Trees, Forests and People 15 (2024) 100511

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

# Carbon sequestration of Hungarian forests by management system and protection status☆

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ARTICLE INFO

*Keywords:*
Climate change mitigation
Carbon sequestration
Forest management system
Nature conservation
Greenhouse gas inventory

ABSTRACT

The Paris Agreement and the European Green Deal set ambitious climate change mitigation goals. In order to achieve these goals and offset the emissions of all other sectors significant additional carbon sequestration is needed in the land use sector. The capacity of the land use sector and especially forests to remove carbon dioxide from the atmosphere is key in climate change mitigation pathways. Well planned forest industry related measures can significantly increase carbon sequestration in living biomass as well as in harvested wood products. In our study we investigated the climate change mitigation effects of forest management systems and nature conservation conducting a Greenhouse Gas Inventory-like analysis on Hungarian forests using a forest management system and protection status specific breakdown and considering only the biomass pool. Our main conclusion was that under similar yield class distribution logging intensity and carbon sequestration are not inversely proportional. We observed that non-protected forests achieve higher net carbon sink under a higher logging intensity. Regarding forest management systems we observed significantly higher net carbon sink under transitional forest management than what was found for all other management systems. Continuous cover management and non-production forest management did not show significantly different carbon fluxes.

## Introduction

The Paris Agreement and the European Green Deal set ambitious goals as regards emission reduction and climate change mitigation (Verkerk et al., 2022; Király et al., 2022). Achieving these goals requires significant and urgent reductions in antropogenic greenhouse gas (GHG) emissions and an efficient offsetting of the inevitable emissions. The capacity of the land use sector and especially forests to remove carbon dioxide ($CO_2$) from the atmosphere and store it in the living and dead biomass and in the soils is considered key in climate mitigation pathways (Verkerk et al., 2022). Greenhouse gas inventory (GHGI) is an efficient tool in monitoring emission reductions and evaluating the fulfilment of climate goals at the country level as well as at the company level. IPCC methodologyical guidelines (IPCC 2006; IPCC 2019) regulate the preparation of GHGIs and describe applicable calculation methods ensuring consistency and accuracy of reporting. According to the Hungarian GHGI the land use and forestry sector (LULUCF) offsets the 10 % of the total GHG emissions of the country (NIR 2023; Borovics–Király 2023). Emissions from croplands in the LULUCF sector include only $CO_2$ emissions because other GHG emissions are reported in the Agriculture sector, which is not part of the LULUCF accounting (Hyyrynen et al., 2023). Emissions of the Agriculture sector in Hungary are the same order of magnitude as removals occurring in the LULUCF sector (NIR 2023; Borovics–Király 2023). In order to be able to offset emissions of other sectors (like Energy, Idustrial Processes and Product Use, and Waste sector) further increase in LULUCF carbon sequestration is needed.

Verkerk et al. (2022) emphasize that forestry is a cross-cuting sector subject to multiple demands from various policies. They define three management objectives related to the forest-based sector: 1. protection, 2. restoration, and 3. management and wood use (Verkerk et al., 2022). According to this interpretation different types of forests and management objectives can all contribute to reach climate goals as climate mitigation can take place through different means and pathways linked to these objectives (Verkerk et al., 2022; Kottek et al., 2023). Carbon storage in forest biomass and soils, carbon storage in wood products (HWPs) and avoided emissions through product and energy substitution are the three main climate mitigation pathways (IPCC 2022; Verkerk

☆ Climate change mitigation / carbon sequestration / forest management system / nature conservation / greenhouse gas inventory

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https://doi.org/10.1016/j.tfp.2024.100511

Available online 29 January 2024

et al., 2022; Borovics 2022; Király et al., 2023). Each management objective and each forest type or function can be caracterised by the predominance of a certain mitigation pathway. The most efficient climate change mitigation can be achieved by finding the optimal combination of measures and management goals for each region and country, and for each type of forest within these geographical boundaries (Verkerk et al., 2022; Borovics et al., 2023).

The Sixth Assessment Report of the IPCC (2022) underlines that the full mitigation effects can be assessed in conjunction with the overall forest and wood use system, and forest management strategies aimed at increasing the biomass stock may have adverse side effects, such as decreasing the stand-level structural complexity, large emphasis on pure fast-growing stands, risks for biodiversity and resilience to natural disasters. Some studies conclude that reduction in forest carbon stocks due to harvest exceeds for decades the joint carbon offsetting capacity of HWPs and material and energy substitution (Soimakallio et al., 2016; Seppälä et al., 2019; Somogyi 2019), whereas others emphasise country level examples where investments in forest management have led to higher growing stocks while producing more wood (Cowie et al., 2021; Diao et al., 2022; Dong et al., 2023; Lin–Ge 2020; Schulze et al., 2020; Ouden et al., 2020). Wernick and Kauppi (2022) stress that forest management should promote the long-term growth of forests rather than maximise their short-term carbon accumulation. According to some studies an actively managed forest landscape that provides a large amount of sustained biomass yield while at the same time maintaining large standing forest carbon stocks, can provide greater climate benefits in the long run compared to unmanaged forests (Nabuurs and Masera 2007; Lundmark et al., 2014; Lundmark et al., 2016).

Among climate change mitigation measures linked to improved forest management the Sixth Assessment Report of the IPCC (2022) lists continuous cover forestry. Continuous cover forestry has been recognized to produce multiple ecosystem services and is seen as an alternative to clear-cut forestry (Csépányi 2017; Lundmark et al., 2016; Tahvonen 2009; Kuuluvainen et al., 2012; Pukkala et al., 2012). Despite the increasing interest, it is still not well described how continuous cover forestry would affect the carbon balance and the resulting climate benefit from the forest in relation to rotation forestry (Lundmark et al., 2016). Positive effects on the carbon dynamics have been suggested by Lindroth et al. (2012) and Pukkala (2014). Lundmark et al. (2016) analysed long-term effects of different forest management and wood use strategies on $CO_2$ emissions, they compared carbon balances of rotation forest management and continuous cover forest management applied as two alternative land-use strategies in Sweeden. When comparing the two forest management systems assuming similar growth, extraction and product use they found that biomass growth and yield was more important than the choice of the forest management system itself, and only minor differences in long-term climate benefits were found (Lundmark et al., 2016). Roth et al. (2023) emphasize that different forest management systems act differently on the quality, degradability, and long-term accumulation of soil organic carbon, which can also be an important aspect of the evaluation of the mitigation potential of each management system. In Hungary Csépányi (2017) evaluated the economic efficiency of continuous cover forest management as compared to rotation forest management. He found that continuous cover forest management could achieve at least the same economic efficiency as traditional rotation forest management in both beech (*Fagus sylvatica*) and in Turkey oak (*Quercus cerris*) stands (Csépányi 2017; Csépányi–Csór 2017). In the Pilis Gap Experiment a comprehensive investigation was launched to assess the beneficial effects of continuous cover forest management on forest structure, vitality, and ecosystem services in Hungary (Horváth et al. 2023, Aszalós et al., 2023).

In addition to the management system, the nature conservation status can also have a significant impact on the standing volume and carbon stock of forest stands (Borovics et al., 2023; Kottek et al., 2023). Kottek et al. (2023) found that in Hungary different cutting age trends apply by forest ownership and function (i.e., production or non-production forests). Borovics et al. (2023) underline the negative effects of nature conservation restrictions on the timely harvesting of high value timber and conclude that among other factors, these restrictions lead to the accumulation of an unused overmature wood stock reserve in Hungary.

As the forest management system and the protection status largely determine the purpose, method and means of forest management, we assume that it can influence the extent and dynamics of carbon sequestration and carbon storage in Hungarian forests. The aim of our research is to evaluate the climate mitigation effects of forest management systems and nature conservation status. The first steps of this complex investigation are presented in this paper. The basis of the analysis was the 2010 and 2020 statistical state of the National Forestry Database (NFD). The goal of the analysis was to prepare a GHGI-like evaluation focusing on the biomass pool of Hungarian forests and broken down into subcategories by management system and protection status. With this analysis we intended to evaluate the total annual emissions/removals of each subcategory as well as the emissions/removals normalised to one hectare. To get a broader picture on the processes leading to the observed carbon fluxes we also investigated the logging intensity and the yield class distribution across management systems and across forest lands under differet protection status.

## Materials and methods

### *Characteristics of Hungarian forest management*

In Hungary the area of forest land amounts to 2,064,000 hectares which is equal to the 20.9 % of the country's territory (Király et al., 2022). More than 40 % of the Hungarian forests have a plantation-like composition of non-native tree species (Király et al., 2022). Hungarian forests are composed of 90.5 % deciduous tree species and are typically mixed forest communities. 55 % of the Hungarian forests is state-owned and managed by 21 state forestry companies, while private forests are owned by 450,000 private persons and managed by nearly 32,000 private forest managers, who typically manage small, fragmented areas (Borovics et al., 2023). According to the Hungarian Forest Act (2023) four different forest management systems can be applied in Hungarian forests, these are: rotation forest management, continuous cover management, non-production forest management, and transitional forest management.

In the case of the rotation forest management system the cultivation of nearly same-aged trees is carried out in the forest stand, and stands are felled and regenerated following a temporal and spatial cycle.

In the case of the continuous cover forest management system no final cutting resulting in regeneration obligation takes place. The composition, age- and spatial structure of the forest stands is diverse and continuous forest cover is achieved. According to Csépányi (2017) the natural continuous cover forest is a forest made up of tree species suitable for the site conditions, having a diverse age-class structure and a diverse horizontal and vertical spatial structure, where the forest is capable of natural regeneration, and natural processes prevail in it, and the soil cover and internal microclimate typical of forests is continuously maintained. Translated into three-dimensional space, this would mean that each stand layer is similarly filled with plant material horizontally and vertically resulting in maximum structural complexity (Stiers et al., 2020).

The main objective of transitional forest management is the transition from rotation forest management to continuous cover forest management, and the more continuous mainainance of forest cover as compared to the rotation forest management system. In order to extend the period of forest regeneration the final harvest and regeneration activities are carried out in several different phases, separated in space and time according to the forest transformation and regeneration plan. Contiguous final cut areas cannot exceed 1.5 hectares by law; and during the implementation of harvesting activities, a key aspect is the continuous provision of forest regeneration and renewal.

In the case of the non-production forest management system no timber management takes place, logging in the forest can only be carried out for experimental purposes or for the sake of forest protection, nature conservation, public welfare, forest regeneration or other public interest. In Hungary the area of alternative forest management systems (i.e., continuous cover management, non-production forest management, and transitional forest management) is constantly increasing. Despite this, in the year 2021 the forest area under alternative management only accounted for the 9.2 % of the total forest area of the country (*Fig. 1*).

In Hungary 62 % of the forest land is under some kind of nature conservation, either under national protection or under Natura 2000, or both (*Fig. 2*). Being under nature conservation does not necessarily mean the restriction of harvesting. In 2021 out of the 1,2 million hectares protected forest lands only 31 thousand hectares were under complete harvesting restriction. On protected forest lands under rotation forest management Nature Protection Authority precribes retention of living single trees or tree patches when final harvesting takes place. The retention of standing and lying dead trees is also precribed when thinning or final harvest is carried out. In this study we created four categories combining the six groups represented in *Fig. 2*. These four categories are: 1) all forest lands under strict national protection, either Natura 2000 or not (hereinafter referred to as strictly protected); 2) all forest lands under (not strict) national protection, either Natura 2000 or not (hereinafter referred to as protected); 3) forest lands under Natura 2000 protection which are not nationally protected (hereinafter referred to as Natura 2000); 4) non-protected forest lands (hereinafter referred to as non-protected).

*Data source and sampling*

In our study we used the National Forestry Database (NFD) as data source which is the official database of the Hungarian Forest Authority. Forest management planning activities cover the entire forest area of Hungary, and approximately 10 % of the forest land is subject to forest management planning each year (Tobisch–Kottek 2013; Kottek et al., 2023). Forest management planning is carried out by the Forest Authority, and it is based on field surveys during which the main stand attributes (such as height, diameter, basal area, age, canopy closure) are surveyed. From sampled data, annual increment is modelled in the NFD for each year in between two surveys (Kottek et al., 2023). Increment modeling is based on yield tables. Harvest is officially registered for each forest stand each year. In order to calculate standing volume for each year modelled annual increment is added and annual harvested volumes are subtracted from the growing stock of each stand for the years in between two sampling. Forest stands in Hungary are units of relatively homogenous tree cover, and they are also called forest subcompartments. In the NFD for each forest subcompartment of the country, digital maps and more than 300 raw and derived data are available (Tobisch–Kottek 2013). Data is stored for each subcompartment on the area and the protection status, the management system, site characteristics, details of soil sampling, dendrometrical parameters, tree species composition, planned harvests and harvest prescriptions, regeneration and afforestation prescriptions, data on harvests carried out and on regeneration carried out. Data on standing volume is stored in tree species rows which are the basic units of the database (Tobisch–Kottek 2013; Kottek et al., 2023). NFD stores total gross above-ground biomass volume (including non-merchantable above-ground components) for each tree species row.

To carry out our investigation we used the digital maps of the NFD for two statistical states, i.e., for the year 2010 and 2020. The study was based on sampling implemented at the points of a 100×100-meter regular grid. In total 1,993,476 sample points were studied representing the entire forest area of the country. A forest subcompartment belonged to each grid-point in the 2010 and in the 2020 state. The sampling grid was used to track the changing status of forest stands in the problematic cases where a forest subcompartment was divided or two subcompartments were merged, or the geometry of a forest subcompartment was changed unidentifiable between the two time points and therefore the subcompartments could not be clearly matched. Thus, each sampling point represented one hectare of forest, and the categorizing variables were known for each sampling point for the two states, i.e., for 2010 and for 2020. For each point the management system, the protection status, and the attributes of all tree species rows (like age, yield class, standing volume per hectare) were known. These descriptive variables formed the basis for the calculation of the carbon stock changes between the two sampling years.

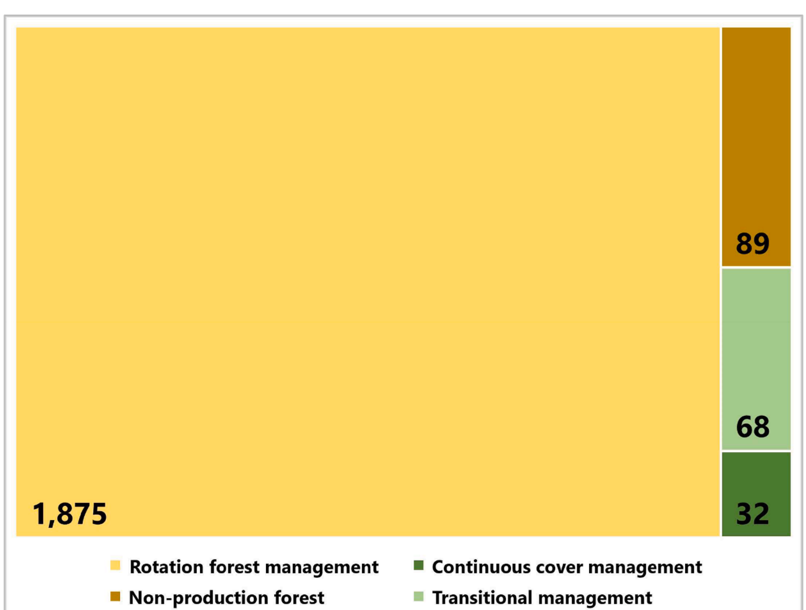



**Fig. 1.** Distribution of forest land by forest management systems as of the 2021 state of the NFD. (Area is expressed in thousands of hectares.).

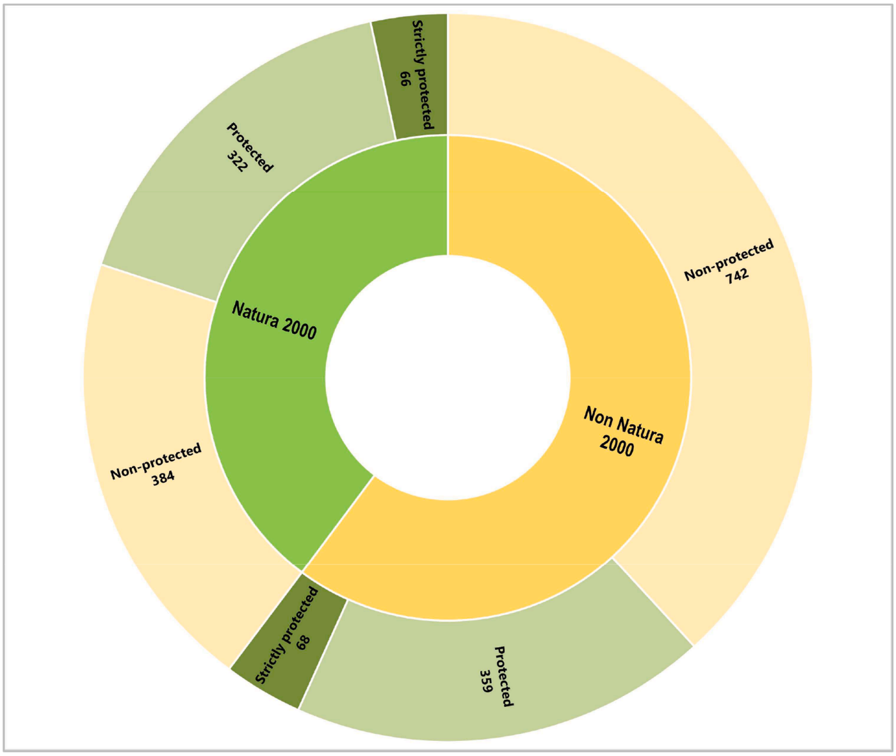



**Fig. 2.** Distribution of forest subcompartments by protection status as of the 2020 state of the NFD. (Area is expressed in thousands of hectares.).

*Methods of the analysis*

Based on the NFD data and using the IPCC (2006, 2019) methodology we calculated the carbon stock change in living tree biomass for each sampling point between the 2010 and 2020 states. We calculated for each sampling point the net carbon stock change for each tree species row separately. We define net carbon stock change of a tree species row as gross carbon sink minus harvest and mortality, and we refer to it as net sink as in the NFD for each year harvest and mortality is subtracted from gross annual increment. We calculated net sink as follows (IPCC 2006; NIR 2023; Somogyi 2008).

$$\Delta C_{tsr} = C_{t2} - C_{t1} \quad (1)$$

$$C_{tn} = \sum_{i=1}^{9} \left( SV_{tn} \times CF \times D \times 1.25 \times \frac{44}{12} \right) \quad (2)$$

Where:

$\Delta C_{tsr}$: net sink (i.e., net carbon stock change) of a given tree species row (t $CO_2$);

$C_{t2}$: carbon stock of the tree species row in year t2 (t $CO_2$);

$C_{t1}$: carbon stock of the tree species row in year t1 (t $CO_2$);

$C_{tn}$: carbon stock of all tree species rows per sampling point in year tn (t $CO_2$);

$SV_{tn}$: gross above-ground standing volume (including non-merchantable above-ground components) of the tree species row in year tn ($m^3$);

CF: tree species specific carbon fraction value (tC/t dm);

D: tree species specific density value (t dm/$m^3$ standing volume);

1.25: above-ground plus below-ground biomass multiplier, based on the root-to-shoot ratio of 0.25 (IPCC 2006);

44/12: the ratio of the molar mass of carbon dioxide to carbon.

After calculating the net sink for each tree species row separately, we summed them up and thus we obtained the total carbon stock change for each point. Then we grouped the sampling points by management system and protection status and summed the carbon stock changes of each group. We calculated the mean carbon stock change per hectare, and the cumulative carbon stock change for each group. We also examined the yield class distribution and the logging intensity for each group based on the 2020 state of the NFD.

In order to compare net sink, yield class distribution and logging intensities across groups we performed one-way ANOVA analysis using Statistica software (Version 14.0.1.25, Tulsa, OK, USA). We performed post-hoc tests (Fisher LSD, Bonferroni, Scheffé, Turkey HSD, Unequal N HSD, Newman Keuls, and Duncan's test) to specify if there were significant differences across group means at a 95 % confidence level.

## Results

According to the ANOVA analysis, the forest management system had a significant effect on the yield class distribution. Post-hoc tests showed that the yield class distribution of non-production forests was significantly different from all other groups at a 95 % confidence level being the less productive yield class overrepresented under non-production forest management (Fig. 3). In contrast protection status had no significant effect on yield class distribution, and the ANOVA analysis showed that none of the group means were significantly different from the others at a 95 % confidence level (Fig. 4).

According to the ANOVA analysis management system had a significant effect on the intensity of logging. The logging intensity was the highest under rotation forest management, and non-production forest management had the lowest logging intensity (Fig. 5). The post-hoc tests performed showed that continuous cover management and transitional management systems had the same logging intensity at a 95 % confidence level. All other group means were significantly different. Protection status also had a significant effect on the intensity of logging. Logging intensity was the hihghest in non-protected forest lands, and the lowest logging intensity was observed under strict nature protection (Fig. 6). According to post-hoc tests when grouping by protection status all group means were different from each other at a 95 % confidence level.

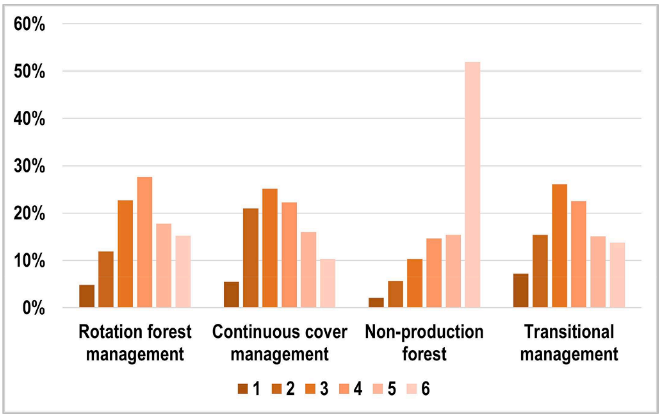



**Fig. 3.** Relative frequency of the yield classes 1–6 across forest management systems as of the 2020 state of the NFD. (Yield class 1 meaning the most productive yield class, and yield class 6 meaning the least productive one.).

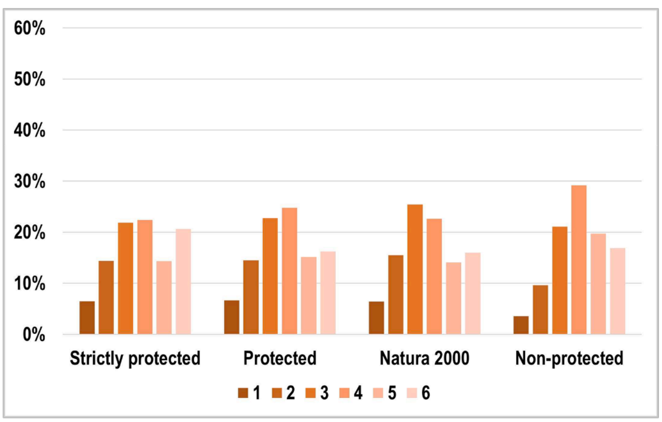



**Fig. 4.** Relative frequency of the yield classes 1–6 across forest lands under different protection status as of the 2020 state of the NFD. (Yield class 1 meaning the most productive yield class, and yield class 6 meaning the least productive one.).

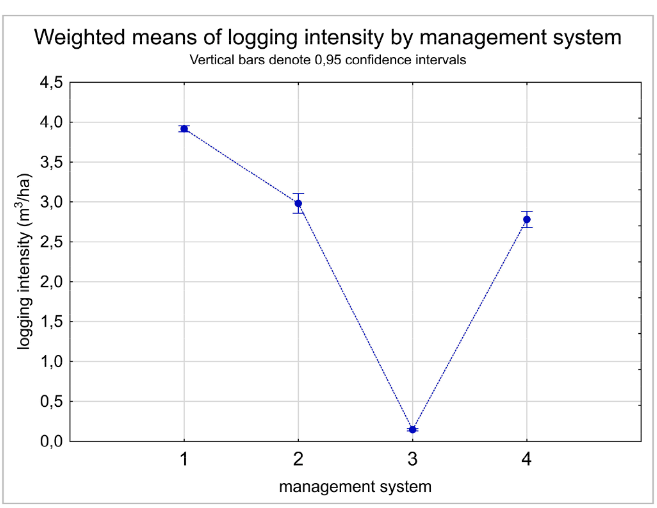



**Fig. 5.** Weighted means of logging intensity by management system as of the 2020 state of the NFD. (The codes of management systems are the following: 1 – rotation forest management, 2 – continuous cover forest management, 3 – non-production forest management, 4 – transitional forest management. Vertical bars denote 95 % confidence intervals.).

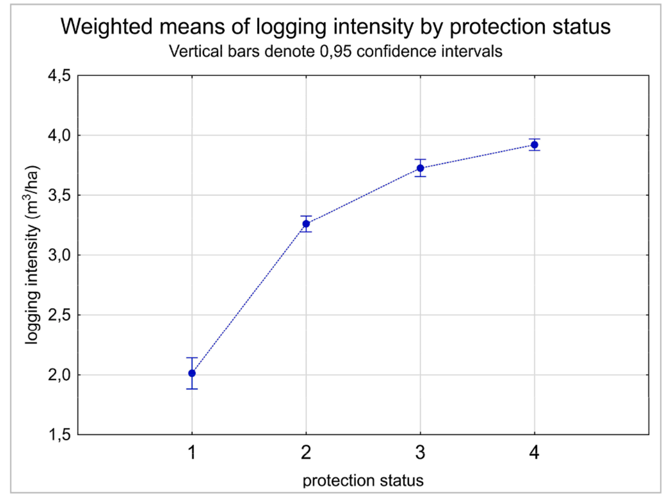



**Fig. 6.** Weighted means of logging intensity by protection status as of the 2020 state of the NFD. (The codes of the protection status are the following: 1 – strictly protected, 2 – protected, 3 – Natura 2000, 4 – non-protected. Vertical bars denote 95 % confidence intervals.).

Summing up mean annual net sink and logging intensity by groups on a per hectare basis we can get an estimate on gross sink of each forest management system and protection category (Fig. 7–8). However, it is important to note that this estimate does not give any information on the mortality rate. According to our results gross sink was the highest under transitional forest management and the lowest under non-production forest management. As regards protection status non-protected forests and Natura 2000 forests performed equally, while protected forests produced lower gross sink and strictly protected forests had the lowest gross sink values. Although logging intensity expressed in $m^3$ was lower in Natura 2000 forests than in non-protected forests, this was not the case when converting it to $CO_2$ values as lower density wood species were overrepresented in the non-protected group.

Fig. 9–12 presents the transition matrix of forest lands between different forest management systems and protection status in the period 2010–2020. Cells with yellow background represent those areas where no change in the forest management system or protection status occurred between 2010 and 2020. Cells with white background represent transitions between different forest management systems/protection status. While the first coloum represents transition from forest land to non-forest land, and the first row represents transitions from non-forest land to forest land (which in the most cases means afforestation or found forests). Positive values mean net carbon dioxide ($CO_2$) emissions and negative values mean net $CO_2$ sink in line with IPCC terms.

Examining only those categories where the management system was

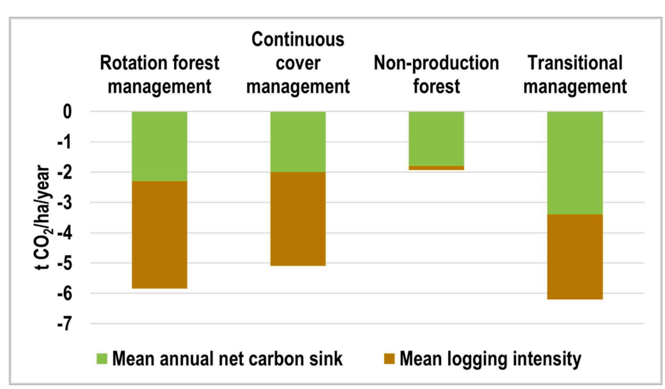



**Fig. 7.** Mean annual net carbon sink (calculated from net growth) and logging intensity by forest management system expressed in t $CO_2$/ha/year.

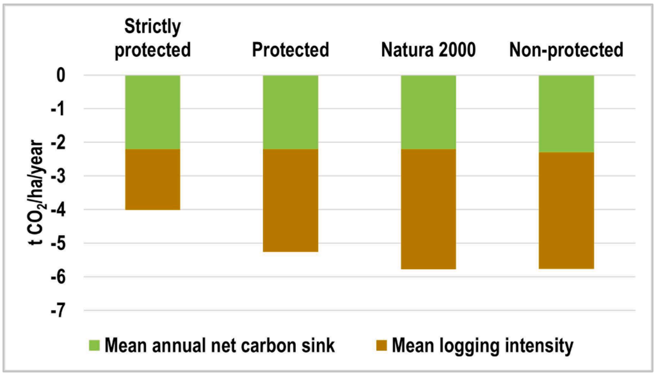


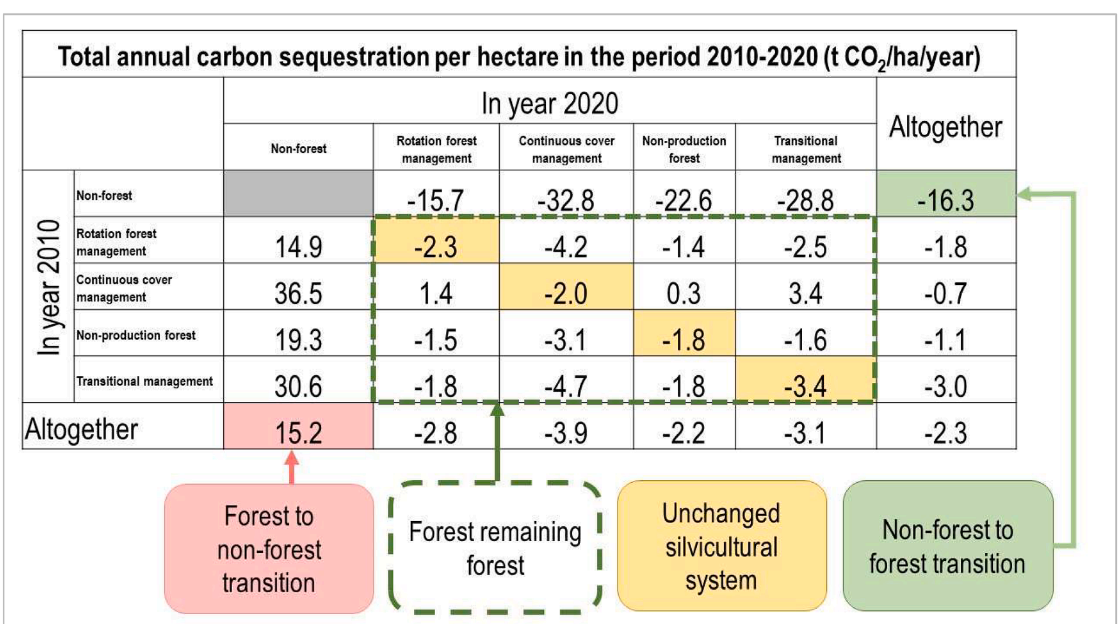

**Fig. 8.** Mean annual net carbon sink (calculated from net growth) and logging intensity by protection status expressed in t $CO_2$/ha/year.

unchanged, we can state that average net carbon sink per hectare was the largest under transitional forest management, and non-production forest management resulted in the lowest net carbon sink values (Fig. 9). It is worth also noting that transition from continuous cover management to all other groups resulted in $CO_2$ emissions (Figs. 9 and 10). As expected, non-forest to forest transitions resulted in net $CO_2$ sink, while forest to non-forest transitions resulted in $CO_2$ emissions. We examined the distribution of net $CO_2$ sink across management systems performing one-way ANOVA analysis and post-hoc tests to compare group means. We examined only those groups where the management system was unchanged between the years 2010 and 2020. We found that the management system had a significant effect on net carbon sink. When comparing group means the difference between continuous cover management and non-production forest management groups was not significant at a 95 % confidence level. According to the Scheffé test and the Unequal N HSD test rotation forest management and continuous cover management, as well as continuous cover management and non-production forest management were not different at a 95 % confidence level either. Transitional forest management group mean was significantly different from all other group means according to all tests performed.

According to our results the protection status also had a significant effect on net carbon sink. We examined the distribution of net $CO_2$ sink across different protection status groups by performing one-way ANOVA analysis and post-hoc tests to compare group means. We examined only those groups where the protection status was unchanged between the years 2010 and 2020. When comparing group means we found that group mean of non-protected forests was significantly different from all other group means according to all tests performed. This means that net carbon sink on a per hectare basis was higher in non-protected forests as compared to forests under nature conservation, although it is important to note that the magnitude of the difference was only a tenth of ton (Fig. 11).

## Discussion

In our study we examined the net carbon sink of Hungarian forests by management system and by protection status. According to our results both protection status and management system had a significant effect on the net carbon sink. We also examined the yield class distribution and the logging intensity across groups. We found that the yield class distribution of non-production forests was significantly different from all other groups (i.e., rotation forests, continuous cover forests and transitional forests), as less productive yield classes were predominant in the non-production forest group. We found that non-production forests had significantly lower logging intensity than all other forest types. Transitional forests showed significantly higher net carbon sink per hectare values than all other forests. The difference in net carbon sink between non-production forest management and continuous cover management was not significant. We also examined gross carbon sink values summing net carbon sink and logging intensity values up. Gross carbon sink was the highest under transitional forest management, however under rotation forest management the magnitude of gross carbon sink was not far below. This means that the productivity of transitional forests and forests under rotation management was very similar, while the intensity of logging was significantly lower under transitional forest management where small-scale interventions are predominant. This is in line with the finging of Hyyrynen et al. (2023) who suggest that annual harvests are the most important driver of the variations in annual carbon sinks realised in forest biomass in the entire EU. However, as increased



Total annual carbon sequestration per hectare in the period 2010-2020 (t $CO_2$/ha/year)

| | In year 2020: Non-forest | Rotation forest management | Continuous cover management | Non-production forest | Transitional management | Altogether |
|---|---|---|---|---|---|---|
| In year 2010: Non-forest | | -15.7 | -32.8 | -22.6 | -28.8 | -16.3 |
| Rotation forest management | 14.9 | -2.3 | -4.2 | -1.4 | -2.5 | -1.8 |
| Continuous cover management | 36.5 | 1.4 | -2.0 | 0.3 | 3.4 | -0.7 |
| Non-production forest | 19.3 | -1.5 | -3.1 | -1.8 | -1.6 | -1.1 |
| Transitional management | 30.6 | -1.8 | -4.7 | -1.8 | -3.4 | -3.0 |
| Altogether | 15.2 | -2.8 | -3.9 | -2.2 | -3.1 | -2.3 |



**Fig. 9.** Transition matrix of different forest management systems. Numbers in the cells indicate average annual net carbon sink per hectare of each category expressed in t $CO_2$ eq/ha/year units. (Negative numbers indicate net carbon sink, while positive numbers indicate net emissions.).

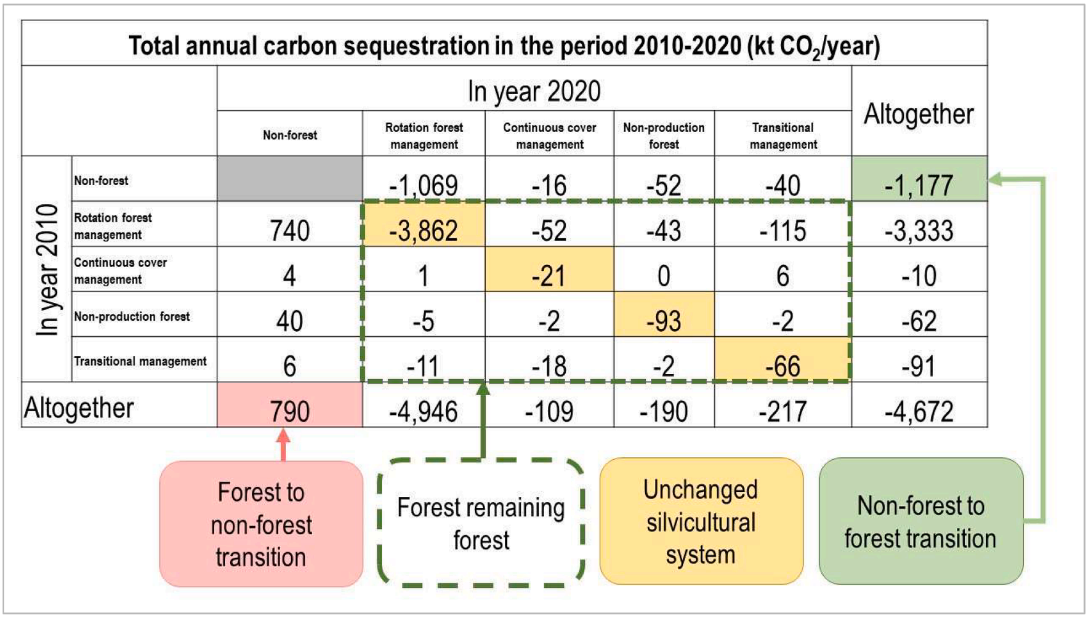



**Fig. 10.** Transition matrix of different forest management systems. Numbers in the cells indicate total annual net carbon sink of each category expressed in kt $CO_2$ eq/year units. (Negative numbers indicate net carbon sink, while positive numbers indicate net emissions.).

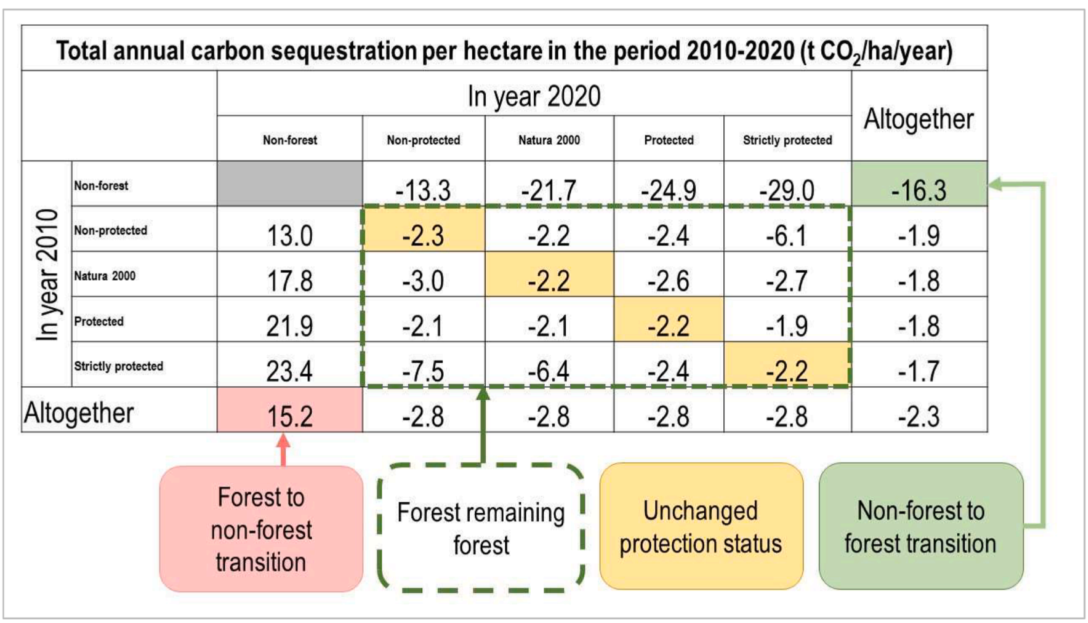
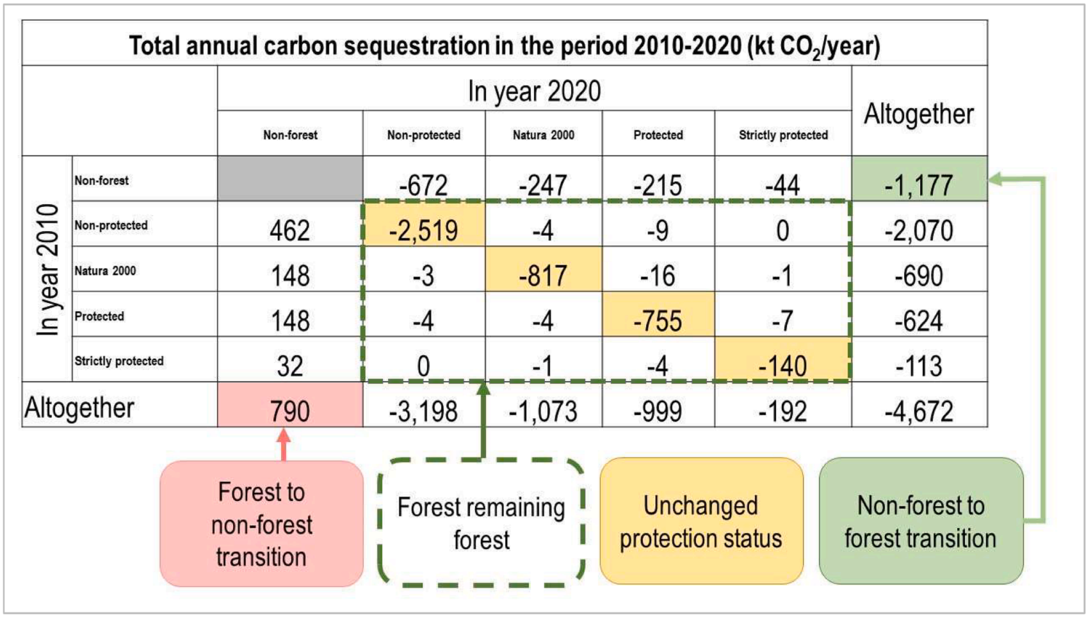



**Fig. 11.** Transition matrix of forest lands under different protection status. Numbers in the cells indicate average annual net carbon sink per hectare of each category expressed in t $CO_2$ eq/ha/year units. (Negative numbers indicate net carbon sink, while positive numbers indicate net emissions.).

harvesting increases the carbon sink of harvested wood products (HWPs) this effect moderates the impact of harvests on forest sinks (Hyyrynen et al., 2023).

Pukkala (2014) compared the carbon balance of rotation forest management and continuous cover forest management considering HWP carbon pool and substitution effects as well as forest biomass carbon balance. They found that the combination of high thinning rotation forestry and continuous cover forestry was the most efficient in terms of carbon sink (Pukkala 2014). This is in line with our finding showing that net carbon sink was the highest under transitional forest management. In our study we did not assess HWP carbon balance nor the effect of product- and energy substitution. As logging intensity was the highest under rotation forest management we could assume that HWP carbon sink and substitution effects are also higher under rotation forest management. However, HWP carbon balance is not only determind by the amount of harvested timber, but assortment composition also has a significant effect on the longevity of HWPs produced (Király et al., 2022). Pukkala (2014) emphasize that under continuous cover forest management increased harvest of saw logs, decreased harvest of pulp wood and increasing wood product size is observed. Nevertheless, the favourable assortment composition characteristic to continuous cover forest equilibrium may not have been reached in Hungarian forests yet, as structural transitions from age-class forests to continuous cover forests is a slow process, requiring more than 60 years (Neumann et al., 2023). Therefore, in order to evaluate the carbon balance of HWPs and substitution effects under different forest management systems in



Total annual carbon sequestration in the period 2010-2020 (kt $CO_2$/year)

| | In year 2020: Non-forest | Non-protected | Natura 2000 | Protected | Strictly protected | Altogether |
|---|---|---|---|---|---|---|
| In year 2010: Non-forest | | -672 | -247 | -215 | -44 | -1,177 |
| Non-protected | 462 | -2,519 | -4 | -9 | 0 | -2,070 |
| Natura 2000 | 148 | -3 | -817 | -16 | -1 | -690 |
| Protected | 148 | -4 | -4 | -755 | -7 | -624 |
| Strictly protected | 32 | 0 | -1 | -4 | -140 | -113 |
| Altogether | 790 | -3,198 | -1,073 | -999 | -192 | -4,672 |



**Fig. 12.** Transition matrix of forest lands under different protection status. Numbers in the cells indicate total annual net carbon sink of each category expressed in kt $CO_2$ eq/year units. (Negative numbers indicate net carbon sink, while positive numbers indicate net emissions.).

Hungary data collection on assortment composition by management system would be essential.

Several field studies showed a higher yield in rotation forest management system as compared to countinuous cover forests (Lundqvist et al., 2013; Nilsen and Strand 2013; Hynynen et al., 2019; Ekholm et al., 2023). On the contrary simulation studies using process-based models predict comparable or higher yields under continuous cover management system (Kellomäki et al., 2019; Kellomaki et al., 2021). In our study we found lower gross carbon sink under continuous cover management as compared to rotation forest management and transitional forests. This result however does not characterise the overall carbon sink performance of continuous cover management as tree species composition and age-class structure is different under different forest management systems, and fast-growing tree species with a short rotation period and higher yields are predominant under rotation forest management in Hungary (Kottek et al., 2023). It is also important to note that field measurements carried out by the Forest Authority during forest management planning may be less effective in continuous cover forests, as these forests have more complex spacial structure, and their thorough assessment may require more time and extended field work. This may cause a systematic error leading to younger age-classes being under-represented in the NFD records of continuous cover forest stands.

According to the results of our study in the case of grouping by protection status yield class distribution was not different between groups. As regards logging intensity we found that all group means where significantly different, logging intensity was the lowest in the strictly protected group and it increased as the strength of protection decreased. The highest logging intensity was observed in the non-protected group. Net carbon sink was not significantly different across protected groups, i.e., Natura 2000, protected and strictly protected forests all had an average net carbon sink of $-2.2$ t $CO_2$/ha/year. The net carbon sink of non-protected forests was significantly higher, though the difference was only 0.1 t $CO_2$/ha/year. Gross carbon sink was the highest in non-protected and Natura 2000 forests followed by protected forests. The gross sink was the lowest in strictly protected forests.

This leads to the conclusion that highly protected forests behave more like carbon stocks rather than carbon sinks. High carbon sink values can be achieved in intensively managed rotation forests, and harvesting does not necessarily work against carbon sequestration. According to the results of this study nature protection and less intensive logging did not increase carbon sink. In the case of non-production forests less favourable yield class distribution can explain the low carbon sequestration observed. Non-production forests are typically located in unfavourable site conditions where the main aim of forest management is soil protection, water protection, settlement protection, or shelterbelt. However, in the case of grouping by protection status, yield class distribution was not different in any of the groups. Tree species and age class structure should also be examined across grups in order to better understand the causes of differences. Fast growing, short rotation tree species may be more favourable from the carbon sequestration perspective (Kottek et al., 2023). The lower carbon sequestration in forests under nature protection may be explained by the predominance of slow-growing species, and the increasing proportion of overmature stands in protected forests (Borovics et al., 2023) as these aging forests may have less annual increment.

We compared the average annual net carbon sink observed in this study with the official numbers of the Hungarian GHGI (NIR 2023). According to the GHGI the net average annual carbon sink of the biomass pool in the 2010–2020 period was $-4121$ kt $CO_2$. According to our calculation it was $-4672$ kt $CO_2$. Although the data source of the GHGI is the same, the NFD, results are not exactly comparable due to the $100\times100$-metre sampling grid applied in this study. In the GHGI found forests are administered in a separate category and their carbon stock is not accounted for as carbon sequestration in the year when finding them due to the prerequisites of conservative estimation. Thus, only the annual increment of these forests is accounted for as carbon sink. In this paper, however, the total carbon stock of found forests is handled as carbon gain in the year when finding the given forest. Taking into account these differences we can state that the results of our study and the estimates of the Hungarian GHGI are close to each other.

In order to estimate the exclusive impact of each forest management system and protection status on the actual carbon sink of forests ceteris paribus conditions should be met. In this study many other factores were present which could have influenced carbon sequestration in the different groups. To get a comprehensive overall picture on the climate change mitigation effects of each forest management system and protection practice not only the living tree biomass pool but all other carbon pools (i.e., soil, dead wood, litter, HWPs) and substitution effects should be considered. We plan to include these pools in a later stage of our research. We also plan to examine under ceteris paribus conditions the carbon sink of forest lands under different forest management systems, especially focusing on beech (*Fagus sylvatica*), sessile oak (*Quercus petraea*) and Turkey oak (*Quercus cerris*) stands.

## Conclusions

In our study we examined the climate change mitigation effects of forest management systems and nature conservation in Hungary. Our main conclusion was that under similar yield class distribution logging intensity and net carbon sink are not inversely proportional. We observed that non-protected forests achieve higher carbon sink values under a higher logging intensity. Regarding forest management systems we observed the highest net carbon sink under transitional forest management. Continuous cover management and non-production forest management did not show significantly different net carbon fluxes considering only the living tree biomass pool. Gross carbon sink was also the highest under transitional forest management, however under rotation forest management the magnitude of gross carbon sink was not far below it. This means that the productivity of transitional forests and forests under rotation management was very similar, while the intensity of logging was significantly lower under transitional forest management. Thus, the ranking of the overall climate change mitigation effects of the two management systems will depend on the soil, dead wood and HWP carbon balance and substitution effects. Further investigations will be needed to evaluate the behaviour of all other carbon pools under different management and protection conditions.

## CRediT authorship contribution statement

**Éva Király:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Attila Borovics:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgements

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

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