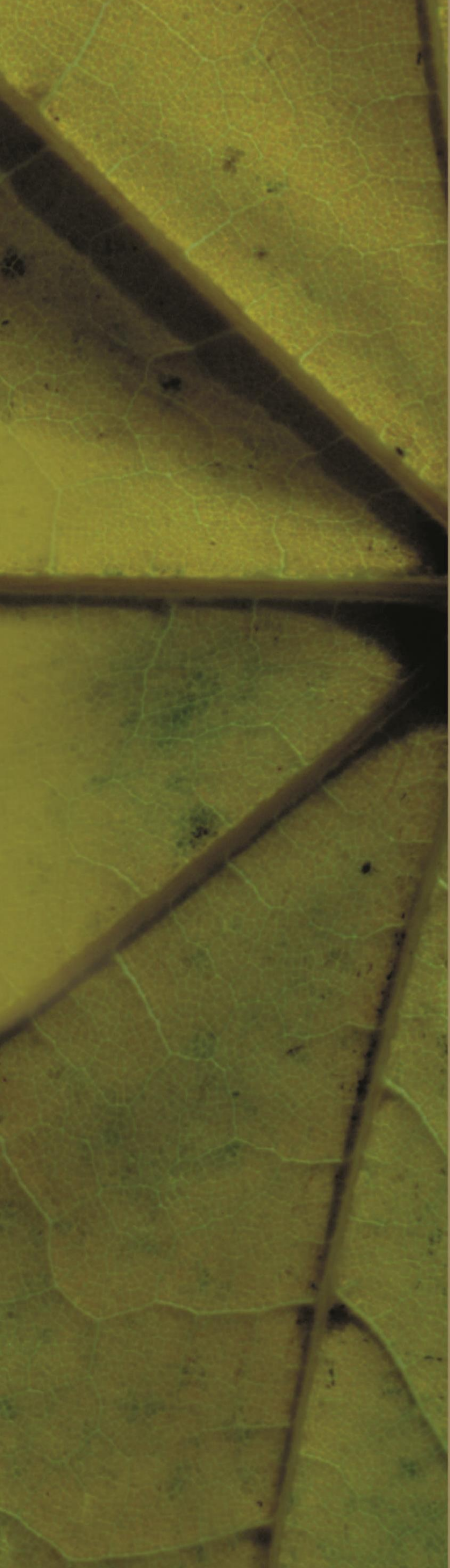

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Sustainable Forest Strategies as Natural Climate Solutions in Degraded Coniferous Forests

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ABSTRACT

The present research implemented two improved forest management practices in a study area in Central Italy (Monte Morello Forest) to analyze their effects on C-sequestration and C-stock in all C pools (above-ground and below-ground biomass, deadwood, litter, and soil). It also estimated silvicultural treatment effects on two additional ecosystem services — wood production and recreational activity. A thinning from below and a selective thinning were applied in a degraded coniferous forest to increase the C-sequestration in the medium-long term. The results showed that after the two thinnings, above-ground biomass and deadwood C-stock decreased (–145 and –220 t CO_2 ha^{-1} after thinning from below and selective thinning, respectively). However, these silvicultural interventions led to an increase in C-sequestration, recovering the lost C-stock in a period of between four and nine years and generating a positive flow in the medium-long term. Moreover, both thinnings positively affected wood production and the aesthetic-visual perception of the forest for visitors.

TANULMÁNY INFÓ

Kulcsszavak:
Szénkészlet
Szénmegkötés
Javított erdőgazdálkodási gyakorlatok
Gyérítés
Toszkána régió

KIVONAT

Fenntartható erdőstratégiák, mint természetes éghajlati megoldások degradált tűlevelű erdőkben. A jelen kutatás két különböző módszerrel menedzselt közép-olaszországi (Monte Morello) erdőt vizsgált. Elemeztük az erdőművelés és erdőgazdálkodási módszerek hatását a szénmegkötésre, a szénkészletre valamint a teljes széntartalékra (föld feletti és föld alatti biomassza, holtfa, avar és talaj). Ezen túlmenően a tanulmány a fatermelésre és a rekreációs tevékenységre gyakorolt hatásokat is vizsgálta és összehasonlította. Egy leromlott állapotú tűlevelű erdőben alulról történő ritkítást és szelektív ritkítást alkalmaztunk a szénkötöttség középtávú növelése érdekében. Az eredmények azt mutatták, hogy a két különböző ritkítás után a föld feletti biomassza és a holtfa szénkészlete csökkent (-145 és -220 t CO_2 ha^{-1} az alulról történő ritkítás és a szelektív ritkítás után). Ezek az erdőművelési beavatkozások azonban a szénkötöttség növekedéséhez vezettek, négy és kilenc év közötti időszakban visszanyerték az elveszett szénkészletet, és középtávon pozitív áramlást eredményeztek. Ezenkívül mindkét ritkítás pozitívan befolyásolta a fatermelést és az erdő esztétikai-vizuális megítélését a látogatók számára.

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1 INTRODUCTION

Forests act as a net sink for carbon dioxide (CO_2), contributing to climate change mitigation by removing atmospheric CO_2 and storing it in five carbon pools (i.e., above-ground and below-ground biomass, soil, deadwood, litter) (Somogyi, 2008; Kotroczó et al., 2012). As confirmed by inventory measurements in managed and unmanaged forests in temperate and tropical regions, forests can offset 2 % to 30 % of expected emissions during this century (Pan et al., 2011). Moreover, forests comprise a vital carbon (C) reservoir since they store about twice the amount of C in the atmosphere. As estimated by Grassi et al. (2022), the mean net global sink was $-1.6\ \mathrm{Gt\ CO_2\ yr^{-1}}$ over the period 2000–2020, largely determined by a sink on forest land ($-6.4\ \mathrm{Gt\ CO_2\ yr^{-1}}$), followed by source from deforestation ($+4.4\ \mathrm{Gt\ CO_2\ yr^{-1}}$). The capacity of ecosystems to store C depends on the balance between net primary productivity (NPP) and heterotrophic respiration. Whether a particular ecosystem functions as a sink or greenhouse gas (GHG) emissions source may change over time, depending on its vulnerability to climate change and other stressors and disturbances. Therefore, monitoring and estimating the biomass and soil C stocks of forests is vital to support the development and verification of GHG inventories in the “Land Use, Land Use Change, and Forestry” (LULUCF) sector (Somogyi et al., 2008).

Absent or inappropriate management can result in forest degradation, implying a decrease in canopy cover and natural regeneration (Kruk and Kornatowska, 2014), which, in turn, affects the annual increment of C-sequestration, reducing the potential of these forests to act as sinks or transforming them into a GHG source (Herold et al., 2011). CO_2 emissions from deforestation and forest degradation have been estimated to account for about 12–20 % of global anthropogenic CO_2 emissions (IPCC, 2007). Deforestation and forest degradation are major contributors to global GHG emissions, but if these processes are controlled, forests can significantly contribute to climate change mitigation. Forest-based strategies offer a cost-effective means to mitigate climate change; therefore, appropriate forest management can help reduce CO_2 emissions from deforestation and forest degradation and increase C removals (Balderas Torres et al., 2013).

In this conceptual framework, Natural Climate Solutions (NCS) comprise a range of strategies involving conservation, restoration, and effective land management practices, primarily aimed at alleviating GHG emissions from terrestrial ecosystems while optimizing their capacity for C sequestration (Griscom et al., 2017). This portfolio of twenty land stewardship options has been introduced as a cost-effective tool that increases C storage in natural and planted forests, grasslands, agricultural lands, and wetlands (Fargione et al., 2018) while also sustaining biodiversity and other ecosystem services (Kaarakka et al., 2021).

Among the NCS practices, forest pathways for NCS — in particular reforestation, avoided forest conversion, and improved forest management (IFM) — have the potential to offset approximately 30 % of GHG emissions and contribute as much as 50 % of the total C-sequestration possible through NCSs globally (Griscom et al., 2017; Fargione et al., 2018). These NCS options offer the best climate mitigation potentials. They also extend the highest positive impacts on provisioning and regulating, and on cultural ecosystem services (Paletto et al., 2021).

IFM offers cost-effective mitigation opportunities, many of which could be quickly realized without land use changes, providing a salient approach to increasing C-sequestration in forested systems (Fargione et al., 2018). Early definitions of IFM comprised only extended rotations and did not consider other IFM strategies that included silvicultural systems such as selection and retention harvesting. Offering a broad and comprehensive overview, Kaarakka et al. (2021) evidenced various definitions of IFM deriving from state and government agency protocols, non-governmental organizations associated with the forest sector, and published literature. According to Kaarakka et al. (2021), IFM includes a variety of silvicultural management practices that incorporate above-ground and below-ground biomass C components and soil C stock. Thinnings in planted and natural forests play a crucial role in increasing growth (i.e., volume increment) and improving crown development and stand stability within these silvicultural management practices. Therefore, thinning interventions can directly and positively affect C-sequestration.

Starting from these considerations, the LIFE14 CCM/IT/905 project "Recovery of degraded coniferous Forests for environmental sustainability Restoration and climate change Mitigation" (FoResMit) has implemented innovative silvicultural practices in degraded coniferous forests to evaluate the impact of IFM interventions on climate change. In particular, different silvicultural practices have been applied in the Monte Morello Forest (Tuscany Region, Central Italy) to increase the C-sequestration in the medium to long term and simultaneously improve the provision of other ecosystem services (e.g., wood production and recreational activity). The following questions address the research objective:

Q1. What impact do thinning interventions (selective thinning and thinning from below) have on the C-stock of an unmanaged coniferous planted forest?
Q2. What impact do thinning interventions (selective thinning and thinning from below) have on the C-sequestration of a coniferous planted forest in the medium and long term?
Q3. What impact do thinning interventions (selective thinning and thinning from below) have on other ecosystem services?

2 MATERIALS AND METHODS

2.1 Study area

Monte Morello Forest (43°51′20″N; 11°14′23″E) is near the urban area of Florence (Tuscany Region), at an altitude of approximately 600 m a.s.l. (*Figure 1*).

The primary stone is calcareous flysch (turbidites) constituted by alternating limestone, marly limestone ("alberese"), marl, claystone, and, subordinately, sandstone. Therefore, soils are mainly calcareous, presenting a loam or clay loam texture, rich in carbonates, with pH ranging between 7.5 and 8.2 (Lagomarsino et al., 2021).

A Mediterranean climate with dry summers characterizes the area, with July and August as the driest months. The average annual rainfall is 876 mm (period 1890–2018), concentrated from autumn to early spring, and the average annual temperature is 13.3 °C.

Monte Morello has been reforested on degraded soils affected by overgrazing. The reforestation activities aimed to provide hydrogeological stability and facilitate the natural succession toward mixed forests with a large component of broadleaved species (Cantiani and Chiavetta 2015; De Meo et al. 2019).

No silvicultural treatments have been applied since the reforestation activities performed between 1909 and 1980, and the stands have been largely abandoned (De Meo et al., 2017). These stands — characterized by a dominant layer of *Pinus nigra* and *Pinus brutia* with minor presence of *Cupressus sempervirens* and *Quercus cerris* — currently exhibit visible degradation symptoms with many dead and damaged trees. *Cupressus arizonica*, with regeneration of Mediterranean shade-tolerant broadleaf species such as *Fraxinus ornus* and *Acer campetris*, occupy the understory layer (Mazza et al., 2019).

The mean tree density in Monte Morello Forest is 980 tree ha^{-1}. The mean basal area is 62.9 m^2 ha^{-1}, and the mean height is 17.1 m (Mazza et al., 2019). De Meo et al. (2017) estimated an average deadwood volume of 75.08 m^3 ha^{-1}. Divided by component, this equals 59.91 m^3 ha^{-1} in lying deadwood, 13.92 m^3 ha^{-1} in standing dead trees, and 1.25 m^3 ha^{-1} in stumps.

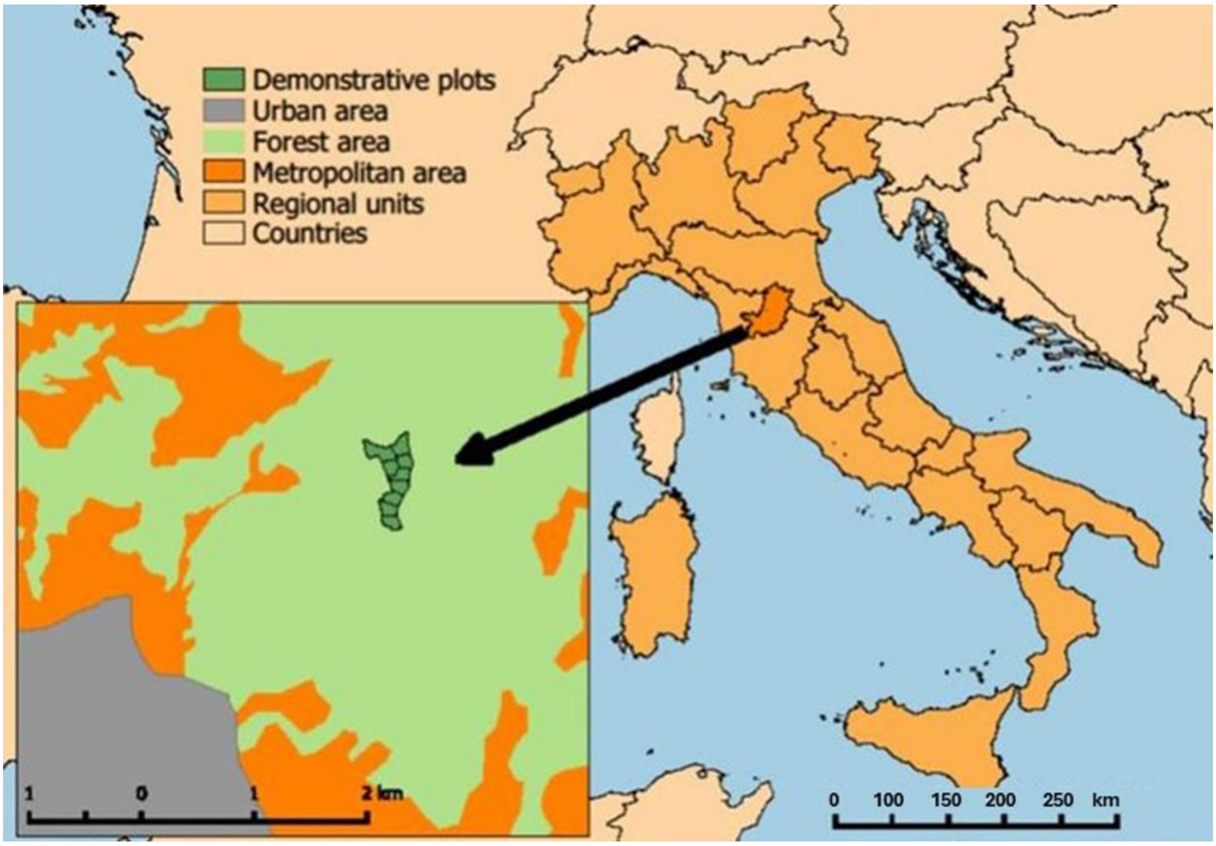

Figure 1. Location of study area (Monte Morello Forest) in Italy

2.2 Experimental design and field measurements

The IFM practices implemented to increase the C stocked in Monte Morello were thinning from below and selective thinning. The C-stock changes these two thinnings caused were estimated from five carbon pools: above-ground and below-ground biomass, deadwood, soil, and litter. The effects of the two silvicultural interventions were compared with each other and with control plots (without interventions).

The data used to assess the C stocked were collected in the field before thinning in the winter of 2016 and two years later in 2018. Thinning implementation followed a randomized design with three replicates for each silvicultural option (thinning from below, selective thinning, without interventions). Each replicate had at least one hectare of area. The field data were collected in two randomly located sampling plots for each replicate (Mazza et al., 2019; Paletto et al., 2021). The 18 sampling plots were circular, with a fixed area of 531 m^2 (13 m of radius).

The main dendrometric data — height and diameter at breast height (dbh) for all standing living trees with a dbh greater than 5 cm, number of stems, and canopy cover overstorey — were collected in each sampling plot. The standing living (stem) volume was estimated using the model elaborated by the second Italian National Forest Inventory (NFI) for black pine species. In this model, the diameter at breast height (dbh) and the total tree height (h) have been adopted as independent variables for the prediction equations (Tabacchi et al., 2011).

All three deadwood, all three components with diameters greater than 5 cm were measured in the sampling plot: lying deadwood (sound and rotting pieces of wood located on the ground), standing dead trees with a height greater than 1.3 m, and stumps with a height of less than 1.3

m. The deadwood volume was estimated per the protocol proposed by De Meo et al. (2017). Species and decay classes were also recorded for each deadwood element using a five-class classification system (Casagli et al., 2022) to improve the C-stock estimate.

Litterfall was collected seasonally using 72 traps. The main litter components (conifers vs. broadleaves: pine needles, deciduous leaves, twigs and branches with diameters less than 5 cm, reproductive structures, and bark) were separated. Forest floor litter was collected once a year (2015, 2016, 2017, and 2018) and separated into three representative fractions: L – fresh or almost undecomposed litter; F – medium to strongly fragmented material with many mycelia and thin roots; H – completely decomposed amorphous material.

Soil was collected once a year (2015, 2016, 2017, and 2018) from the same position as forest floor litter at depths of 0–10 and 10–30 cm within each plot. Soil samples were homogenized at 0.5 mm, and C content was measured using a CN elemental analyzer (Flash 2000, Thermo Fisher sci.). Undisturbed soil samples were collected for soil bulk density (BD) measurement to calculate soil organic C-stock for each depth.

2.3 Improved forest management (IFM) practices

The IFM practices were applied on a pilot area of 10.09 ha in Monte Morello forest, while 6.35 ha were used as control plots. In particular, the three silvicultural options can be summarized as follows:

- Selective thinning applied on a surface of 4.74 ha. In this thinning, the choice of the trees to be cut is based on a positive selection, and around 100 trees per hectare are selected from among the better-formed and mechanically stable subjects. All crown-volume competitors are harvested to increase the growth of selected trees (30–40 % of the basal area is removed). Standing dead trees and lying deadwood slightly decomposed are also removed.
- Thinning from below applied on a surface of 5.35 ha. In this thinning, the choice of the trees to be cut is based on a negative selection, and only dominated, small, or standing dead trees are harvested during in-field operations (thinned from below 15-20 % of basal area). Logs are not removed during the harvesting operations (Pieratti et al., 2019). Thinning from below is the most common silvicultural treatment applied in Central Italy in both natural forests and plantations, developed according to regional forest acts (Marchi et al., 2018).
- Baseline/Control option to monitor the forest on a surface of 6.35 ha. In this case, no silvicultural treatments are implemented, and deadwood is not removed from the forest. The forest is temporarily left to its natural evolution.

The three silvicultural options were analyzed and compared considering a rotation period of 15 years (the period between two thinning). The 15-year rotation period is hypothetical and based on typical thinning in young planted coniferous forests, also prescribed by forest management plans. Moreover, a longer term could result in a higher error in wood and biomass growth estimates (Paletto et al., 2021).

2.4 Climate change mitigation assessment

The impact of silvicultural options on climate change mitigation was quantified as difference in C-stock and C-sequestration after the two IFM practices considering all five carbon pools. The data collected in the control plots (without interventions) defined the baseline.

The changes of C-stock in above-ground and below-ground biomass due to the two thinnings have been calculated following the equations proposed by Vacchiano et al. (2018) (eq.1):

$$\mathrm{C_{stock-biomass}} = \mathrm{k} \cdot \left[(1-\mathrm{b}) \cdot \left(\mathrm{V_{i,IFM}} - \mathrm{V_{i,baseline}}\right) \cdot \mathrm{BEF} \cdot \mathrm{WBD}\ (1+\mathrm{R})\right] \qquad \text{(eq.1)}$$

Where:

$C_{stock\text{-}biomass}$:	tons of CO_2 per hectare lost due to the thinning actions (t CO_2 ha^{-1})
k :	conversion factor from C to CO_2
$V_{i,IFM}$:	volume post thinning (m^3 ha^{-1})
$V_{i,baseline}$:	volume in the control plots without IFM actions (m^3 ha^{-1})
BEF:	species-specific biomass expansion factor (1.33 for black pine)
WBD:	species-specific wood basal density (0.47 for black pine)
R:	species-specific root/shoot ratio (0.36 for black pine)
b:	carbon lost from emissions due to unplanned natural disturbances
i:	reference thinning method (i= thinning from below or selective thinning.

Regarding the deadwood (lying deadwood and/or standing dead trees) removed during the silvicultural treatments, the change in deadwood C-stock has been calculated as follows (eq.2):

$$\mathrm{C_{stock-deadwood}} = \mathrm{k} \cdot \sum\nolimits_{n}\left[\left(\mathrm{D_{i,IFM}} - \mathrm{D_{i,baseline}}\right) \cdot \mathrm{WBD}\right] \qquad \text{(eq.2)}$$

Where:

$C_{stock\text{-}deadwood}$:	tons of CO_2 per hectare lost due to the deadwood harvesting (t CO_2 ha^{-1});
k:	conversion factor from C to CO_2
$D_{i,IFM}$:	deadwood volume post thinning (m^3 ha^{-1})
$D_{i,baseline}$:	deadwood volume in the control plots without IFM actions (m^3 ha^{-1})
WBD:	wood basal density of each decay class (kg m^{-3})
n:	number of decay classes (5).

The Wilcoxon signed-rank test determined whether the changes in C-stock after the two silvicultural treatments were statistically significant. A non-parametric rather than parametric test was adopted for two reasons: data does not follow a normal distribution (Anderson-Darling test: A^2=1.035, p=0.008), and the sample size is small (18 sampling plots in total).

The effect of silvicultural treatments on C-sequestration in woody biomass was calculated using the annual increment of volume measured in the study areas before and after thinning: 12.16 m^3 ha^{-1} yr^{-1} in the control plots, 25.96 m^3 ha^{-1} yr^{-1} after the thinning from below, and 17.29 m^3 ha^{-1} yr^{-1} after the selective thinning. The formula used to estimate CO_2 yearly sequestered is the following (eq.3):

$$\mathrm{C_{seq-biomass}} = (\mathrm{BEF} + \mathrm{R}) \cdot \mathrm{I} \cdot \mathrm{WBD} \cdot \mathrm{k} \qquad \text{(eq.3)}$$

Where:

$C_{seq\text{-}biomass}$:	tons of CO_2 sequestered per cubic meters of biomass yearly [tCO_2 m^{-3} yr^{-1}];

BEF: biomass expansion factor (1.33 for black pine);
WBD: wood basal density (470 kg m^{-3} for black pine);
R: root to shoot ratio (0.36 for black pine);
k: wood carbon content (50 %) multiplied for 3.67 kg CO_2 kg^{-1} (conversion factor from C to CO_2).

Finally, the change in C-sequestration before and after the thinning interventions were calculated with eq. 4 and 5:

$$\Delta_{C_t} = C_t - C_b \qquad \text{(eq.4)}$$

$$\Delta_{C_s} = C_s - C_b \qquad \text{(eq.5)}$$

Where:

C_b: tons of CO_2 sequestered by the annual wood increment in the control plots without IFM actions
C_t: tons of CO_2 sequestered by the annual wood increment after thinning from below
C_s: tons of CO_2 sequestered by the annual wood increment after selective thinning.

The C-sequestration in soil was calculated as the difference between C accumulation in the soil organic and mineral layers after thinning and the quantity of CO_2 equivalents lost as emissions of CO_2 equivalents (CO_{2eq}). The formula used to estimate the C-sequestration in soil is the following (eq.6):

$$C_{seq-soil} = k \cdot \left(C_{soil\ post} - C_{soil\ pre}\right) - CO_{2eq}\ \text{emitted} \qquad \text{(eq.6)}$$

Where:

$C_{seq-soil}$: amount of CO_2 accumulated in the soil net of GHG emissions (t CO_2 ha^{-1} yr^{-1})
k: conversion factor from C to CO_2
$C_{soil\ post}$: C stock in the first 30 cm 2 years after thinning (t ha^{-1})
$C_{soil\ pre}$: C stock in the first 30 cm before thinning (t ha^{-1})
CO_{2eq} emitted: sum of annual cumulative emissions in the second year after thinning multiplied for specific coefficients: $CO_2 + 34{*}CH_4 + 298{*}N_2O$ (t CO_2 ha^{-1} yr^{-1}).

2.5 Other ecosystem services assessment

The impacts of silvicultural treatments were estimated on two additional ecosystem services to climate change mitigation: wood production for the provisioning services category and recreational activity for the cultural services category.

Wood production was assessed considering the current local market prices and wood volumes harvested during the silvicultural treatments in each scenario. The economic value of wood production was evaluated through the direct calculation of profit from the annual income derived from the sale of wood assortments (€ ha^{-1} yr^{-1}) considering the local price and a rotation period of 15 years (eq.7):

$$R = \frac{Vt_0}{\frac{(1+i)\cdot[1-(1+i)^{-t}]}{i}} \qquad \text{(eq.7)}$$

Where:

R:	annual income derived from the sale of wood assortments at the time t_0 (€ ha^{-1} yr^{-1})
V_{t0}:	total current value derived from the sale of wood assortments (€ ha^{-1})
i:	average inflation rate in Italy for the last five years
t:	rotation period (15 years).

The impact of thinning on recreational activities was assessed through a semi-structured questionnaire to a sample of visitors to the Monte Morello Forest. The questionnaire focused on visitors' preferences towards visual-aesthetic impacts of the two silvicultural treatments (thinning from below and selective thinning) and the estimation of consumer surplus (CS) through the Travel Cost Method (TCM).

The respondents assigned their visual-aesthetic preferences for the three forest management scenarios (baseline/control, thinning from below, and selective thinning scenarios) by comparing pairs of images of Monte Morello Forest representing the three scenarios (pairwise comparison). In addition, the questionnaire collected all key data of the TCM, including visitor residence, number of site visits in the past year, the length of the trip, the amount of time spent at the site (hours), and travel expenses (e.g., accommodation, meals, and transportation).

During the data processing, the image preferred by the visitors was identified by calculating the priority value of each image/scenario using the Analytic Hierarchy Process (AHP) approach (Saaty, 1987). The image/scenario preferred by the visitors was identified with the calculation of the priority value of each image using the eigenvalue method. The distribution of visitors' visual-aesthetic preferences for the three images was used to estimate the potential number of visitors in the three forest scenarios and the changes from the baseline/control scenario. Besides, the recreational value was indirectly calculated using the TCM and considering individual total cost expenditures for the trip to Monte Morello Forest. The TCM assumes that visitors are travel cost-sensitive, meaning that the expected number of trips to a specific site is lower when the cost to reach the destination increases. Finally, the typical welfare measure estimable from a TCM was calculated. This is CS, a proxy for the benefit people derive from visiting. CS is calculated as the negative inverse of the travel cost coefficient.

3 RESULTS

3.1 Climate change mitigation assessment

The results show that above-ground biomass and deadwood C-stock decreased by 145 t CO_2 ha^{-1} after the thinning from below (96 % of changes were in the above-ground biomass and 4 % in deadwood), while C-stock decreased by 220 t CO_2 ha^{-1} after the selective thinning (95 % of changes were in above-ground biomass and 5 % in deadwood). Consequently, both thinnings reduced C-stock in these two carbon pools in the short term, as shown in *Figure 2*. Conversely, thinning did not directly affect the below-ground biomass C-stock because roots were not removed during the silvicultural interventions.

However, the Wilcoxon signed-rank test results (α=0.01) show that the differences in C-stock for both silvicultural treatments between before and after thinning are not statistically significant: thinning from below and selective thinning (p=0.031 for both, respectively).

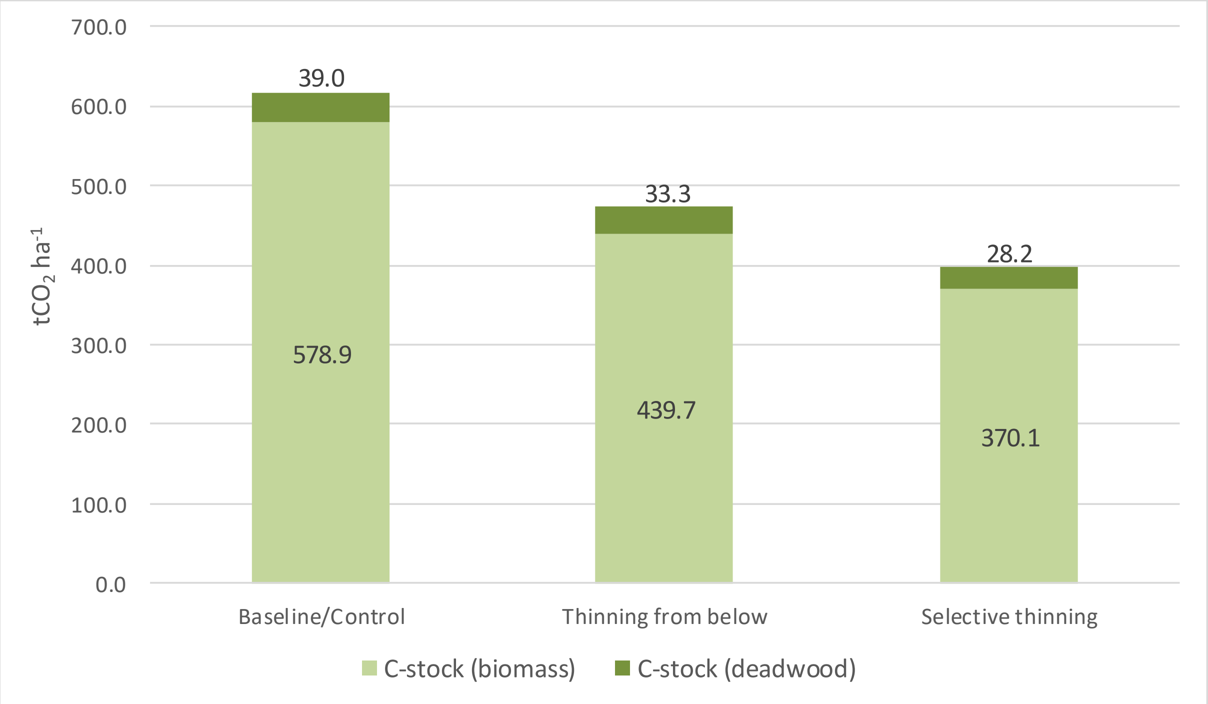

Figure 2. Change in C-stock in biomass and deadwood after thinning from below and selective thinning compared to the baseline

Regarding the C fluxes, the results show that the C-sequestration in the control plots (without IFM interventions) was 17.71 t CO_2 ha^{-1} yr^{-1}, while after the implementation of silvicultural treatments, there was a marked increase (*Figure 3*). In the plots managed with thinning from below, the C-sequestration was estimated at 37.80 t CO_2 ha^{-1} yr^{-1} (Δ_{Ct} = 20.09 t CO_2 ha^{-1} yr^{-1}), while in the plots managed with selective thinning, the C-sequestration was equal to 25.18 t CO_2 ha^{-1} yr^{-1} (Δ_{Cs} = 7.47 t CO_2 ha^{-1} yr^{-1}). These results indicate that it takes four years to restore the C lost in the above-ground biomass and deadwood with thinning from below and nine years with selective thinning. However, C-stock lost by the forest ecosystem is closely related to the lifespan of the forest products obtained (from a minimum time for woodchips/fuelwood to a maximum for timber for building).

Table 1 shows the effect of the two thinning treatments on soil and litter C-stock in the four years of the project's monitoring. The results indicate that the effect of thinning on soil C-stock became evident two years after treatments (*Table 1*), with an increase of 29 % and 33 % in thinning from below and selective thinning, respectively. Overall, 32.0 and 35.6 t CO_2 ha^{-1} yr^{-1} were sequestered into the soil up to 30 cm depth with thinning from below and selective thinning, respectively.

Concerning litter, the results show that coniferous litterfall fraction decreased after selective thinning compared to the control plots, while deciduous litterfall fraction increased. Thinning increased litter biomass in all horizons immediately after the intervention, whereas two years after thinning, a reduction of litter was observed, which was more evident in selective thinning (*Table 1*).

Table 1. Changes in C-stock (MgC ha^{-1}) in soil and litter after thinning from below and selective thinning in the study area

Year	2015	2016	2017	2018
		Soil		
Control	99	148	119	100
Thinning from below	102	133	105	129
Selective thinning	104	161	131	134
		Litter		
Control	9.0	9.2	11.8	9.1
Thinning from below	8.1	14.7	12.0	10.3
Selective thinning	9.8	11.8	12.1	7.3

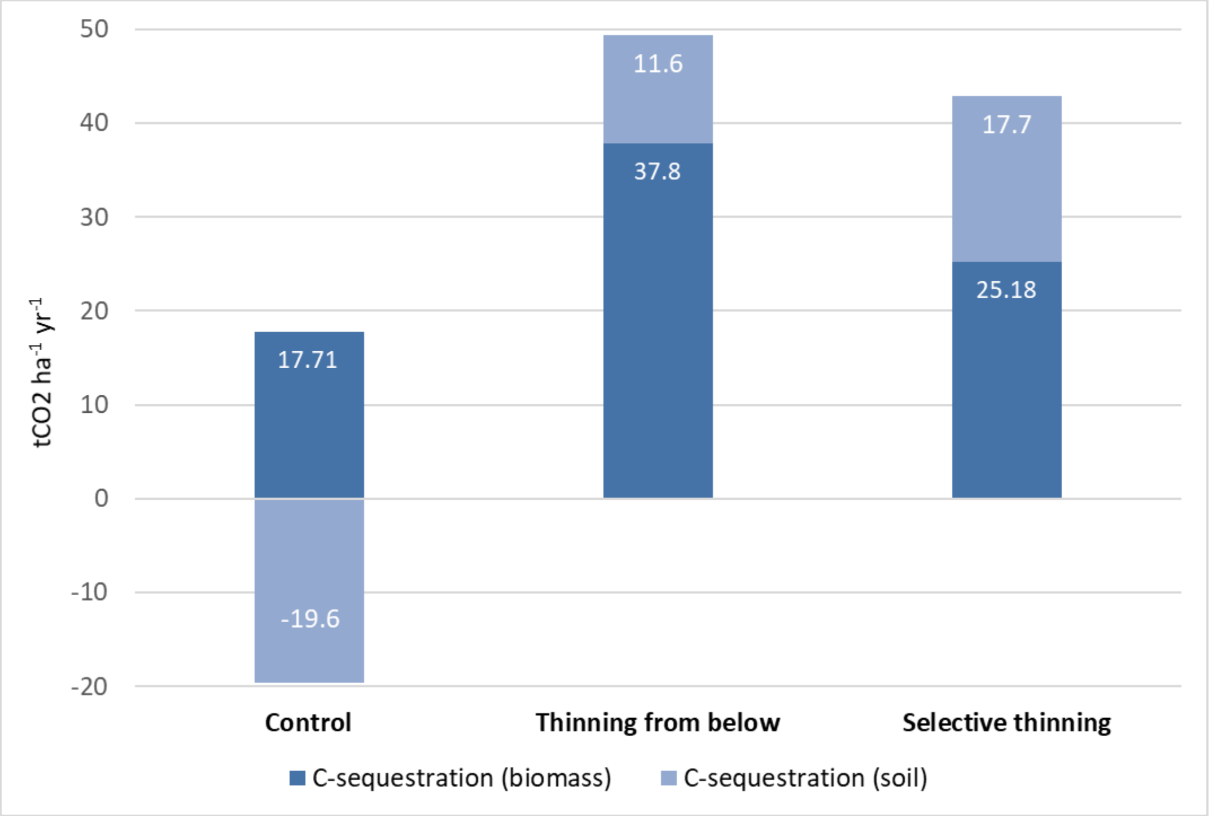

Figure 3. Change in C-sequestration in biomass and soil after thinning from below and selective thinning

3.2 Other ecosystem services assessment

Regarding wood production, the results show that following the silvicultural treatments, 24 % of the growing stock was harvested in the forest area managed through thinning from below (134.7 m^3 ha^{-1}), and 36 % of the growing stock in the forest area managed with the selective thinning (202.0 m^3 ha^{-1}). In addition, in the selective thinning, logs, and snags (deadwood) of the first two decay classes were harvested to produce woodchips (18.2 m^3 ha^{-1}). With thinning from below, only snags of the first two decay classes were harvested (9.5 m^3 ha^{-1}).

All wood volume harvested (144.2 m^3 ha^{-1} with the traditional thinning, 220.2 m^3 ha^{-1} with the selective thinning) was chipped due to the low quality of wood and delivered to a combined heat and power (CHP) plant 12 km away from the Monte Morello Forest. Based on the current local prices, the average annual income is estimated at 337.8 € yr^{-1} ha^{-1} after the thinning from below and at 515.8 € yr^{-1} ha^{-1} after the selective thinning. Conversely, in the baseline/control scenario, the income is zero because active management is not implemented.

Concerning recreational activity, 201 visitors of the Monte Morello Forest filled out the questionnaire at the end of the survey administration period. The results of pairwise comparison reveal Image 3, "Selective thinning scenario" (priority score of 0.5034) as the most appreciated image of Monte Morello Forest, followed by Image 2, "Thinning from below scenario" (0.2873), and Image 1, "Baseline scenario" (0.2093). In other words, respondents prefer managed forests (Image 2 and Image 3), while visitors negatively evaluated unmanaged forests (baseline/control scenario – Image 1) from a visual-aesthetic point of view (*Table 2*). The priority score of each image has been used as an indirect measure of visitor attendance to estimate the potential change in the number of visitors after the silvicultural treatments in each scenario. The hypothesis is that site attendance is directly related to the preferences assigned for that site. Currently, the annual number of visitors to Monte Morello Forest (baseline/control scenario) is 18,475. Therefore, the thinning from below scenario assumes a +7.8 % visitor increase (19,916 visitors), while selective thinning assumes a +29.4 % increase (23,908 visitors).

The estimated Consumer Surplus (CS) is 10.04 € per visit with a consequent total social surplus in terms of recreational benefits in the site equal to 179.2 € ha^{-1} yr^{-1} (baseline/control scenario). In the future, the potential economic benefits related to recreational activities could increase to 193.2 € ha^{-1} yr^{-1} in the thinning from below scenario and to 231.9 € ha^{-1} yr^{-1} in the selective thinning scenario in accordance with the visitors' preferences from a visual-aesthetic point of view (*Table 2*).

Table 2. Changes in the recreational activities in Monte Morello Forest in the three forest management scenarios

Scenario	Baseline/Control	Thinning from below	Selective thinning
Priority score (AHP)	0.2093	0.2873	0.5034
Annual number of visitors	18,475	19,916	23,908
Recreational economic benefits (€ ha^{-1} yr^{-1})	179.2	193.2	231.9

4 DISCUSSION

The European Union (EU) has recently identified Nature-based solutions (NbS) as key climate change adaptation and disaster risk reduction tools (EEA, 2021). Within this "umbrella" concept, the NCS includes all actions aimed at storing carbon by reducing CO_2 related to land use and changes in land use, capturing and temporarily storing additional CO_2 from the atmosphere, and improving the resilience of natural ecosystems. Improved management of natural forests and plantations (IFM) are the two actions on the forest resource that can increase C-sequestration in the medium-long term and simultaneously improve the provisioning and regulating ecosystem services provided (Paletto, 2019). The present study confirmed these theoretical principles by implementing two IFM practices (thinning from below and selective thinning) in a degraded coniferous forest in Central Italy. Implementing IFM practices led to an initial loss of C-stock (–145 and –220 t CO_2 ha^{-1} after thinning from below and selective thinning, respectively) since all harvested above-ground and deadwood volume went to woodchip production. As some authors highlight, the lifespan of woodchips is approximately six months with a short-term remission of CO_2 into the atmosphere if compared to other wood products such as poles, packaging, and timber for buildings (Karjalainen et al., 1999;

Deniz and Paletto, 2022). Despite this weakness of the destination of wood products in the case study, the results show a positive increase in C-sequestration following both thinning: 37.8 and 11.6 t CO_2 ha^{-1} yr^{-1} in biomass and soil after thinning from below, respectively; 25.18 and 17.7 t CO_2 ha^{-1} yr^{-1} in biomass and soil after selective thinning, respectively. When comparing these data with the control plots (without interventions), it is crucial to emphasize that the positive effects of silvicultural treatments can recover the above-ground and deadwood C-stock lost in a few years and generate a positive flow in the medium-long term. In response to our research questions, the results of this study conducted within the LIFE FoResMit project showed a negative effect of thinning on C-stock in the short term, offset by a very positive effect on C-sequestration in the medium to long term.

In addition, our results showed that the aforementioned silvicultural interventions positively impact climate change mitigation and other ecosystem services, such as provisioning and cultural services. Regarding provisioning services, thinning produces raw materials (mainly woodchips, wood for packaging, and poles) destined for the wood market. In particular, the results of the present study estimated an average annual income of 337.8 € yr^{-1} ha^{-1} after the thinning from below and of 515.8 € yr^{-1} ha^{-1} after the selective thinning over the 15-year rotation period. Regarding cultural services, thinning in degraded coniferous forests can improve landscape aesthetics and the consequent recreational attractiveness of the site (Paletto et al., 2017). The results of this study showed that thinning from below could positively impact site attractiveness, leading to a +7.9 % increase in the number of visitors, while the impact of selective thinning could lead to an estimated +29.4 % visitor increase. As other studies have emphasized, thinning interventions can also increase the mechanical stability of the stand (regulating services), reducing slenderness (height/diameter) ratio and improving the vertical and horizontal stand structure and tree species composition (Marchi et al., 2018). These last two aspects are related to the natural diversity of forest ecosystems and, consequently, supporting services. However, although synergistic with wood production and recreational opportunities, thinning to improve C-sequestration can hinder some aspects of forest biodiversity. As some authors have emphasized, the biodiversity of ecological communities in forests is crucial (direct and indirect impacts) for long-term carbon storage (Díaz et al., 2009; Burton et al., 2013). Therefore, thinning can have synergistic effects with stand structure and tree species composition diversity (Marchi et al., 2018), but potential trade-offs with ecological communities.

For practical applicability, the obtained results on a limited portion of the Monte Morello forest (10.09 ha) were used to predict the future impacts of active management on the entire forest (1,035 ha). In particular, the results showed that selective thinning can impact C-sequestration, wood production, and recreational activity more positively than thinning from below. Therefore, implementing selective thinning in the Monte Morello Forest and all unmanaged coniferous planted forests in Central Italy is more appropriate for climate change mitigation.

5 CONCLUSIONS

This study has pointed out that a rational and efficient forest management practice based on two IFM practices helps increase C-sequestration. In addition, the project results showed that the two methods positively impact the different categories of ecosystem services. From a political point of view, selective thinnings in unmanaged coniferous planted forests in Italy could contribute to achieving the Paris Agreement objectives set during the UN Climate Change Conference (COP21) in 2015. Additionally, active management of Italian unmanaged planted forests is of fundamental importance to achieving a zero-emission circular economy by 2050 per the National Forestry Strategy (2022). As a lesson learned, choosing an optimal IFM method (e.g., thinning from below, selective thinning, or other silvicultural interventions) for a forest area must be based on the objectives and ecosystem services to be valorized (e.g., climate change mitigation through CO_2 storage). For this objective, the results of the present study allow us to consider the trade-offs and synergies between ecosystem services during NCS implementation.

Future findings of this study could involve testing other IFM approaches, like different silvicultural interventions, that can enhance forest C storage and increase the C-sequestration in the medium-long term. These kinds of best management practices and silvicultural systems offer guidance for practitioners and researchers in Italy, but the methodological approach can be replicated in different contexts all over Europe and beyond.

In addition, testing the effects of other silvicultural treatments to increase the climate mitigation potential of forests can improve the quality of information provided to support the forest planning decision-making process.

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Logging as an Environmental Risk for the Forest Environment

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ABSTRACT

This article aims to evaluate the impact of logging on water, soil, and vegetation in forest stands (736; 746 affected by logging and control area 400 — without logging) — and the occurrence of herbal synusia. The NES (non-polar extractable substances) indicator exceeded limits in all surface water samples. Thirty percent of the samples taken from Forest Stand 736 exceeded NES limits. In Stand 746, the ratio was 60 %. Forest area 400 remained under NES limits. Operating fluid leaks from transport-mechanization machines, pollution from older environmental loads, and the content of humic substances are possible reasons for the increased concentration of physic-chemical indicators. The NES content did not affect the number and coverage of species in the monitored areas. The EAI (Environment Accident Index, which utilizes knowledge about ecotoxicity) index method confirmed the environmental risk of logging in the forest environment.

TANULMÁNY INFÓ

Kulcsszavak:
Nem-poláros kivonható anyagok (NES)
Fakitermelés
Erdei környezet
Környezeti kockázat
Ökotoxikológia

KIVONAT

A fakitermelés, mint környezeti kockázat az erdei ökoszisztémára. Közleményünkben a fakitermelés hatását vizsgáltuk a vízre, a talajra valamint a fás- és lágyszárú növényzetre a fakitermeléssel érintett (736, 746) és kontroll (400) erdőterületeken. A nem poláros kivonható anyagok (NES) mutatója minden felszíni vízmintában meghaladta a határértéket. A talajminták NES értékei a 736-os erdőterületen 30 %-kal, míg a 746-os erdőterületen 60 %-kal haladták meg a határértéket. A 400-as erdőterületen a NES tekintetében nem volt határérték túllépés. A fizikai-kémiai paraméterek megnövekedett koncentrációjának oka lehet a szállító és fakitermelő gépekből történő üzemanyag és kenőanyag szivárgás, a régebbi környezeti terhelésekből visszamaradó szennyezés, valamint a minták humusz tartalma. A NES értékek nem befolyásolták a megfigyelt területeken található fajok számát és fedettségét. Az EAI (az ökotoxicitási indexek alapján számolt Környezeti Baleset Index) megerősítette a fakitermelés erdei környezetre gyakorolt hatásának környezeti kockázatát.

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1 INTRODUCTION

A forest is a specific complex ecosystem that is also a renewable natural resource, a producer of wood matter (production function of the forest), and a provider of ecosystem services. Logging — a vital activity in economic forests — affects the forest environment through transport-mechanization mechanisms (chainsaws, harvesters, forest rail tractors, and other machines) (www.lesy.sk 2018). Petroleum substances from operating fluids used in transport-mechanization machines (diesel, engine oil, transmission oil, hydraulic oil, and others) are a significant problem in forestry because they pollute the water. Concentrations of 0.1 $mg \cdot l^{-1}$ are enough to degrade water and make it undrinkable. Petroleum substances are poorly soluble in water and form water filters or insoluble emulsions on water surfaces. Toxicity depends on the degree of solubility. The more petroleum substances emulsify in water, the higher the toxicity (Hybská et al., 2017).

Oil substances on water surfaces cause oxygen deficits, reduce light access to the depths, and affect photosynthesis. Solar radiation absorption increases water temperature and endangers aquatic plant development, causing eutrophication (Nowak et al., 2019). Lighter, more volatile hydrocarbons contaminating the forest environment tend to evaporate. Sunlight oxidizes other photosensitive substances, causing density stratification and segregation in the water column, droplet condensation, and solidification (Zhang et al., 2019). Oil pollution also affects the physical properties of the soil — water evaporation decreases, and the hydrophobicity of soil aggregates increases. A greasy oil film on the soil surface restricts air circulation between the soil and the atmosphere. Soil particles coated with oil substances prevent the soil from “breathing,” i.e., CO_2 escapes from the soil into the air (Blońska et al., 2016). It is also more difficult for water to soak into the soil and for plant roots to absorb water, causing plants to suffer from drought.

Oil pollution also changes the chemical properties of the soil — alkalinity increases, and the availability of nutrients (especially P and K) for plants decreases. Nutrient mobility decreases as their movement and dissolution in the soil solution become limited. The most significant effect of pollution is the deterioration of the biological properties of the soil. The content of petroleum substances in the range of 0.6–40 $mg \cdot kg^{-1}$ of soil is enough to alter the species composition of the microorganism community. The representation of species from the genera *Penicillium* and *Mortierella* increases at the expense of species from the genera *Streptomyces*, *Mucor*, and others. New species of *Aspergillus ustus* and *Penicillium tardum* are appearing (Chakravarty et al., 2022). The stabilization of organic contaminants due to interactions with hydrated iron and manganese oxides, clay minerals, and reactive $CaCO_3$ is, in principle, like the stabilization of “natural” organic substances naturally accumulating in the soil (Curiel-Alegre et al., 2022). The content of petroleum substances >270 $mg \cdot kg^{-1}$ of soil means the complete death of all microscopic organisms in the soil. After that, the contaminated soil requires radical rehabilitation. Even 10 ml of oil substances per kg of soil has a significantly negative effect on the soil macrofauna, and 20 ml will destroy all types of fauna in the soil. Oil substances with a concentration of >50 $ml \cdot kg^{-1}$ are toxic to plant roots and will cause a significant reduction in seed germination (Curiel-Alegre et al., 2022).

Plant species are resistant to the effects of petroleum hydrocarbons and can survive in polluted soils (petrophilic species: *Phragmites australis. Calamagrostis epigejos, Carex hirta, Bromus tectorum, Elytrigia repens, Lolium perenne, Dactylis glomerata, Deschampsia cespitosa, Agrostis stolonifera, Melilotus albus, Lotus corniculatus, Artemisia vulgaris, Medicago lupulina, Solidago canadensis, Cirsium arvense, Rubus caesius, Conyza canadensis, Urtica dioica, Galium aparine)* (Ollerová, 2004; Hybská et al., 2015; Bakina et al., 2021).

This article discusses the influence of selected chemical substances, determined as non-polar extractable substances, on the forest environment via the logging process.

2 MATERIALS AND METHODS

2.1 Characteristics of research sites

The research sites are in the Kremnické vrchy (Hills) mountain range, in Slovakia Two sites represent forest stands affected by logging, while the third is a control. From the phytocoenological point of view, these forest stands are classified as mesotrophic forest communities with beech dominance, occurring on deep soils of temperate Europe (*Fagion sylvaticae* Luquet 1926). More specifically, they belong to the association *Dentario bulbiferae-Fagetum sylvaticae* Mikyška 1939 nom. Invers. Concerning tree species representation, *Fagus sylvatica* dominates (50–75 %) in all sites. Other tree species are present to a lesser extent, including *Acer pseudoplatanus* (5–15 %), *Fraxinus excelsior* (3–10 %), *Picea abies*, and *Abies alba* (less than 10 %). Beech-stand ages on the control plot (No. 400) and plots 736 and 746 are 150 years, 110 years, and 95 years, respectively. The individual sites are similar in tree species occurrence and herb layer but differ in age. The soil type is cambisol.

2.2 Collection and preparation of samples

Soil sampling was from the area marked on the map Figure 1, as an area for phytocenological releves. Water samples were taken from the closest possible place to this surface.

Samples of soil and water were taken according to STN EN ISO 5667-1 (2006) and STN 48 1000 (2000) in the sense of the monitoring plan in the period from May 2021 to December 2022 on defined areas in forest stands:

No. 400: the control area, 8.09 ha, without logging, GPS 48.66060446313148, 19.03239290173866 (*Figure 1a*);
No. 736: the area with active logging, 21.18 ha, GPS 48.65188844667602, 19.023738640149453 (*Figure 1b*);
No. 746: the area with active logging, 16.66 ha, GPS 48.640456234455556, 19.018261886120037 (*Figure 1c*).

Soils were sampled from a depth of 0–10 cm into plastic bags. The weight of a soil sample was at least 1 kg. Plastic containers with volumes of 1.5 l and 1 l glass containers were used for sampling surface water at the Breznický Stream and the spring Bieň Stream. According to the map portal (www.zbgis.skgeodesy.sk), the monitored streams are as follows:

Breznický Stream: hydrological character – year-round; origin of the hydrographic object: natural, native; the stream is unnavigable on the terrain surface and is 2023 m long.
Bieň Stream: hydrological character – occasional; origin of the hydrographic object: natural, native; the stream is unnavigable on the terrain surface and is 524 m long.

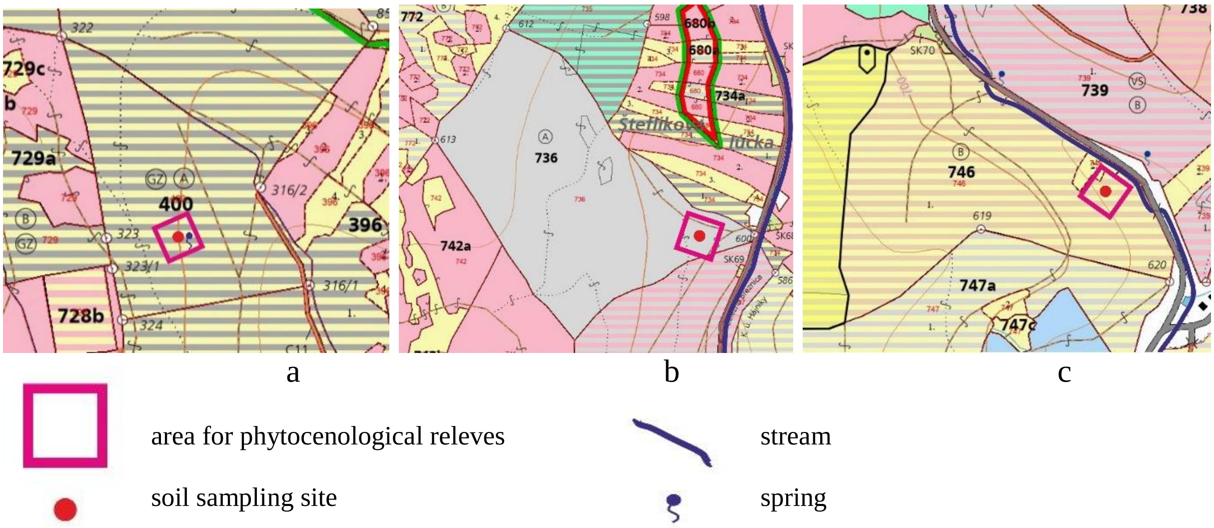

Figure 1. Forest stand: a – 400, b – 736, c – 746 (www.gis.nlcsk.org)

2.3 Principles of determination in surface water samples

Indicators determined in surface water samples: pH, conductivity, chemical oxygen demand by potassium dichromate (COD-Cr), non-polar extractable substances (NES), and biochemical oxygen consumption (BOD_5).

The chemical oxygen demand (COD-Cr)
Chemical oxygen demand is defined as the oxygen mass concentration, which is equivalent to the mass of the strong oxidation agent consumed under well-defined conditions of sample processing for the oxidation of the substances in 1 L of water. Potassium dichromate ($K_2Cr_2O_7$) is used as a reagent to determine the COD, in accordance with the ISO standard 8467 (2000).

The biological oxygen determination (BOD_5)
Biochemical oxygen consumption (BOD_5) is the amount of oxygen consumed by microorganisms for the biochemical decomposition of organic substances contained in water for five days under specified conditions, in accordance with the STN EN 1899-2(2001). Used device: oximeter WTW Oxi 340i, StirroxOxG.

Determination of the pH
The pH value significantly affects the chemical and biochemical reactions in water. A SenTix 81 electrode pH meter (WTW GmbH, Weilheim, Germany) was used to determine the pH: WTW GmbH, Weilheim, Germany InoLab pH Level 3 in accordance with the ISO standard 10523 (2008).

Conductivity determination
Conductivity is a basic criterion for assessing the number of electrolytes present in water. The determination of conductivity reflects the concentration of dissolved substances in the form of ions and water mineralization. A WtW LF 318 conductometer (GmbH, Weilheim, Germany) was used to determine the conductivity in accordance with the STN EN standard 27888 (1998).

NES determination
Oil substances in soil were determined as non-polar extractable substances (NES) using a spectrophotometer in an infrared area by the extraction with organic diluent (S-316 – polychlorotrifluoroethylene). The detection limit of NES was 0.15 $mg \cdot l^{-1}$. An artificial mixed

standard from compounds was prepared to control the measurement: methylbenzene, hexadecane, and pristane (2,6,10,14-tetramethylpenthadekane). The measurement was taken on an infrared spectrophotometer FTIR ATI MATTSON GENESIS (STN 83 0530-36: 1981).

2.4 Principles of determination of selected indicators in soil samples

Dry matter, pH/H2O, and non-polar extractable substances (NES) indicators were determined in forest soil samples. An InoLab Terminal level 3 - pH meter was used to measure pH/H_2O in the soil using a SenTix 41 pH electrode (WTW, Germany). (STN ISO 10390: 2005).

Dry matter was determined gravimetrically by drying to a constant weight at 105°C (STN ISO 11465:2001).

Non-polar extractable substances (NES): The NES content in the samples was determined after extraction in a solvent (S 316) and analysis in the IR spectrum 2960 cm^{-1}, 2925 cm^{-1}, 3055 cm^{-1} (ATI MATTSON GENESIS SERIES FTIR instrument). The detection limit of NES was 0.02 $mg \cdot l^{-1}$. The measurement was checked using an artificial mixed standard (description is in section Principles of determination in surface water samples – NES determination). The calculation was performed according to the Lambert-Beer law, while the necessary constants were obtained by measuring the calibration curves for the relevant standards or by calculation methods (TNI ISO/TR 11046: 2003).

2.5 Calculation of the EAI index (Environment Accident Index)

The EAI index result determines the further evaluation procedure. The EAI index is calculated according to the relationship:

$$EAI = Tox \times Am \times (Con + Sol + Sur), \text{ where}$$

Where:

Tox:	acute toxicity for aquatic organisms ($mg \cdot l^{-1}$)
Am:	stored/transported quantity (t)
Con:	kinematic viscosity of the substance (cSt)
Sol:	solubility of the substance (wt. %)
Sur:	expresses the characteristics of the environment (distance to the nearest watercourse, depth of groundwater, gradient of groundwater, thickness of soil above groundwater).

For a detailed assessment of environmental risks, it is recommended to consider all scenarios with an EAI index value > 100. For scenarios with an EAI value ≤100, the primary assessment of environmental risks is sufficient, and it is not necessary to take further measures in the form of a detailed risk assessment (according to the law of the Slovak National Council of the Republic No. 359/2007 Coll.).

Several authors (Scott, 1988; Pahl et al., 2005; Scott et al., 2007; Sikorova et al., 2017) document the use of EAI, but its use for impact assessment in the forest has not been published. The following sources were used for the calculation: Hybská (2018), MSDS of Cartechnic Hydrauliköl HLP 46, and maps of the locality.

2.6 Vegetation research

Phytocoenological records were used to study the vegetation and create a database of plant species occurring in the studied area, according to which syntaxonomic, synmorphological, and synecological characteristics of plant communities were developed. The recording areas were accorded with the soil sampling points for determining the NES. Phytocoenological records were conducted based on the principles of the Zurich-Montpellier school according to Braun-Blanquet (1964) and were completed three times in the growing seasons of 2021 and 2022, in the spring, summer, and autumn aspects on an area of 400 m^2. Qualitative and quantitative characteristics were observed within the records:

- Qualitative characteristics of plant coenoses represent a set of all species that occurred in the investigated area. The names of plant taxa are given according to Marhold and Hindák (1998).
- From the quantitative characteristics, the coverage estimate was evaluated using the combined seven-item scale of abundance and dominance according to Braun-Blanquet (1964).

The entries were processed in the Turboveg program into the database and subsequently exported and edited into tables in MS Excel. In the research areas, we obtained information about the biodiversity of herbaceous synusia in the forest stand.

3 RESULTS AND DISCUSSION

3.1 Surface water monitoring

NES, pH, conductivity, BOD5, and COD-Cr were determined. The Government of the Slovak Republic Regulation No. 269/2010 Coll., which establishes requirements for achieving good water status, was used for results evaluation.

Surface water samples were taken from small water sources and streams flowing near handling areas and unpaved roads in Stands 736 and 746. Water was not sampled in August and September 2022 due to the influence of weather conditions (high temperatures, extreme dryness), which dried out the streams. The Bieň Stream, from which the water samples were taken, originated in forest stand 400.

Conductivity and pH in samples from forest stand 736 comply with the Government of the Slovak Republic Regulation No. 269/2010 Coll. limits. NES limits were exceeded in samples during all samplings. BOD5 does not meet limit concentrations in 36 % of all samples. The results from the determination of COD-Cr do not show exceeding the limit (*Table 1*). The increased concentrations of NES and BOD5 were caused by the impact of the ongoing mining in 2022. Hybská (2010) monitored the same physicochemical indicators in surface water in Forest Stand 736. Due to the impact of the ongoing mining in the following years, we found that the water pollution in the stream increased in the monitored area, as noted in *Table 1.*

Table 1. Monitoring of surface water in Forest Stand 736

Forest stand No.	Date of sampling	Parameters				
		pH	Conductivity [mS·cm^{-1}]	NES [mg·l^{-1}]	BOD$_5$ [mg·l^{-1}]	COD$_{Cr}$ [mg·l^{-1}]
736	08.07.2021	7.56	1.14	0.37±0.03	1.32	2.21±0.04
	20.09.2021	7.45	1.96	0.25±0.07	0.54	5.47±0.27
	26.10.2021	7.29	0.15	0.5±0.07	0.88	7.04±0.88
	10.11.2021	8.44	1.48	0.25±0.03	0.47	6.21±0.04
	15.02.2022	7.47	0.55	0.15±0.06	0.58	1.24±0.08
	14.03.2022	7.35	1.32	1.85±0.03	5.32	15.54±0.06
	26.04.2022	6.71	1.09	1.72±0.04	7.55	12.02±0.10
	24.05.2022	7.61	1.10	1.91±0.03	8.43	15.28±0.16
	13.06.2022	8.22	0.10	2.29±0.01	13.13	10.02±0.08

Forest stand No.	Date of sampling	Parameters				
		pH	Conductivity $[mS\cdot cm^{-1}]$	NES $[mg\cdot l^{-1}]$	BOD_5 $[mg\cdot l^{-1}]$	COD_{Cr} $[mg\cdot l^{-1}]$
	28.07.2022*	-	-	-	-	-
	24.10.2022	7.49	0.13	2.6±0.03	8.73	17.05±0.09
	12.12.2022	7.51	1.79	1.51±0.04	6.43	18.02±0.04
Indicators**		6-8.5	<110	<0.1	<7	<35

* *Water sources were dried up due to high temperatures.*

** *The Government of the Slovak Republic Regulation No. 269/2010 Coll., which establishes requirements for achieving good water status.*

Table 2 lists the surface water monitoring values in Forest Stand 746. The pH and conductivity indicators were satisfactory compared to the limit concentrations. NES limits were exceeded compared to the declared limit during the entire monitoring period. BOD_5 did not comply in 40 % of samples, and COD-Cr was <35 mg/l; the values were within tolerance. We note that the ongoing mining influences the water quality in the Breznický Stream.

Table 2. Monitoring of surface water in the Forest Stand 746

Forest stand no.	Date of sampling	Parameters				
		pH	Conductivity $[mS\cdot cm^{-1}]$	NES $[mg\cdot l^{-1}]$	BOD_5 $[mg\cdot l^{-1}]$	COD_{Cr} $[mg\cdot l^{-1}]$
746	08.07.2021	7.57	1.37	2.07±0.03	6.01	12.26±0.09
	20.09.2021	7.21	0.60	2.54±0.01	8.38	17.29±0.19
	26.10.2021	7.38	1.86	2.83±0.03	9.15	18.04±0.07
	10.11.2021	7.14	1.95	2.01±0.03	5.38	14.36±0.16
	15.02.2022	7.19	2.95	5.03±0.03	10.54	21.25±0.04
	14.03.2022	7.17	0.86	2.04±0.03	8.41	11.33±0.09
	26.04.2022	6.69	0.26	0.83±0.01	1.64	7.06±0.09
	24.05.2022	7.35	0.52	0.46±0.03	0.98	6.25±0.04
	13.06.2022	7.26	0.25	1.46±0.04	3.08	8.05±0.01
	28.07.2022*	-	-	-	-	-
	24.10.2022	7.20	0.15	1.12±0.02	-	-
	12.12.2022	7.39	0.84	1.63±0.04	4.24	7.06±0.01
Indicators**		6-8.5	<110	<0.1	<7	<35

* *Water sources were dried up due to high temperatures.*

** *The Government of the Slovak Republic Regulation No. 269/2010 Coll., which establishes requirements for achieving good water status.*

Lindén and Palsson (2013) found up to 900 times the concentration of NES (7420 $\mu g\cdot l^{-1}$) compared to World Health Organization (WHO) recommendations when monitoring surface waters in Nigeria. The dissolved oxygen content ranged from 1.5 to 6.9 $mg\cdot l^{-1}$, depending on the water flow and aquatic flora. Salinity and conductivity ranged from 3.0 $\mu S\cdot cm^{-1}$ to 27,600 $\mu S\cdot cm^{-1}$. They report an active soil reaction (pH) between 4.7 and 7.3 and an average of 6.1.

Moslen and Aigberua (2018) found the total content of petroleum hydrocarbons in surface waters near oil refinery storages in Nigeria to be 20.34±1.79 - 27.40±5.32 $mg\cdot l^{-1}$.

In their work dealing with the contamination of surface and groundwater due to oil extraction, Raimi et al. (2021) report a biological oxygen demand of 3.8 $mg\cdot l^{-1}$ and an acidic pH for all surface water samples as evidence of the presence of oil pollution.

Table 3. Monitoring of surface water in the Forest Stand 400

Forest stand no.	Date of sampling	Parameters				
		pH	conductivity [mS·cm^{-1}]	NES [mg·l^{-1}]	BOD$_5$ [mg·l^{-1}]	COD$_{Cr}$ [mg·l^{-1}]
400	08.07.2021	6.95	0.95	0.04±0.01	0.36	0.98±0.01
	20.09.2021	6.58	1.95	0.05±0.01	0.44	1.00±0.03
	26.10.2021	6.27	0.21	0.08±0.01	0.57	1.09±0.01
	10.11.2021	7.01	0.99	0.13±0.01	0.87	1.21±0.01
	15.02.2022	7.24	0.98	0.10±0.71	0.71	1.15±0.01
	14.03.2022	6.85	2.12	0.08±0.01	0.67	1.08±0.01
	26.04.2022	6.84	0.09	0.07±0.01	0.59	1.01±0.02
	24.05.2022	8.21	0.15	0.04±0.01	0.43	0.96±0.01
	13.06.2022	7.49	0.11	0.04±0.01	0.42	0.97±0.03
	28.07.2022*	-	-	-	-	-
	24.10.2022	7.50	0.09	0.07±0.03	0.58	1.01±0.03
	12.12.2022	7.72	0.94	0.08±0.01	0.66	1.08±0.01
Indicators**		6-8,5	<110	<0,1	<7	<35

* *Water sources were dried up due to high temperatures.*

** *The Government of the Slovak Republic Regulation No. 269/2010 Coll., which establishes requirements for achieving good water status.*

The samples complied with the limit parameters resulting from the legislation at control site 400 (*Table 3*). The graph (*Figure 2*) confirms the impact of oil pollution from logging on water quality. The impact of logging (*Tables 6 and 7*) confirms the load of oil pollution on water.

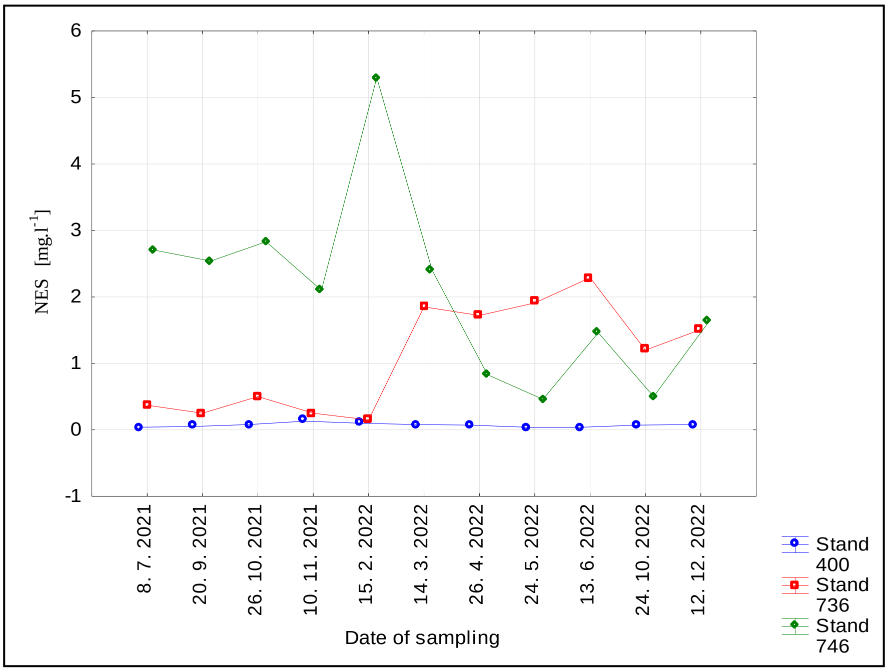

Figure 2. Water pollution due to logging in monitored stands

3.2 Monitoring of forest soils

NES content monitoring and physicochemical parameter analysis in soil and surface water were performed in samples from forest stands with different logging intensities. Forest Stand 400 was a control area, without intervention (no logging), and Stands 736 and 746 were designated as areas with active logging. *Tables 4*, *5*, *7*, and *Figure 3* show the sample analysis results. Based on Decree No. 59/2013 Coll. on the protection and use of agricultural land, the limit value of NES in agricultural land is 100 mg·kg^{-1} of dry matter. NES results in *Table 4* stay within the limit, confirming that there are no operations related to wood harvesting or other activities in Forest Stand 400 that could result in increased NES content.

Table 4. Forest soil monitoring in Forest Stand 400

Date of sampling	Parameters		
	pH	Dry matter [%]	NES [mg·kg^{-1}] of dry matter
08.07.2021	6.73	94.88	10.12±0.04
20.09.2021	6.91	96.76	14.24±0.03
26.10.2021	5.91	93.76	10.59±0.04
10.11.2021	5.68	96.73	8.97±0.06
15.02.2022	6.40	98.23	2.54±0.07
14.03.2022	5.64	97.63	2.41±0.06
26.04.2022	5.50	97.23	7.25±0.10
24.05.2022	6.20	86.36	16.19±0.14
13.06.2022	6.98	87.45	5.28±0.07
28.07.2022	5.66	92.10	2.16±0.07
24.10.2022	5.91	95.69	5.84±0.04
12.12.2022	8.03	96.30	5.11±0.03

Sáňka and Materna (2004) notes the active soil reaction (pH) that is valid for all types and horizons of forest stands and classifies these into five classes. We classify them in the fourth class of soil with an acidic pH (5.6–6.5), in the fifth class of slightly acidic to neutral soil (6.6–7.2), and finally in the sixth class of alkaline soil with a pH above 7.2. Based on this classification, the pH results in *Table 3* ranged between 5.5 and 8.03. Soils from Forest Stand 400 showed strongly acidic, acidic, slightly acidic – neutral to alkaline pH.

Table 5. Forest soil monitoring in Forest Stand 736

Date of sampling	Parameters		
	pH	Dry matter [%]	NES [mg·kg^{-1}] of dry matter
08.07.2021	4.84	95.12	32.22±1.41
20.09.2021	5.68	96.86	77.51±0.08
26.10.2021	5.60	96.27	85.45±0.01
10.11.2021	6.69	96.16	36.24±0.04
15.02.2022	6.09	96.76	119.14±1.48
14.03.2022	6.94	97.35	120.25±0.13
26.04.2022	6.09	97.16	85.35±0.24
24.05.2022	6.98	82.42	74.14±0.14
13.06.2022	6.48	89.05	55.45±0.11
28.07.2022	5.64	93.70	45.54±0.04
24.10.2022	6.18	98.02	132.64±0.11
12.12.2022	5.57	98.02	154.41±0.04

Based on the overview of wood harvesting in Forest Stand 736 (*Table 6*), 500 m^3 of woody plants were harvested during the monitoring period 2021–2022, of which 11 m^3 were coniferous and the remaining 489 m^3 were deciduous.

Table 6. Overview of timber harvesting in Forest Stand 736 (www.gis.nlcsk.org)

Year	Wood [m^3]		Together [m^3]
	Coniferous	Deciduous	
2014	256	380	636
2015	272	250	522
2016	68	192	260
2017	0	24	24
2019	174	190	364
2020	-	-	-
2021	-	-	-
2022	11	489	500

In Forest Stand 736 (*Table 5*), 30 % of the samples exceeded the limit values compared to Decree No. 59/2013 Coll. on the protection and use of agricultural land. According to Sáňka and Materna (2004), the soil pH values were strongly to slightly acidic, ranging from 4.84 to 6.98.

Table 7. Forest soil monitoring in Forest Stand 746

Date of sampling	Parameters		
	pH	Dry matter [%]	NES [$mg \cdot kg^{-1}$] of dry matter
08.07.2021	5.34	93.99	50.54±0.10
20.09.2021	5.34	95.96	122.14±0.03
26.10.2021	5.74	95.10	135.25±0.16
10.11.2021	5.46	98.30	127.84±0.07
15.02.2022	5.92	98.30	137.97±0.04
14.03.2022	5.93	96.93	125.47±0.16
26.04.2022	5.92	96.30	105.65±0.06
24.05.2022	5.99	93.36	57.87±0.06
13.06.2022	6.15	93.44	57.47±0.17
28.07.2022	6.16	94.43	34.58±0.03
24.10.2022	5.58	95.13	65.96±0.04
12.12.2022	5.66	92.99	70.47±0.08

In Forest Stand 746 (*Table 8*), 796 m^3 of woody plants were harvested during the 2021–2022 monitoring period, of which 212 m^3 were coniferous and 584 m^3 deciduous.

Table 8. Overview of timber harvesting in Forest Stand 746 (www.gis.nlcsk.org)

Year	Wood [m^3]		Together [m^3]
	Coniferous	Deciduous	
2014	221	245	466
2015	196	477	673
2017	450	612	1062
2020	0	29	29
2021	108	579	687
2022	104	5	109

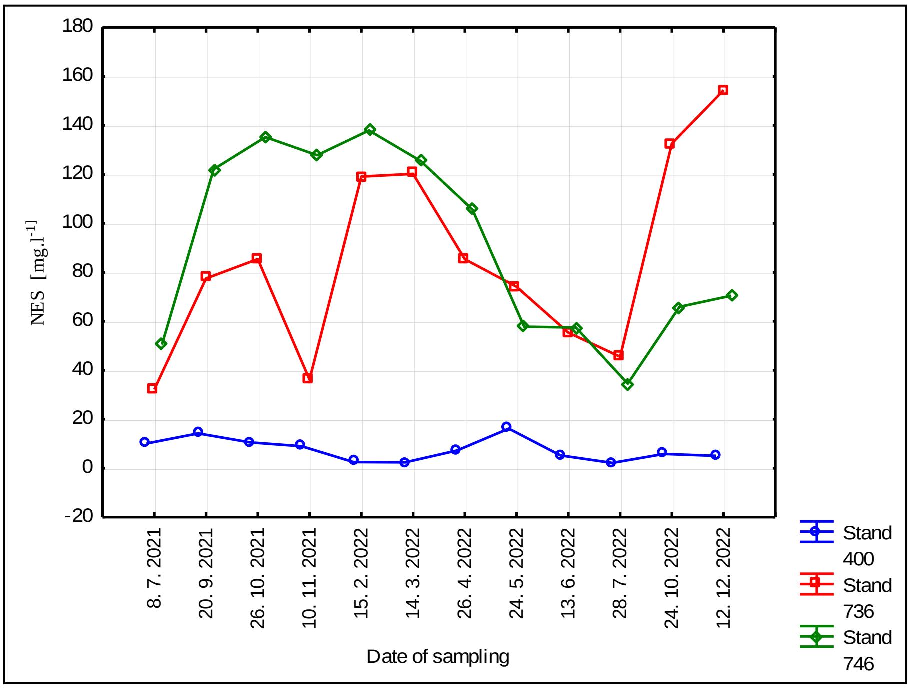

Figure 3. Soil pollution due to logging in the monitored stands

The NES limit value was exceeded in 50 % of the analyzed samples in Forest Stand 746. We conclude that the increased NES contents were related to logging intensity (*Table 7*). According to Sáňka and Materna (2004), the pH results in *Table 7* are sorted into the classification classes of strongly acidic, acidic, slightly acidic-neutral, and alkaline, in total, ranging from 5.34 to 6.16.

Klamerus-Iwan et al. (2015) monitored the influence of operating oils of petroleum origin on physical and biological processes in forest soil and stated that forestry work using transport-mechanization mechanisms causes annual leakages of up to 7 million liters of various mineral oils into forest soils. These oils are toxic and affect various biological and physical processes in the soil environment. They also found that soil contaminated by petroleum substances at concentrations of 100 $g \cdot m^{-2}$ of soil will reduce the porosity of soils by 4 %, and at concentrations of 200 $g \cdot m^{-2}$, reduce soil breathability by 10 %. Increased concentrations of mineral oils increase soil hydrophobicity and affect enzyme activity. The lowest amount of oil (50 $g.m^{-2}$ of soil) causes only a slight decrease in urease activity, but 100 and 200 $g.m^{-2}$ of soil reduce it by 40-50 % compared to the control area (area without pollution).

Buzmakov et al. (2019) found that coniferous and deciduous forest ecosystems are less susceptible to oil pollution. Their studies found that forest soil becomes acutely toxic (bioassay with test organisms *Daphnia magna* Straus) at oil concentrations above 200 $g.kg^{-1}$ soil for animals.

Acidic to neutral pH characterizes most forest soils. Rather et al. (2022) noted higher pH (6.797 ± 0.136) and electrical conductivity (0.286 ± 0.028) in the polluted area in contrast to the undisturbed area with a pH (5.39 ± 0.230). The increased pH in the deforested and affected forest zone disrupts the natural habitats of flora and fauna and reduces the amount of organic material, leading to the spread of bare and disturbed forests. Increased pH can also mitigate soil organic residues, causing the flow of organic acids into the soil solution. Increased pH and electrical conductivity in disturbed forest stands are attributable to poor forest vegetation cover.

3.3 Characteristics of vegetation on monitoring areas affected by economic activity (mining)

In 2021, the number of species in the herbaceous layer in the monitored areas ranged from 11 to 31 at the time of optimal vegetation development (summer aspect). In 2022, during the summer aspect, the number of species was lower than the previous year, in the interval from 6 to 13. In both years, the number of species logically decreased from the spring to the autumn aspect.

In the mining-affected area (746), we recorded the highest number of species, 31, in the summer of 2021. The area was illuminated after mining, and the increased light caused the occurrence of a higher number of species. In 2022, the number of species dropped to 13, which is more than a 50% reduction. The species missing include, *Rubus fruticosus* agg., *Rubus idaeus, Asarum eurapaeum, Carex 34ilosa, Fragaria vesca, Hypericum maculatum, Prenanthes purpurea, Prunesla vulgaris, Urtica dioica, Epilobium montanum, Cerastium holosteoides, Mentha longifolia, Poa nemoralis, Ranunculus repens, Actea spicata, Senecio vulgaris, Sonchus arvensis, Stachys sylvatica,* and *Plantago media*.

We recorded fewer species in the second area (736). In 2021, the number of species was 25, and in 2022 it was 12. Again, less than half. Species missing included, *Rubus fruticosus* agg., *Rubus idaeus, Euphorbia amygdaloides, Asarum eurapaeum, Fragaria vesca, Hypericum maculatum, Prunesla vulgaris, Glechoma hederacea, Scrophularia nodosa, Senecio nemorensis, Stachys sylvatica, Plantago media, Equisetum sylvaticum, Lycopus europaeus, Melittis melissophyllum, Mycelis muralis, Stellaria media,* and *Veronica prostrata.*

We observed the lowest number of species in the control area unaffected by logging – 11 in 2021 and 6 in 2022.

A few factors — climatic, soil, ecological, economic, and cultivation — influence the downward trend in the number of species in the areas between two years. The monitored research period is very short from the point of view of vegetation assessment, and more vegetation periods are needed to assess and evaluate vegetation development trends.

The coverage of the herbaceous layer varied from 10 % to 60 % in all areas in the observed period. We recorded 74 species in total on the E1 floor. The vegetation in the areas is relatively species-poor, which corresponds to communities from the *Fagion sylvaticae* association. This union brings together the most widespread climax communities of mesotrophic to eutrophic mesophilic beech trees in Western and Central Europe. Communities are linked to cambism with balanced nutrient content and favourable humification.

Stand 746 reached 60 % coverage in E1 in the first year of monitoring and 50 % at the same time in the second year. Stand 736 reached 30 % coverage in 2021 and 40% in 2022. The coverage did not change significantly even at the control site, reaching values of 10 % and 20 %. However, these are the lowest coverage values of all monitored areas.

The herbaceous species with the highest stability are *Galium odoratum, Rubus fruticosus* agg., *Salvia glutinosa,* and *Dryopteris filix-mas*. The species *Dentaria bulbifera, Galium odoratum, Rubus fruticosus* agg., and juvenile individuals of *Fagus sylvatica* achieve the highest abundance and coverage. Of the shrubs, *Fagus sylvatica, Fraxinus excelsior, Picea abies,* and *Acer platanoides* represent the highest stability and coverage. *Fagus sylvatica*, forest beech, is the growth edifier in all of the areas. In addition to the dominant beech, *Fraxinus excelsior, Picea abies, Abies alba,* and *Acer pseudoplatanus* are represented in E3.

The plant community in the monitored areas belongs to the association *Dentario bulbiferae-Fagetum sylvaticae* Mikyška 1939 nom. Inverse. The community does not have a high number of species, which is also confirmed by the control area. Economic stands have a simple vertical structure, with no canopy layer under the beech canopy, or the layer consists of young beech and several other species. *Dentaria bulbifera* mainly achieves a higher coverage in the spring aspect. Only sciophyte (shade-loving) geophytes with special adaptations to these conditions (vegetative reproduction, mycorrhiza, heterotrophy) — *Dentaria bulbifera, Neottia nidus-avis, Epipactis helleborine, Monotropa hypopitys* — often prevail in heavily shaded undergrowth and on the thick layer of litter. Permanent species with low abundance values are usually the most common species of mesotrophic beech trees of the *Fagetalia sylvaticae* family – *Galium odoratum, Mycelis muralis, Dryopteris filix-mas, Viola reichenbachiana* (Valachovič et al. 2021). We also recorded these species in the monitored areas.

The intense competitive pressure the dominant tree exerts limits the development of the herbaceous layer, especially on the northern slopes of lower mountain positions or in the rain shadow. The relatively smaller amount of precipitation can only effectively use the surface root system of beech, and the competition of roots in the rhizosphere of herbs is the main explanation for the existence of nodal types (Slavíková et al., 1986; Barna et al., 2011).

When evaluating the ecological requirements, we can state that the species with the highest stability represented in the research areas are mesotrophic. According to soil moisture, these are moist soil types. The species are neither significantly drought-loving nor moisture-loving. According to the soil reaction, these are plants that like weakly acidic to neutral soils, and according to the nitrogen supply in the soil, they are moderately nitrophilous species.

Dependence was not confirmed. NES content in soil and surface water did not affect vegetation — the number and coverage of species in the monitored areas. The amount of NES was the lowest in the control plot, which was not affected by logging. At the same time, the lowest number of species was also recorded here, influenced by the abovementioned factors (canopy, light conditions, and fallow height).

3.4 Determination of the EAI index

The EAI index method used in environmental risk assessment depends primarily on the amount of hazardous substances that can escape into the environment. Economic activities in the forest, such as logging, should be performed in a way that causes no changes in biodiversity, water quality deterioration, and soil composition. The proposed scenarios result from engineering approaches that aim to clearly describe the qualitative and quantitative causality of the respective scenario.

Three scenarios were chosen to determine the EAI for operating fluids that can escape into the natural environment from three different mechanisms: Zetor 7245, LKT 81 ITL, HSM 805 (traffic accident (damage to the tank with the operating fluid), leakage, and equipment neglect).

Scenario 1: leakage of the entire volume of operating fluid from the tank
Scenario 2: leakage of 1/2 volume of operating fluid from the tank
Scenario 3: leakage of 1/3 of the volume of operating liquid from the tank.

Table 9. Results of the EAI index of operating fluids Zetor 7245, LKT 81 ITL, HSM 805

Oil	Tox	Am	Con	Sol	Sur	EAI index		
						Scenario 1	Scenario 2	Scenario 3
hydraulic oil	6	1	3	2	7	72	72	72
diesel fuel	4	1	4	2	7	52	52	52
motor oil	2	1	3	2	7	24	24	24
gear oil	2	1	3	2	7	48	48	48

Mechanisms move on unpaved surfaces and use operating fluids, including diesel fuel, engine oil, hydraulic oil, and gear oil. The calculated values of the EAI index are ≤ 100 (*Table*

9); further detailed assessment is unnecessary (Act of the National Council of the Slovak Republic No. 359/2007 Coll.).

The mechanisms use the same operating fluids. According to the selected scenarios (leakage of 100 %, 50 %, and 33 %), we found that when the amount of operating fluid in the mechanism does not exceed 0.5 t (Am = 1), the result of the EAI index is the same within one type of operating fluid. The purpose of the EAI index calculation was to determine the degree of load on the components of the environment (water, soil) and subsequently propose measures against the leakage of operating fluids into the environment. Given the facts, we propose to increase care for the technical condition of these devices, especially Zetor 7245, which was manufactured in the 1970s and has an increased failure rate. LKT was produced in 2018, and HSM in 2007. The adsorbent and tools are included in the equipment of these machines, but we recommend adding a chemical mobile emergency kit, which contains loose sorbent, sorption mats, sorption snakes, sorption pillows, sealant, gloves, protective glasses, shovel with a whisk, and bags for used waste. It is necessary to provide training for service personnel on procedures for accidental spillage of operating fluids. It is crucial to maintain the satisfactory condition of the equipment, but considering their age, it would be advisable to replace them with modern ones that are safer for the environment.

4 CONCLUSIONS

The indicator of non-polar extractable substances was chosen to evaluate the impact of mining on the forest environment. NES content monitoring and physicochemical indicator analysis in soil and surface water were conducted in samples from forest stands with different logging intensities. Forest Stand 400 was a control area, without logging, and Stands 736 and 746 were areas with active logging. A small water source flowed through the growth of 736 and 746. During water pollution monitoring in surface sources, concentrations of NES, BOD5, and COD-Cr that exceeded limits set by the Government of the Slovak Republic Regulation no. 269/2010 Coll., were recorded. The NES indicator was exceeded in all analyzed surface water samples.

In Forest Stand 736, 30% of the samples exceeded the limit values set by Decree No. 59/2013 Coll. on the protection and use of agricultural land. The NES limit value in Stand 746 was exceeded in 60 % of the analyzed samples. The soil from the control area, Forest Stand 400, was the least contaminated and did not exceed the NES limit. Increased physicochemical indicator values could be caused by operating fluid leaks from transport-mechanization mechanisms, pollution from older environmental loads, or the content of humic substances.

Dependence was not confirmed. NES content in soil and surface water did not affect vegetation — the number and coverage of species in the monitored areas. NES was the lowest in the unlogged control plot. At the same time, the lowest number of species was also recorded here. The low species number is influenced by the above-mentioned factors (canopy of the stand, light conditions, and fallow height).

The EAI index method was used to assess the environmental risk in the logging environment. Three operating fluid leak scenarios — traffic accident, tank damage, leakage, and equipment neglect — were chosen for Zetor 7245, LKT 81 ITL, and HSM 805 equipment used to determine EAI. The calculated EAI index values for all operating fluids used in all three mechanisms are ≤ 100 (*Table 9*), rendering further detailed assessment unnecessary (Act of the National Council of the Slovak Republic No. 359/2007 Coll.). Based on these findings, we recommend adding a chemical mobile emergency kit to transport vehicles and machines used in economic activities in the forest.

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Assessment of Tree Species Availability Based on Sawmilling and Timber Markets Survey in Sinnar State, Sudan

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ABSTRACT

This study assesses tree species availability in Sinnar state, Sudan, to identify the types of wood used, marketed and explores the selection criteria driven by the continuing demand for timber in construction, furniture, and energy sources. The research included interviews with 87 randomly selected respondents from three timber trading and sawmill companies (Elsuki, Sinnar, and Singa). The surveys utilize descriptive analysis using SPSS and Excel. Findings revealed 28 historically available timber species, of which only eight are currently on the market. Selection criteria for trading species include viability, durability, and market demand. Approximately 47.9 % of timber comes from reserved forests, mainly for sawmill use, while 31.3 % comes from private and community-managed forests. The study highlights a significant decline in the availability of timber species, with 88 % of respondents expressing concerns about this trend due to overexploitation, revealing the urgent need for conservation efforts. This study suggests planting indigenous fast-growing trees to meet the region's timber needs.

TANULMÁNY INFÓ

Kulcsszavak:
Fafajok elérhetősége
Fűrészüzemek dinamikája Szudánban
Fakereskedelem és piaci igények
Erdő megőrzési stratégiák
Őshonos fafajok
Fenntarthatóság

KIVONAT

Fafajok elérhetőségének értékelése a fűrésztelepek és fapiacok felmérése alapján Szinnár Államban, Szudánban. A tanulmány a fafajok elérhetőségének felmérését irányul Szinnár államban, Szudánban, annak érdekében, hogy azonosítsa az építőanyagként, bútorok készítéséhez és energiatermeléshez használt fafajtákat, valamint feltárja a választási szempontokat, melyeket az állandó fa iránti kereslet hajt, az építkezések, bútoripar és energiaforrások területén. A kutatás magában foglalt interjúkat 87 véletlenszerűen kiválasztott válaszadóval három faanyag-kereskedelmi és fűrészüzemi vállalattól (Elsuki, Szinnár és Singa). A felmérések leíró elemzést alkalmaznak SPSS és Excel segítségével. Az eredmények azt mutatják, hogy a korábbi 28 fafajból jelenleg nyolccal kereskednek. Az eladási fafajták kiválasztási szempontjai közé tartozik a megfelelőség, a tartósság és a piaci kereslet. Az összes fakitermelés körülbelül 47,9 %-a tartalékolt erdőkből származik főként fűrészipari felhasználásra, míg a 31,3 %-a magán és közösségi kezelt erdőkből jön. A tanulmány rávilágít a fafajok elérhetőségének jelentős csökkenésére, a válaszadók 88 %-a aggodalmát fejezi ki ezzel a tendenciával kapcsolatban, ami az erőforrás túlkihasználására vezethető vissza. Sürgős megőrzési erőfeszítésekre hív fel. Ez a tanulmány azt javasolja, hogy ültessenek be őshonos, gyorsan növő fákat annak érdekében, hogy kielégítsék a régió faigényét.

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1 INTRODUCTION

According to Newton et al. (2022), a significant proportion of the world's population resides in rural regions. Of the approximately 4.17 billion people in non-urban areas, 95 % lived within a 5-kilometer radius of a forest in 2019. Furthermore, 75 % of the global population, equivalent to approximately 3.27 billion people, resided less than one kilometer from a forest. A strong association between the proximity of forests and the prevalence of extreme poverty is plausible, as evidenced by the approximately 80 % of individuals living in extreme poverty are in rural regions (Castañeda et al., 2018).

The data published by the Population Census Council in 2008 determined that around 29.5 % of Sudan's population concentrates in urban regions, whereas the remaining (70.5 %) reside in rural areas (Hussein, 2014; Idris, 2020). A sizable portion of the rural population depends on the forest to live and uses round timber and poles for construction and wood as a primary energy source. The aggregate extent of forest plantations in Sudan amounts to slightly less than 1,300,000 hectares in the country's northern region.

According to FAO/FNC (1995) findings and Keenan et al. (2015), the national forest inventory conducted in Sudan, specifically in the region north of latitude 10° N, revealed that the annual average increment of forest resources was around 11 million m^3. FAO/FNC (1995) and Hansen et al. (2013) estimate a yearly national wood consumption rate of around 16 million m^3, significantly lower than the recorded wood consumption in this case. Notably, energy consumption plays a significant role in driving deforestation. At the same time, other factors, such as horizontal expansion of agriculture, fires, drought, and overgrazing, contribute to the overall loss of forest resources.

The primary purpose of establishing forest plantations has been to acquire fuel wood and building materials, namely eucalyptus and acacias, within irrigated plantations (Riveiro et al., 2023). Furthermore, plantations were established for sawn timber production in many regions of Sudan. These include the cultivation of *Acacia nilotica* in riverine forests, the growth of softwood plantations in Jebel Marra, and the establishment of teak and mahogany plantations in central Sudan. In addition, forest plantations have been employed as a means of environmental conservation, such as establishing shelterbelts and windbreaks inside agricultural initiatives and introducing acacia plantations to mitigate desertification in semi-arid regions.

Preserving watersheds has also been a primary goal, as seen by the plantations established along seasonal rivers and watercourses, canal site plants in northern Sudan, and plantations in Jebel Marra. Non-timber forest products, including gum, forest fruits, tannin, and fodder, have been cultivated by utilizing out-growers and plantations within reserved forest areas (Gafaar, 2011).

FAO (2022) states that wood products have lower levels of greenhouse gas emissions throughout their life cycles than products sourced from non-renewable resources or materials with high emissions. Adequately responding to the increasing demand sustainably entails enhancing the supply by implementing restoration, reforestation, and afforestation programs on lands that have undergone degradation. According to Nhantumbo et al. (2013), forestry initiatives such as allocating resources towards alternative options to large-scale private sector concessions, such as community-owned forests and community-based concessions for various resources, including timber, fuelwood, charcoal, and high-value resources, as well as community licenses for wood and biomass energy, holds promise in enhancing forest management and restoration efforts.

The stated research challenge pertains to the need for a more comprehensive investigation of the availability and distribution of tree species within the designated study sites. This demand is present notwithstanding ample research that has yielded substantial insights into forest-based small-scale businesses (F-BSSIs) and the timber market. The main objective of this study was to assess tree species availability in Sinnar state, Sudan, to identify the types of wood used and marketed, and to explore the selection criteria driven by the continuing demand for timber in construction, furniture, and energy sources.

2 MATERIALS AND METHODS

2.1 Description of study area

The study area is about 400 Km south-to-south-east of Khartoum along the Blue Nile River. Sinnar State occupies a total area of 40,680 km^2 with a population of 1,508,552 million (Sinnar State, Central Statistics Office 2016). It is located between latitude 12° 5′.and 14° 7′ North and longitude 32° 58′ and 35° 42′ East (Nassrelddin, 2012) (*Figure 1*).

The region's topography is predominantly flat, punctuated only by a few isolated hills. The soil composition consists of dark-colored alkaline clay. Annual precipitation typically falls within 550 to 620 millimeters, mainly between June and October. The primary economic activity in this region revolves around agriculture, with the farming system as the predominant livelihood strategy. Livestock, including goats, cows, sheep, and camels, contributes approximately 23 % to the overall national economy within the study area.

The local vegetation falls within the low rainfall woodland savanna category, characterized by clay-rich soils. Notable tree species dominating the landscape include *Acacia seyal*, *Acacia mellifera*, and *Balanites aegyptiaca*. Additionally, the depressions and periodically inundated plains along the Blue Nile serve as the natural habitat for the renowned Sunut (*Acacia nilotica*) forests, which hold significant cultural and ecological importance in Sudan. Sinnar state was selected as the study area due to its environmental significance, the presence of many stakeholders, and the opportunity to study a range of forest types, particularly the riverine Sunut forests, making it a valuable location for in-depth research and analysis.

Figure 1. Map of the study area

2.2 Data collection

This study applied a purposive sampling technique. The sampling frame comprised 112 sawmilling and timber markets. The sample size was determined by applying the formula (Yamane, 1967) in Equation (1), an approach that has been widely used in various studies (Pello et al., 2021; Amare et al., 2019; Hemida et al., 2023).

$$n = N(1 + N(e)^2) \tag{1}$$

Where:

n: sample size
N: the total number of participants from sawmilling and timber markets
e: marginal error at a 5 % precision level.

Accordingly, 87 respondents were selected randomly from two groups: 37 sold firewood and small wood for construction, and 50 were engaged in timber trading for sawmills. These individuals were chosen from three localities: Elsuki (37 respondents), Singa (30), and Sinnar (33). Participants were included based on their availability and willingness to participate.

Data was collected through primary and secondary means. Primary data was gathered through face-to-face interviews using a semi-structured questionnaire complemented and validated by key informant interviews. Before the formal interview, the questionnaire was rigorously pre-tested with a cohort of 10 farmers to assess its reliability and validity.

Secondary data comprised various documents, including archival records, FNC and FAO reports, literature (articles, books, policy briefs), and internet sources. This secondary data played a crucial role during the primary data collection phase and was instrumental in determining the indicators and factors utilized in the study and designing the questionnaire for data collection.

2.3 Statistical methods

The collected data were processed and analyzed using statistical software, specifically SPSS (version 25) and Excel 2016. Descriptive statistics, such as percentages and frequencies, were employed to present and summarize the data.

3 RESULTS

3.1 Demographic and educational profile of timber traders and sawmill owners

The study results reveal that all respondents were male (100 %), revealing a male-dominated industry (*Table 1*). The table indicates that most sample participants' ages range between 50–59 years (43.5 %) and 40–49 years (40 %) for timber traders and sawmill owners, respectively. The educational levels of timber traders and sawmilling owners show that many respondents have secondary education (30.4 % and 28 %), respectively.

The educational backgrounds in the timber trading and sawmilling industries display distinctive trends. Timber traders have higher enrollment in Khalwa (13 %) than sawmill workers (4 %), indicating a more substantial influence of traditional education in trading. Basic education is more common among timber traders (26.3 %) compared to those in sawmilling (21 %). Primary education is more prevalent in sawmilling (16 %) than in timber trading (4.3 %). Both sectors have similar secondary education rates, with 30.4 % timber traders and 28 % sawmill workers. University education is slightly higher among timber traders (13 %)

than sawmill workers (9 %). Given the sector's need to comprehend technical documentation and safety regulations, 21 % of sawmill workers are literate, compared to 13 % in the timber trading industry.

The presence of a significant portion of respondents with 20–30 years of experience (30.4 % in timber traders and 48.0 % in sawmilling) suggests stable involvement in the industry. Conversely, those with less than 20 years of experience highlight ongoing entry into the market (30.4 % in timber traders and 16 % in sawmilling). Additionally, 30.4 % of the timber traders reported having been in the business for 31 to 40 years. The figures for those with over 40 years of experience are lower, representing only 8.8 % of timber traders and 16 % of sawmilling.

Table 1. Age, sex, years in business, and education level profiles of timber traders (% of respondents in each class)

Characteristics		% of respondents	
		Timber traders (37)	Sawmilling (50)
Age (years)	18-29	0	4.0
	30-39	8.7	8.0
	40-49	17.4	40.0
	50-59	43.5	28.0
	above 60	30.4	20.0
Sex	Male	100	100
Educational Level	Khalwa*	13.0	4.0
	Basic	4.3	16.0
	Secondary	30.4	28.0
	Primary	26.3	21.0
	University	13.0	9.0
	Literacy	13.0	21.0
Years in Business	Less than 20	30.4	16.0
	20-30	30.4	48.0
	31-40	30.4	20.0
	above 40	8.8	16.0

**Islamic school for The Holy Quran and its studies.*

3.2 Types of wood used/sold in depots (Mawrda) and sawmilling for the past three decades

The study results show 27 timber tree species in the marketplace over the past three decades. Most species are unavailable due to conservation protection, overharvesting, prohibitive costs, habitat destruction, geographic inaccessibility, and regulatory restrictions (*Table 2*). The same table shows that the main timber species in the market (Mawrda) were *Acacia nilotica* (52.2 %), *Cordia sinensis* (43.5 %), and *Khaya senegalensis* (34.8 %). Respondent rankings of wood types available for sawmilling revealed 48 % for *Acacia polyacantha* and *Diospyros mespiliformis*, 44 % for *Khaya senegalensis* and *Balanites aegyptiaca*, and 36 % for *Acacia nilotica*.

Table 3 illustrates the incidence of timber and sawing wood the respondents traded in the study area according to their importance. The same table indicates that the main timber species were *Acacia nilotica*, representing (100 %) and (95.7 %) for marketing and sawmilling timber, respectively. Besides that, *Azadirachta indica* and *Mangifera indica* were the second most crucial wood species after *Acacia nilotica* in sawmilling 88 % and timber traders 69.6 %. This may be due to their availability, market demand, market price, and the available income for the buyers (Blair et al., 1982; Nautiyal, 1988).

Table 2. Species of Market Traded Timber over the last 30 Years

No	Binomial Nomenclature	Local Name (Arabic)	% of respondents	
			Timber traders	Sawmilling
1	*Acacia nilotica* subsp. *tomentosa*	Sunut	52.2	36.0
2	*Acacia polyacantha* Willd	Kakamut	17.4	48.0
3	*Acacia seyal* var *seyal* Del.	Talh	13.0	0
4	Adina microcephala (Del.) Hiern	Mishka	0	8.0
5	*Albizia aylmeri* Hutch. ex. Broun	Sereira	0	8.0
6	*Anogeis. leiocarpus* (DC.) Guill. & Perr.	Sahab	17.4	0
7	*Balanites aegyptiaca* (L.), Del.	Higlig	26.1	44.0
8	*Borassus aethiopum* Mart.	Delieb	8.7	0
9	*Cono. lancifolius* Engl. ex Engl. & Diels	Damas	8.7	4.0
10	*Cordia africana* Lam	Gimbil	0	4.0
11	*Cordia sinensis* Lam.	Andrab	43.5	32.0
12	*Crateva adansonii* DC	Dabkar	0	4.0
13	*Dalbergia melanoxylon* Guill. & Perr.	Babanus	13.0	0
14	*Diospyros mespiliformis* Hochst. ex DC.	Goghan	30.43	48.0
15	*Eucalyptus camaldulensis* Dehn.	Ban	26.1	0
16	*Fagus sylovatica*	Zan	4.3	0
17	*Faidherbia albida* (Delile) A.Chev.	haraz	13.0	0
18	*Ficus sycomorus* Linn	Gameiz	0	12.0
19	*Hyphaene thebaica* (Linn.) Mart	Dom	8.7	0
20	*Khaya senegalensis* (Desr.) A. Juss	Mahogany	34.8	44.0
21	*Oxytenanth. abyssinica* (A. Rich.) Munro	Gana	17.4	0
22	*Piliostigma reticulatum (DC.) Hochst.*	Abukhmira	0	12.0
23	*Pseudocedr. kotschyi* (Schweinf.) Harms	Duruba	8.7	4.0
24	*Pterocarpus lucens* GuilL. & Perr.	Taraya	26.1	0
25	*Sterculia setigera* Del.	Tartar	8.7	0
26	*Tamarix nilotica* (Ehrenb.) Bunge	Tarfah	0	4.0
27	*Tectona grandis* L	Teak	8.7	12.0
28	*Ziziphus spina-christi* (Linn.) Desf	Sidr	0	28.0

Table 3. Traded timber Species in 2023

No	Timber species	% of respondents	
		Timber traders	Sawmilling
1	*Acacia nilotica* subsp. *tomentosa*	100.0	95.7
12	*Acacia seyal* var *seyal* Del.	0	8.7
7	*Anogeissus leiocarpus* (DC.) Guill. & Perr.	0	26
5	Azadirachta indica A. Juss	88.0	69.6
9	*Balanites aegyptiaca* (L.), Del.	12.0	17.4
3	*Eucalyptus camaldulensis* Dehn	0	13.0
10	*Ficus sycomorus* Linn	0	8.7
4	*Mangifera indica* Linn.	88.0	47.8
6	*Oxytenanthera abyssinica* (A. Rich.) Munro	0	21.7
11	*Psidium guajava* (L.)	0	26.1
8	*Ziziphus spina-christi* (Linn.) Desf	0	21.7
	Total		100.0

3.3 Reasons for choosing Sunut timber

The data analysis found that *Acacia nilotica* is the primary species used by the respondents for sawmilling (100 %) and timber (95.7 %) in the market. Respondents (*Figure 2*) rank *Acacia nilotica* timber products according to market choice. The responding timber traders (67 %) and sawmill timber (76 %) chose timber according to species availability. In contrast, some respondents (28.4 %) chose *Acacia nilotica* timber based on demand.

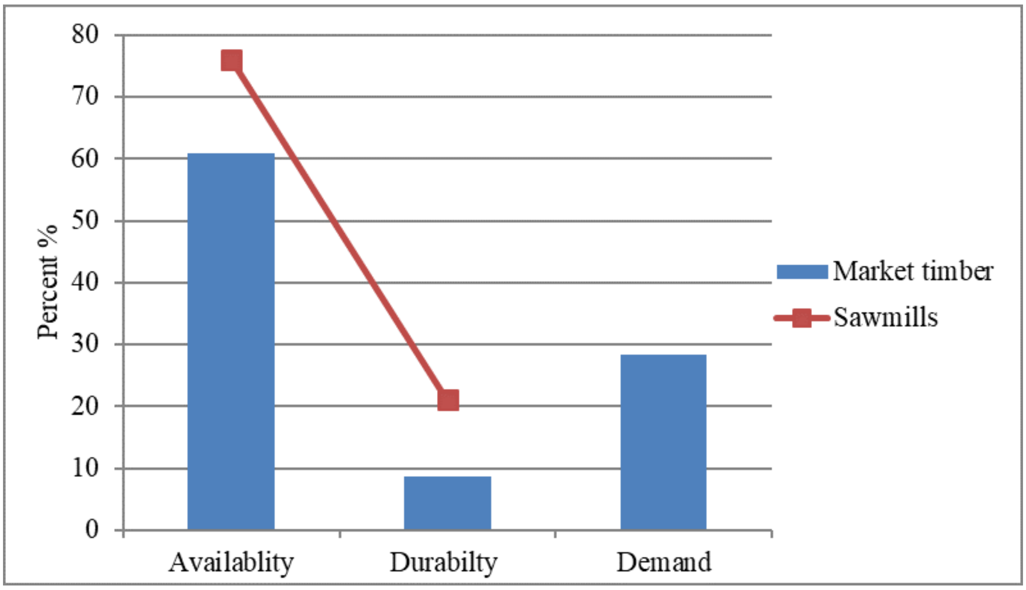

Figure 2. Reasons for choosing Sunut Timber

The study identifies forest reserves, unique forests, and community forests as the primary timber suppliers, as shown in *Table 4*. The comparison of timber sourcing between the timber traders and sawmilling sectors highlights distinct preferences, underscored by a chi-square test statistic of 73.55 and (P = 0.000), indicating significant differences in the sources of timber for trade and sawmilling. With timber traders, 30.42 % of respondents source from forest reserves, 4.38 % from notable and community forests, and 65.20 % utilize a combination of sources, reflecting a broad sourcing strategy aimed at risk mitigation. In contrast, sawmilling shows a more substantial reliance on local sources, with 76.90 % sourcing from forest reserves and 11.50 % from community forests, suggesting a dependency on localized timber supplies. Only 7.40 % of sawmill respondents use multiple sources, indicating less diversity in their sourcing strategy than timber traders. The notable disparity in sourcing practices reveals operational differences and carries implications for regulatory and sustainability considerations, emphasizing the need for targeted policies ensuring sustainable resource utilization.

Table 4. Timber sources used by respondents

Timber soures	% of Respondent		X^2	df	p
	Timber traders	Sawmilling			
Missing	0.0	4.20	73.55[a]	3	0.000
Forest reserves	30.42	76.90			
Special and community forest	4.38	11.50			
All of the above	65.20	7.40			
Total	100	100			

[a] = Chi-squared test indicates significant differences

3.4 Wood product preference

The study results on timber species selection criteria in marketing indicate that timber availability is the predominant element influencing the decision-making process for 40 % of participants. By comparison, a notable proportion of individuals, precisely 28 %, choose based on species durability and market demand. Furthermore, a mere 4 % of participants justify their selection based on the economic aspect of the species. Concerning sawmilling, most sellers (47.8 %) choose according to a mixture of the reasons above, as depicted in *Figure 3*. The study findings are consistent with the discoveries made by Nautiyal (1988), wherein a combination of factors, including consumer demand, market dynamics, availability of raw materials, and consumer purchasing power, influences the importance of these items.

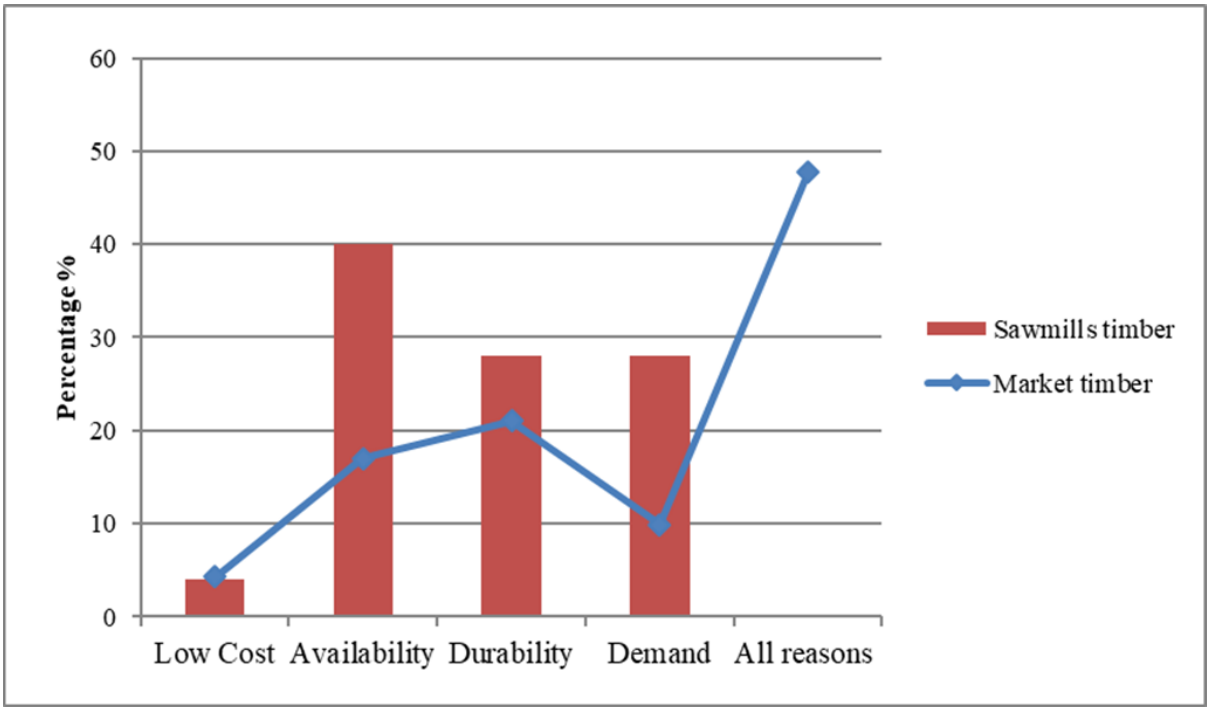

Figure3. Reasons for choosing trading timber species

According to the data presented in *Table 5*, most participants (88 %) have observed variations and declines in the availability of trade timber species over the past three decades. As *Table 6* shows, timber traders have confirmed that various factors contribute to these fluctuations, including seasonality, general overexploitation, and seasonal overexploitation.

Table 5. Fluctuations in Species Availability for trade

	% of respondents		X^2	df	p
	Timber traders (37)	Sawmilling (50)			
Missing	4.38	4.58			
yes	65.14	87.40	5.973[a]	2	0.0145
No	30.48	8.02			
Total	100	100			

[a] = Chi-squared test indicates significant differences

Table 6. Reasons for fluctuation in timber species availability for trading

	% of Respondent		X^2	df	p
	Timber traders (37)	Sawmilling (50)			
Missing	12.92	7.69	9.264[a]	4	0.05
Seasonality	34.79	56.15			
General overexploitation	4.38	0.0			
Seasonal overexploitation	39.17	36.15			
All of the above	8.75	0.0			
Total	100	100			

[a] = Chi-squared test indicates significant differences

The study findings indicate that fourteen timber species have become endangered due to a significant decrease in their market availability. *Table 7* shows that most respondents, specifically 73.9 % and 96 %, expressed concern regarding the endangered status of *Balanites aegyptiaca* for marketing and sawmilling, respectively.

Table 7: Respondent perceptions of endangered timber species in the study area

No	Binomial Nomenclature	% of respondents	
		Timber traders (37)	Sawmilling (50)
1	*Acacia senegal* (L.) Willd	21.7	8.0
2	*Acacia seyal* var *seyal* Del	26.14	8.0
3	*Balanites aegyptiaca* (L.), Del.	73.9	96.0
4	*Borassus aethiopum* Mart	13.0	0
5	*Cordia sinensis* Lam	8.7	0
6	*Dalbergia melanoxylon* Guill. & Perr.	4.3	0
7	*Diospyros mespiliformis* Hochst. ex DC.	8.7	0
8	*Ficus sycomorus* Linn	4.3	0
8	*Hyphaene thebaica* (Linn.) Mart	13.0	0
10	*Khaya senegalensis* (Desr.) A. Juss	0	12.0
12	*Tectona grandis* L	4.3	0
13	*Fagus Sylvatica*	4.3	0
14	*Ziziphus spina-christi* (L.) Desf	21.7	24.0

4 DISCUSSION

This study offers significant findings regarding market preference for timber species distinguished by their exceptional quality, strength, and durability. As a result, many species have been subjected to extensive exploitation. This discovery further corroborates Nasroun (1975) and Chen et al. (2019), illustrating that various criteria influence species choice, including accessibility, aesthetic appeal, durability, and capacity to absorb varnish and adhesive substances. As a result, certain species, including *Pterocarpus lucens, Khaya senegalensis, Diospyros mespiliformis*, and *Sterculia setigera* demonstrate limited availability and are not readily obtainable within the commercial sphere. Furthermore, the forested regions in Sudan have experienced a significant reduction due to inadequate management practices and unregulated land utilization, with current coverage standing at approximately 19 % (Yagoub et al., 2017; Sulieman, 2018, Sompougdou et al., 2024). The endangerment of these species contributed to a significant decrease in their availability within the commercial market (Fremout et al., 2020). In addition to supporting the findings of Mukhtar (2002), Newbold et al. (2015), and Fremout et al. (2020), which assert that certain crucial tree species face threats and are at risk due to recurring droughts or excessive logging activities, some of these species lack the capacity for natural regeneration.

Examples of such species include *Adansonia digitata*, *Borassus aethiopum*, *Hyphaene thebaica*, *Cordia africana*, *Dalbergia melanoxylon*, *Anogeissus leiocarpus*, *Ziziphus spina-christi*, and *Khaya senegalensis*. Famuyide et al. (2012) have also documented that excessive exploitation in Nigerian forests and forest reserves, driven by rising requests for these species, has restricted the market availability of species such as *Khaya spp., Afzelia africana, and Terminalia spp.* (Sambe et al., 2022; Ali et al., 2023). *Table 7* documents and presents the endangered species found in Sinnar State. *Table 3* displays several presently traded wood species, including *Khaya senegalensis*, Azadirachta indica, *Acacia nilotica*, and *Balanites aegyptiaca*. The present study's findings indicate that 88% of participants experienced changes in the availability of timber species traded over the past three decades (Chabi et al., 2013; Lusweti et al., 2021).

According to FAO (2010), there is evidence to substantiate the many explanations provided by participants about the fluctuating availability of timber species within the investigated region. FAO estimates indicate that forest areas in Sudan have been depleted by approximately 19%. The standing volume of the stock witnessed a decrease, with estimates suggesting a reduction from roughly 2.4 billion cubic meters during the mid-1970s to around 1.5 billion cubic meters by the mid-1980s. The result is consistent with the findings of Hansen et al. (2013) and Keenan et al. (2015), wherein deforestation and degradation were discovered. According to those two research studies, an estimated 11.4 million hectares of natural forests across the globe undergo deforestation annually.

Nevertheless, it is essential to acknowledge that many natural forests have shifted from a production focus to preservation-oriented utilization. Presently, around 290 million hectares are designated as legally protected and reserved. In addition, wood species choice for commercial purposes is consistent with Idumah and Awe (2011), who noted that furniture producers in the Ibadan Metropolis consider characteristics such as hardness (strength) and longevity when selecting wood species.

Moreover, choosing between unprocessed Sunut logs and processed Sunut timber depends on the wood product, such as furniture of local or high-quality nature. The transportation of raw logs is a costly undertaking. Most logs are crooked and uneven, which disqualifies them from regional sawmilling. As a result, the timber obtained from such logs are of lower quality than logs allocated for state sawmilling. These designated logs are used for railway sleepers and other *Acacia nilotica* timber products based on special orders (Gubartalla, 2003).

Most participants claim to possess sufficient expertise and information regarding diverse timber species within the designated duration of the research, as evidenced by their disclosure of the number of years they had been engaged in the industry (Poudyal et al., 2020).

5 CONCLUSIONS

The area researched has witnessed a substantial decrease in the accessibility and variety of timber species throughout the preceding three decades. Incorporating social values into the concept of sustainability does not inherently guarantee an expanded set of harvesting alternatives for forest managers. The research findings show that only eight of 28 timber species commonly available over the past 30 years are on the market. The observed change is ascribable to the adverse consequences of extensive logging and overexploitation of these specific species.

Furthermore, the present study found that the supply of traded timber species fluctuates due to seasonal variations and excessive exploitation. Several species currently at risk of extinction include *Balanites aegyptiaca* (commonly known as Higlig), *Borassus aethiopum*, *Tectona grandis*, *Hyphaene thebaica*, and *Khaya senegalensis*.

A comprehensive assessment of forest policy is necessary to identify the stakeholders responsible for protecting forests from excessive exploitation and degradation. Additionally, comprehending the difficulties associated with conserving and preserving economically valuable species across various forested regions within the state is essential. Promoting the cultivation of *Tectona grandis*, *Khaya senegalensis*, and fast-growing tree species alongside commercially desirable species is a possible approach to mitigating the declining supply of popular timber species. This method minimizes the potential depletion of precious and high-quality timber species. Furthermore, assessing the legality of used timber to ensure that only legitimate timber with minimal risk is in responsible supply chains and marketplaces is essential. Further investigation is necessary to examine the diverse factors that affect the successful management of species of high value, with the aim of satisfying market demand.

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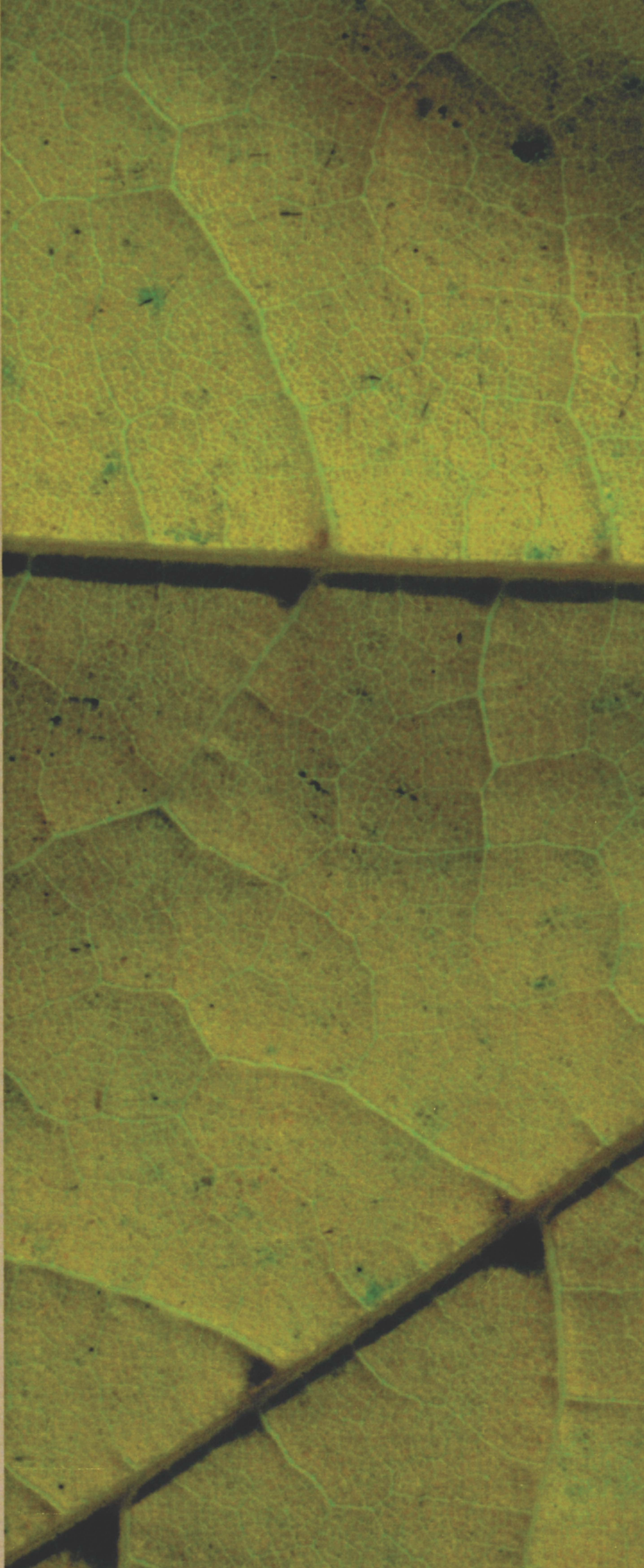

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