 10 EUR/ton CO_2 up to 300 EUR/ton CO_2. The objective was to establish a marginal abatement cost (MAC) curve for carbon sequestration. Our findings are presented below.

Figure 21 illustrates the volume of additional carbon sequestration projected for the next 1, 2, and 3 decades (assuming a starting point in 2020). No incentives are observed below 100 EUR/ton CO_2. However, at this level, a total of 31 million tons of additional carbon sequestration is projected over 10 years, 64 million tons over 20 years, and 98 million tons over 30 years. Beyond 100 EUR/ton CO_2,

there are no notable additional incentives until reaching 160 EUR/ton CO_2, where some increase in carbon storage is observed. The peak incentive effect is seen at 180 EUR/ton CO_2, resulting in 53 million tons, 110 million tons, and 172 million tons of supplemental carbon storage for the three respective time horizons, compared to the baseline scenario without any carbon payments.

Figure 22 presents the marginal abatement cost curve for the three time horizons, illustrating how the annual average value of additional carbon sequestration changes with different levels of carbon payments. The pattern observed in Figure 21 is consistent, with no significant impact observed below 100 EUR/ton CO_2 and the maximum impact achieved at a payment level of 180 EUR/ton CO_2. Additionally, it is worth noting that longer time horizons result in higher average annual values of sequestration.

Figure 21 Increase in net carbon sequestration as a result of adding carbon payments to the 80% LIMIT scenario

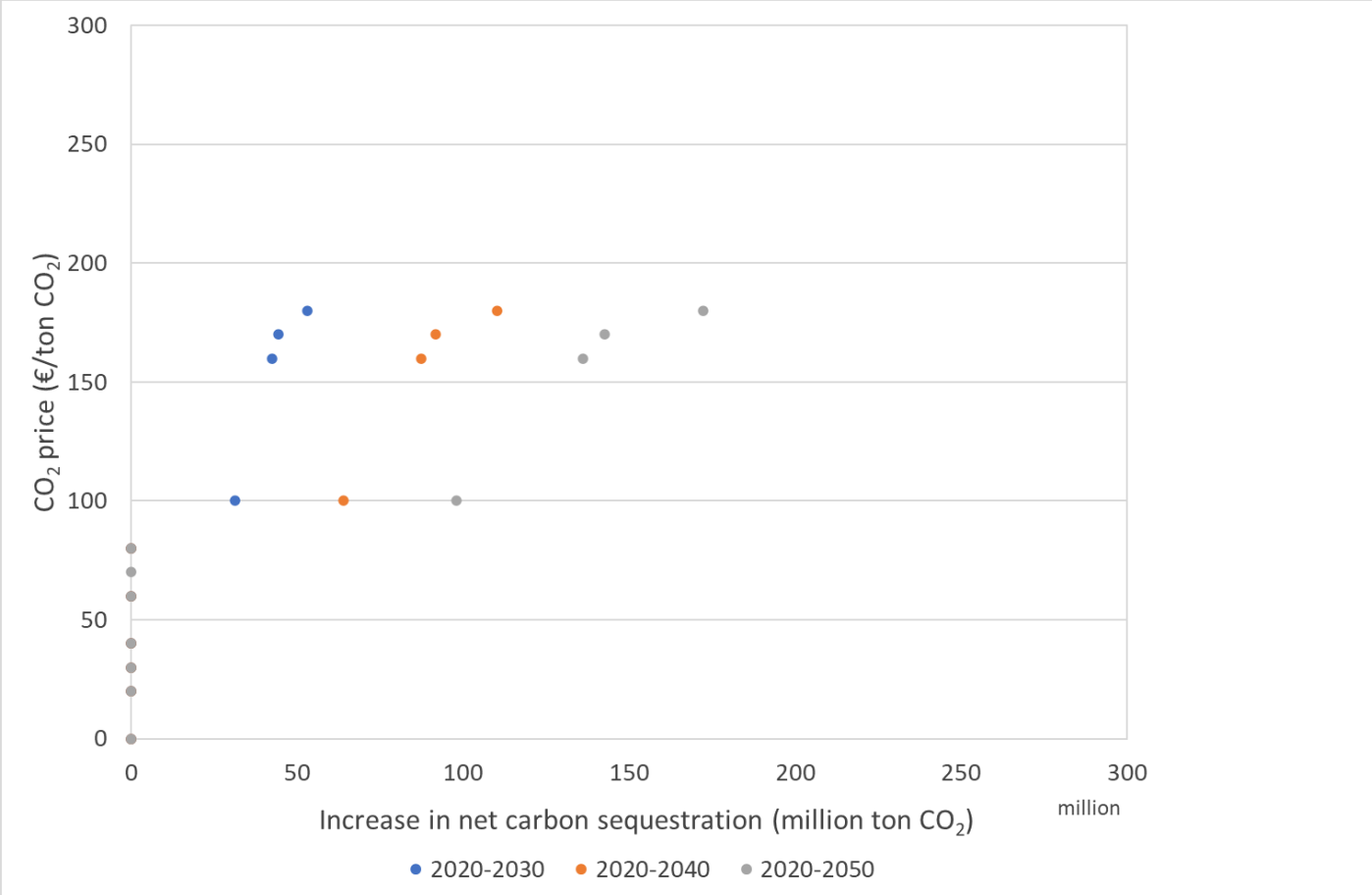
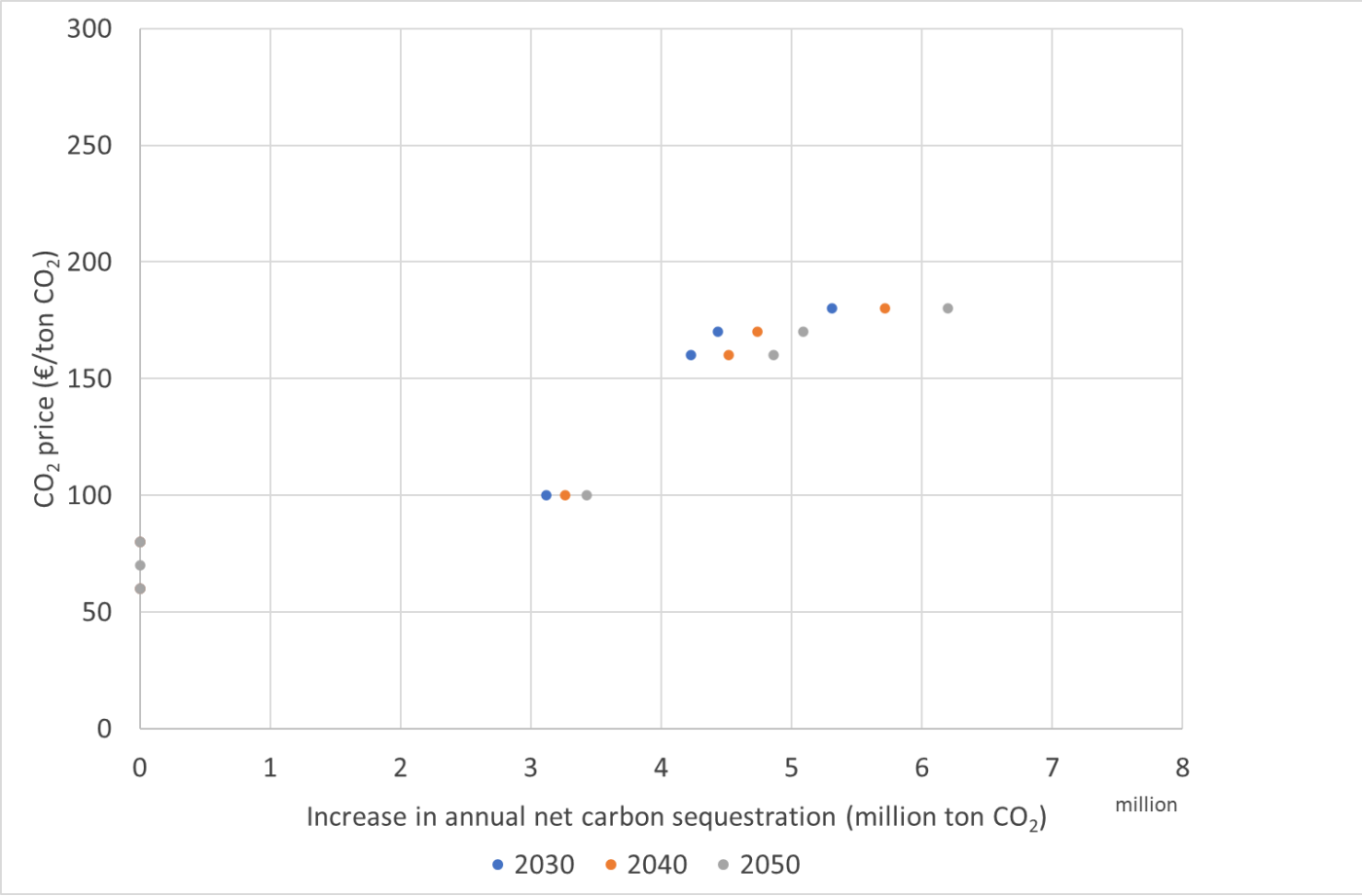


Figure 22 The marginal abatement cost curve of forest based sequestration as a result of adding carbon payments to the 80% LIMIT scenario with annual average sequestration



As a conclusion, introducing carbon payments in addition to the existing harvesting restrictions brings moderate benefits. The biggest incentive takes place at 100 EUR/ton CO_2, while the incentive effect peaks at 180 EUR/ton CO_2. This is a substantial unit cost for carbon storage, there are lower cost options, including other measures in the forestry sector (see e.g. Chapter 6.4). Carbon payments for BiH high forests are at present difficult to justify.

6.4 Transformation of coppice to high forest

As discussed in Chapter 3.2, the transformation of coppice forests into high forests is a stated objective, but it is not implemented on a significant scale due to the short-term costs involved and the long-term nature of the benefits. In order to assess the costs and changes in carbon sequestration resulting from this transformation, we utilized the cost and price data collected for FOX and the model's capability to simulate forest growth.

For this analysis, we focused on two types of forests: oak coppice and beech coppice, both currently 80 years old. We assumed that these forests could be characterized by the average parameter values described in Chapter 5 for their respective forest types. We conducted the analysis over a 10-period (100-year) time horizon.

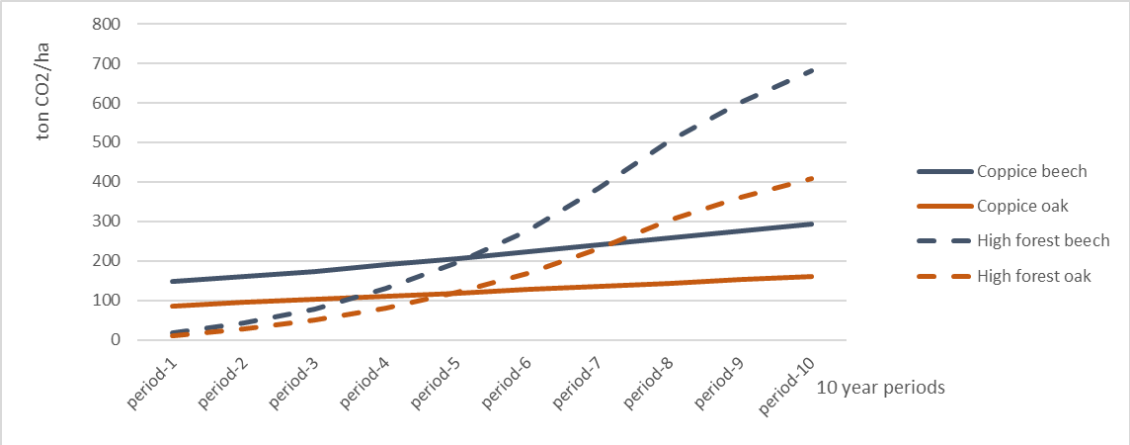
Two scenarios were compared:

1. The coppice forest is left uncut, allowing it to continue growing along the yield curve.

2. The coppice forest is replaced by high forest. All the 80-year-old coppice trees are harvested, and a high forest is planted in their place.

The carbon pathways for both scenarios, depicted in Figure 23, illustrate the results. After the final cut of the coppice forests, the carbon sequestration of the high forests begins at zero. However, after 50 years, the cumulative carbon stock in the high forests surpasses that of the coppice forests. In 100 years, the carbon advantage of the high forest is estimated to be 390 tons CO_2/ha for beech and 247 tons CO_2/ha for oak.

Figure 23 CO_2 stored in 80+ year coppice forests and newly planted high forests



The transformation of coppice forests into high forests holds significant potential from a climate policy standpoint. However, in practice, this transformation is not occurring on a meaningful scale. To better understand the motivations, or lack thereof, of forest managers, we conducted an economic analysis. The results of our calculations are summarized in Table 10.

In the table all costs are presented as negative values, while benefits (revenues) are shown as positive values. The "Immediate net benefit" row reflects the short-term financial position of the forest manager. If the coppice forest remains untouched, the corresponding value is 0. However, if the transformation to high forest takes place, the balance of costs and revenues - related to cutting, timber sales, and reforestation - is negative, indicating that the revenues from timber sales do not offset the costs. It is understandable, then, that forest managers are not inclined to transition to high forests.

Nevertheless, when considering the future revenue stream from thinning and the value of the forest (measured by the value of timber) in 100 years, the switch to high forests becomes attractive. Both of these factors were discounted to present value using a 3% real discount rate. The "Total net benefit" row represents the sum of all current and discounted future costs and revenues. In other words, from a purely financial perspective, it makes sense to undertake the conversion.

However, in practice, decision makers generally have shorter time horizons and tend to focus on immediate costs rather than future benefits that may occur 100 years from today. In economic terms, they discount future cash flow, in this case future benefits. In our analysis a 3% discount rate is used,

but private investors often use a higher rate, depending on perceived risk. As a result, if policy makers aim to trigger large-scale transformation from coppice to high forests, they would need to establish a compensation mechanism to cover these initial costs, amounting to approximately 1,000 KM/ha for beech coppice and 1,600 KM/ha for oak coppice. (see row in Table 10 titled 'Immediate net benefit')

Table 10 A simple cost-benefit analysis of coppice transformation to high forest (KM/ha)

	Beech coppice without transformation	Transformation of beech coppice to beech high forest	Oak coppice without transformation	Transformation of oak coppice to oak high forest
Cost of cutting (KM/ha)	0	-4,490	0	-2,620
Initial revenue from sale of timber (KM/ha)	0	7,537	0	5,006
Cost of reforestation (KM/ha)	0	-4,000	0	-4,000
Immediate net benefit (KM/ha)	**0**	**-954**	**0**	**-1,614**
Present value of revenue from thinning over the next 100 years (KM/ha)	340	465	676	99
Present value of main stock in 100 years (KM/ha)	342	1,619	231	1,968
Total net benefit (KM/ha)	**681**	**1,130**	**907**	**453**
Carbon stock in 100 years (ton CO_2/ha)	*292*	*682*	*160*	*408*
Difference in carbon stock due to transformation from coppice to high forest (ton CO_2/ha)	*390*		*247*	

We can now also determine the unit cost of CO_2 abatement based on the current payment of 1,000-1,600 KM/ha, which yields 250-390 tons of CO_2 abatement in 100 years. To calculate this unit cost, we need to ensure that both the payment and the CO_2 abatement figures are referenced to the same point in time. We can achieve this by either calculating the present value of the future figures or the future value of the present figures. The direction of this calculation does not affect the resulting unit cost, which has been calculated to be 24 EUR/ton CO_2 for beech coppice conversion and 64 EUR/ton CO_2 for oak coppice conversion[4].

[4] Note that the cost-efficiency of coppice transformation heavily depends on the discounting factor, which manifests various expectations of return on monetary expenditure. If the project is supposed to compete with alternative investment options, the discounting factor will have to be high enough to represent rates of return in other sectors of the economy. In a different approach, the future costs and benefits can be discounted with very low factors, appreciating the constant flow of ecosystem services forests can provide. As an investment to social and natural capital, one may consider future generations' welfare undiscountable, meaning a zero discount factor and thus a much higher return on coppice transformation.

These figures indicate that the compensation payment to forest managers represents an attractive climate policy option, as it falls below the current carbon prices. It also stands as a prudent business decision for forest management.

We acknowledge the diversity of coppice forests and their habitats. It is important to recognize that different forests may necessitate varying levels of compensation payments to incentivize the conversion to high forests. The figures provided in our analysis serve as an initial indication, highlighting the need for further investigation to gain a deeper understanding of the heterogeneity within coppice forests and the potential for transformation.

The above analysis is based on direct conversion following clear cut of the coppice forest. Indirect conversion through selective cutting is another option, but we have not investigated it due to lack of the required data on the costs of this type of management.

7 Conclusions, policy recommendations

7.1 Conclusions

In Bosnia and Herzegovina, the active forest management in plantations and coppice forests is currently not economically viable due to relatively low timber prices and high reforestation costs. Higher timber prices and/or lower reforestation costs would incentivize active management in these forest types.

In the case of plantations, if timber prices were at least 30% higher, the implementation of a carbon payment or other policy instrument may be necessary to discourage excessive harvesting and maintain higher levels of carbon storage.

Reforestation costs have a more pronounced influence on rotation forestry in coppice forests compared to assortment prices. Lower reforestation costs, such as through natural regeneration, can make rotation forestry a viable economic option. However, the feasibility of natural reforestation is specific to each location, and suitable sites would need to be identified through targeted research.

The current practice in BiH, denoted as the 80% LIMIT scenario, demonstrates sustainable forest management practices. This scenario limits final felling to maximum 80% of annual growth in high forests, resulting in steady forest growth, increased carbon sequestration, and consistent harvests. However, without strict enforcement of harvest limits, additional policy interventions like carbon payments at around 100 EUR/ton CO_2 would be necessary. This highlights the importance of continued monitoring and enforcement under the present forest management regime. It is important to note that the successful implementation of a carbon payment scheme also relies on the presence of a competent enforcement authority. This authority would be responsible for monitoring and verifying that carbon payments are directed to forests that are preserved. Conversely, the authority would ensure that harvested forests are subject to the carbon tax. Thus, robust enforcement mechanisms are vital to maintain the integrity and effectiveness of both of the discussed policies.

In contrast, the 100% LIMIT scenario, where the harvest is set at 100% of annual growth, leads to a slow decline in the main stock of high forests and a higher overall harvest than under the current practice. As timber reserves dwindle, the amount of CO_2 stored in high forests also slowly declines.

The NO LIMIT scenario, where there are no regulatory limits on harvests, results in intensive initial harvesting followed by minimal cuts and gradual forest stock recovery. This scenario highlights the importance of harvesting limits for sustainable forest management. Furthermore, assuming that under the present institutional setup it is easier to enforce harvesting limits in state owned forests compared to private forests, our findings also underline that the potential privatization of forests carries a risk of overharvesting.

In the absence of harvesting limits, the introduction of carbon payments provides a powerful incentive to delay harvesting in high forests. Modelling results show that a payment level of at least 100 EUR/ton CO_2 is required to act as a strong incentive for forest conservation and consequent increased carbon sequestration. A payment of 200 EUR/ton CO_2 would lead to a steep increase of carbon sequestration as it would result in a complete halt to harvesting in all high forests. Of course, this is not desirable from the perspective of the forestry sector and timber industries. This extreme scenario should be viewed as a theoretical result, not a recommendation.

Based on the above findings the introduction of a carbon payment in the BiH forestry sector is not warranted at this time.

The transformation of coppice forests into high forests can lead to increased carbon sequestration over time. After 50 years, the cumulative carbon stock in high forests surpasses the carbon stored by coppice forests. However, an initial financial support of at least 1,000-1,600 KM/ha is needed to initiate the conversion, which translates to a unit cost of abatement of about 24-64 EUR/ton CO_2. The conversion of coppice to high forests merits further analysis, especially because of the attractiveness of this measure is likely to be very much location dependend.

Modelling results could be further improved if more detailed data was available on high forests, enabling us to segment these forests based on productivity, and model each segment separately. These results would also enable the integration of the carbon potential of the forestry sector to the national marginal abatement cost curve for greenhouse gas emissions, which is a critical component of cost-effective climate policy.

Current results provide the stepping stone for further analysis in several areas. With FOX results now available for BiH, Hungary and Romania, and soon finalised for Bulgaria, the integrated modelling of Central and South East European forests and timber markets can be considered. Another area for research is the impact of climate change on the forests and forest management of BiH. The uneven-aged, mixed species high forests, as currently managed, are probably less vulnerable to climate change than most other types of forests in Europe. If this is the case, then the economic aspects of forest management for sustainable and resilient forests may be further studied with the FOX model.

7.2 Policy recommendations

The current policy of limiting harvests to maximum 80% of annual growth plays a crucial role in maintaining net carbon sequestration while ensuring sustainable timber harvests. However, it is important to consider the potential challenges that may arise if future timber prices significantly increase. Higher prices could exert pressure to modify this limit, or they could lead to an increase in illegal harvesting. In such scenarios, the introduction of carbon payments to delay harvests could complement harvesting limits and ensure that the interests of forest owners are aligned with climate goals.

Our analysis demonstrates that the transformation of coppice forests into high forests offers a substantial and cost-efficient increase in carbon sequestration by BiH forests. It is important to explore the potential for climate financing to support this transition, as well as identify suitable and location-specific methods for the transformation process. Options may include clear-cutting followed by proper planting and maintenance of high forests, selective cutting to facilitate a more natural and expedited transition or allowing natural succession to drive the transformation.

Sustainable forest management practices heavily rely on effective monitoring and enforcement of harvesting limits. It is advisable for decision makers to allocate adequate resources to support and enhance these activities, ensuring that current good practices continue in the future.

Finally, transparent and high-quality data on forest resources and activities are essential for making efficient policy decisions and garnering public support for sustainable forest management practices. Therefore, it is recommended to develop a comprehensive plan to collect, validate, and publish high-resolution data on the forests of BiH entities, facilitating informed decision-making and promoting transparency in forest management efforts.

8 References

Bilten of forestry 2021. Agency of statistic of Republic of Srpska, Banja Luka

Bilten of forestry, 2021. Agency of statistic of Federation of BiH, Sarajevo

Cadastre of forests and forest land of the Republic of Srpska

Cadastre of forest and forest land of the Federation of Bosnia and Herzegovina

Report of the Statistics Institute of the Republic of Srpska and Bosnia and Herzegovina

Execution of Production and Financial Plans of PFE Forest of Republika Srpska

Forest Management Plans of FMU of the Republic of Srpska

Drinic et al., 1980. Tables of taxation elements of tall forests and coppice forests in Bosnia and Herzegovina, Sarajevo 1980.

FAO (2015). The Forest Sector in Bosnia and Herzegovina. Preparation of IPARD Forest and Fisheries Sector Reviews in Bosnia and Herzegovina. Food and Agriculture Organization of the United Nations.

Forest management plans of cantons in Federation of BiH

Govedar Z., Mataruga, M. 2021. Plan of afforestation of bare land and management of forest plantations, Banja Luka.

Federal Ministry of forestry, agriculture and watermanagement, 2021-2022.

Implementation of the Production and Financial Plan of the JPŠ "Forests of the Republic of Srpska" a.d. Sokolac for 2021,

Incremental yield tables for even aged stands (Wiedemann 1943);

Master plan of afforestation of bare forests and management of forest crops of the Republika Srpska, Faculty of Forestry, Banja Luka in 2021

Matić, V. 1984. Prirast i prinos šuma, Univerzitet u Sarajevu, p.339

Matić, V., 1969. Uređivanje šuma. Dio 1. Sarajevo: Univerzitet.p.245.

Maunaga 2005. Yield tables for even aged spruce stands in Bosnia.

Pukkala, Timo et. al. (2009) Growth and yield models for uneven-sized forest stands in Finland. Forest Ecology and Management 258 (2009) 207–216

Pussinen, A., Schelhaas, M.J., Verkaik, E., Heikkinen, E., Liski, J., Karjalainen, T., Paivinen, R. and Nabuurs, G.J. (2001) Manual for the European Forest Information Scenario Model (EFISCEN 2.0). Internal Report No. 5. European Forest Institute, Finland.

Vanclay, Jerome K. (2012) Modelling Continuous Cover Forests. In Pukkala T. and K. von Gadow (eds.) Continuous Cover Forestry, Managing Forest Ecosystems 23.