CARBON SEQUESTRATION MODELING IN A TEMPERATE NEAR-NATURAL BEECH FOREST USING CO2FIX

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Summary: As climate change becomes a more and more pressing issue, the role of forests as carbon sinks will increase further. Carbon sequestration models can be a useful tool in planning future management strategies, but only if they are properly calibrated for the ecosystem in question. In our study we used data from the literature and other publicly available data for the parameterisation of the CO2Fix model and compared the model results to reference estimations based on data from a field survey carried out in autumn 2015 in some beech and hornbeam-dominated stands of Haragistya-Lófej forest reserve (Aggtelek Karst). Due to the less favourable site conditions, effects of earlier management and the relatively young age of the stands the carbon content of the biomass was found to be somewhat lower than in other beech forests. We also examined the effect of using different mortality settings on the results. The model with 'no mortality' settings was found to give the best results, however the performance was species-dependent. The model tends to underestimate the carbon content of the biomass for beech-dominated plots, but the higher the proportion of hornbeam, the higher the chance that the model overestimates the carbon content.

Key words: carbon sequestration, CO2Fix, near-natural forest, forest reserve, Fagus sylvatica

1. INTRODUCTION

Climate change, as one of the most important contemporary environmental issues, draws attention to the global climate regulation ecosystem service of the natural vegetation, in which forests play an outstanding role. In the process of photosynthesis carbon dioxide is fixed in different compartments of living biomass (stems, branches, foliage and roots) and in the soil. After timber harvesting and industrial processing, the carbon content of wood may be stored further in wood products with different life spans. In the end, it returns to the atmosphere as a result of turnover or logging. Earlier it was generally thought that ageing forests should be at best considered carbon-neutral (Odum 1969). This was based (among others) on the assumption that the growth trends of individual trees and even-aged monospecific stands can be directly extended to natural forests. However, it was found that growth and carbon acquisition in old natural forests cannot be extrapolated from the productivity of even-aged stands (Carey et al. 2001, Harmon 2001). Recently, research on the effects of forest management intensity has shown that forest management and disturbances affect forest soils and biomass carbon stocks and emissions to the atmosphere (Luyssaert et al. 2011). Harvesting frequency and structural retention significantly affect mean carbon storage, and the mean carbon sequestration is significantly greater for non-managed stands compared to any of the active management scenarios (Nunery and Keeton

2010). Of the harvest treatments, those favouring high levels of structural retention and decreased harvesting frequency have been shown to store the greatest amounts of carbon (Neilson et al. 2006; Taylor et al. 2008; Nunery and Keeton 2010). Greater harvest intensity results in less carbon storage, and the carbon in wood products does not make up for harvest losses (Nunery and Keeton 2010, Fischer 2013). Carbon sequestration models, particularly those including a wider context (e.g. wood products, avoided emission, carbon accounting schemes) provide an opportunity for decision-makers to consider the effects of a management decision on the ecosystem services of a forest in a more complex manner. However in order to be used that way, the models must be sound concerning the function and the natural carbon fluxes of the particular ecosystem in question. Empirical data needed for model calibration are generally scarce and poorly representative across forest biomes (Keith et al. 2010) therefore some of the complexity needs to be traded for more general usability. However, too much simplification may lead to the underestimation of the carbon sequestration capacity of near-natural forests, which in turn could lead to erroneous management decisions.

One aim of the present study is to test the performance of the biomass module of the relatively simple, widely used CO2Fix model (Masera et al. 2003) against stand-level empirical data from a forest reserve (unmanaged for the last 20 years) using the literature and widely accessible data for model parameterisation. When using CO2Fix in a previous study we found that mortality rates (not including management mortality) strongly affected the model results (Kiss et al. 2011). It is known that mortality rates in a stand are not constant over time, they are highly stochastic and the most probable cause of death differs according to the size and role of a tree (Holzwarth et al. 2013, Tanács and Barta 2014). Mortality is often higher in young stands, followed by a phase of relatively lower rates and then it increases again in old age (e.g. Holzwarth et al. 2013). Major disturbances (due e.g. to climate events like a major thunderstorm or a lasting heat wave) can locally additionally modify the mortality rate. We used three different approaches in order to find out how best to include mortality in the model.

2. MATERIALS AND METHODS

2.1. Study area

Haragistya-Lófej Forest Reserve is situated in the north-western corner of Aggtelek National Park, NE Hungary. Except for a part of its buffer zone in the south, the area is under strict protection. Haragistya is a continuation of Silická planina, and it bears all the hallmarks of a typical karst plateau. Its surface is dry and highly varied, covered by series of dolines and dry valleys. The 90 ha sample area is situated in the south-eastern part of the plateau. Wetterstein Limestone and Dolomite make up the bedrock, dolomite being more typical within the selected study area. However, in the bottom of hollows such as dolines, valleys and slope curves, Cretaceous red clay sediments have accumulated, and in certain places serve as a basis for soil formation. The tops and ridges are characterised by extremely shallow black rendzinas, and the slopes by slightly deeper brown rendzinas. On the red clayey patches red rendzinas and deeper brown forest soils developed.

The zonal forest types of the karst plateaus of the Aggtelek Mts. are xerotherm sessile oak forests (*Quercetum petraeae-cerris*, but mainly without the turkey oak), which occupy the lower hilltops, ridges and southern-facing slopes, while mesophilous sessile oak-

hornbeam forests (*Carici pilosae-Carpinetum*) are the characteristic association of the high plateaus and northern-facing slopes. Submontane beech forests (*Melitto-Fagetum*) can be found in small patches, mainly in valleys and on north-facing slopes. According to the forest inventory, the age of the forests in the sample area varies between 60 and 110 years. Management activity in the last decades mostly consisted of thinning; however some of the area has not been actively managed for at least 40 years. Recruitment and early regeneration dynamics are currently strongly affected by the high number of browsing game.

For the purposes of long-term structure monitoring in the forest reserve, a 50 m resolution grid of 361 permanent plots was established in 2006, each consisting of a 10 m radius circle (Fig. 1). The plots were divided in 3 age groups (61–80, 81–100 and 101–120 yrs) based on the inventory data and 3 broad forest types (dry oak, mezophilous oak and beech stands).
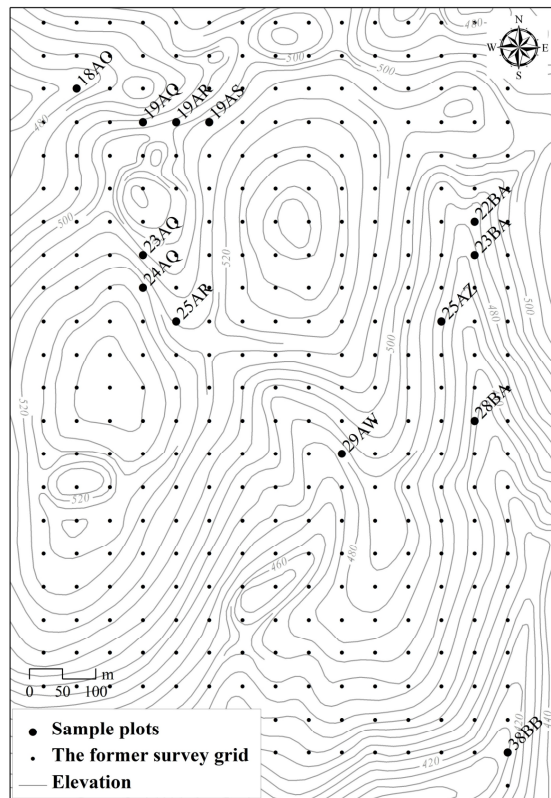

Fig. 1 The study area

2.2. Data

In the course of the baseline survey in 2006–2007 we recorded the position, diameter at breast height (dbh) species and crown class (according to the Kraft-classification) of every living tree and snag exceeding a dbh of 5 cm or a height of 5 m within the 10 m-radius circle plots. Tree heights were measured for a few hundred individuals (Zboray et al. 2007). The survey was partly repeated in autumn 2015, in 53 of the original plots. For the present study we used the data of 13 sample plots from beech stands, representing each of the 3 age groups (Fig. 1, Table 1). The chosen stands are mainly dominated by beech or hornbeam, accompanied mainly by *Sorbus torminalis* and downy oak (*Quercus petraea*). We chose plots where signs of earlier thinning (e.g. tree stumps) were not evident.

For both model parameterisation and as reference we used some results and equations from the baseline survey of 2006–2007, data from the repeated survey, and also from the literature. Wood density data came from the Chave et al. (2009). For the estimation of the species-specific C-content of dry matter in the different biomass compartments and the

proportion of C stored in the roots and the foliage compared to the stem and the branches we used the results of Führer and Jagodics (2009) who carried out specific measurements in beech stands in Hungary.

Table 1 Stand characteristics of the examined plots

Plot ID	Age (y)	No. of trees (2015) in the plot	Proportion			Yield class		
			Fagus s.	*Carpinus b.*	other	*Fagus s.*	*Carpinus b.*	other
19AS	105	19	0.26	0.53	0.21	5	4	4
23AQ	105	17	0.41	0.24	0.35	2	5	5
24AQ	105	13	0.77	0.08	0.15	4	5	4
25AR	105	13	0.38	0.46	0.15	6	5	5
18AO	100	18	0.39	0.28	0.33	5	5	5
19AQ	100	19	0.53	0.16	0.32	5	5	5
19AR	100	18	0.39	0.61	0.00	4	4	5
28BA	100	14	0.29	0.71	0.00	5	4	5
22BA	75	12	0.67	0.00	0.33	4	5	4
23BA	75	17	0.76	0.18	0.06	5	5	5
25AZ	70	18	0.83	0.11	0.06	4	5	5
29AW	70	18	0.39	0.28	0.33	6	5	5
38BB	75	14	0.43	0.29	0.29	5	4	5

Estimations serving as reference data for the C-content of the tree stem and branches were calculated using tree volume, density and species-specific C-content. In order to calculate the volume of each individual tree, Király's tree volume equation was applied (see Veperdi 2008). Tree height, which is a necessary input to this equation, was estimated on the basis of species-specific diameter-height equations set up using data from the first survey of 2006 (Tanács 2011). The C-content of the roots and foliage were then estimated on the basis of their above-mentioned proportions. The results were up-scaled to a 1-ha area for each plot.

2.3. Carbon sequestration modeling

2.3.1.Brief description of the CO2Fix model

CO2Fix (v. 3.2) is a simulation model developed as part of the CASFOR II project. It quantifies the carbon stocks and fluxes in the forest biomass, the soil organic matter and the wood products chain (Masera et al. 2003; Schelhaas et al. 2004). These are estimated with a time-step of one year using the 'cohort' as a unit, where each cohort is defined as a group of individual trees assumed to exhibit similar growth. The model consists of six modules: biomass, soil, wood products, bioenergy, financial and carbon accounting. The total carbon content of the system is obtained by adding up the amount of live biomass and soil carbon content and the carbon stored in wood products. The overall effect on the climate system depends on the changes of the carbon content and the so-called avoided emission. Avoided emission characterizes how much less carbon dioxide is released into the atmosphere through substituting fossil fuels with biomass; it is also calculated by the bioenergy module. Since the present analysis aims to find the appropriate parameterisation for the biomass module, which is the basis of the model calculations, only the biomass module was used. It uses the following equation to calculate carbon content:

$$Cb_{it+1} = Cb_{it} + Kc\,[Gb_{it} - Ms_{it} - T_{it} - H_{it} - Ml_{it}] \quad \text{(tC ha}^{-1}) \qquad (1)$$

where
- Cb_{it}: C-content of the living biomass of cohort 'i' at time 't'
- Kc: constant to convert biomass to carbon content (MgC per Mg biomass dry weight).
- Gb_{it}: biomass growth
- Ms_{it}: tree mortality due to senescence
- T_{it}: turnover of branches, foliage and roots
- H_{it}: amount of harvest
- Ml_{it}: mortality due to logging

2.3.2. Model parameterisation

The model calculates the biomass increment using the following equation:

$$Gb_{it} = (Kv_i \ Ys_{it} \ (1 + \Sigma \ (F_{ijt}))) \cdot Mg_{it} \qquad (\text{Mg ha}^{-1} \text{ yr}^{-1}), \qquad (2)$$

where:
- Kv_i: basic wood density (Mg dry biomass per m^3 of fresh stemwood volume) for each cohort 'i'
- Ys_{it}: is the volume yield of stem wood for each cohort 'i' (m^3 ha^{-1} yr^{-1}),
- F_{ijt}: is the biomass allocation coefficient of each living biomass component 'j' (foliage, branches, and roots) relative to stems, for each cohort 'i' at time 't' (Mg per Mg stemwood), and
- Mg_{it}: is the growth modifier due to interactions among and within cohorts (dimensionless).

Wood density data came from the Wood Density Database (Chave et al. 2009). The annual yield of stem wood was derived from the national yield tables (Sopp 1974, Béki 1986, Mendlik 1986, Béki 1987). These are available for the commercially significant tree species of Hungary. Yield classes were determined according to the maximum height for each species at the plot and checked against the increment between 2006 and 2015. Since the eroded karstic soils do not provide a favourable environment for growth, we generally worked with the tables for classes 4 or 5 (in a few cases 3 or 6). In order to calculate the relative growth of the other biomass compartments (roots and foliage) we used data from Führer and Jagodics (2009). They measured the amount of C-content/ha in the different compartments of a beech stand and we used the proportions as a constant value for relative growth. For the relative growth of branches, we used the small branches' proportions tables available along with the yield tables. Percentages for each species and age group were given based on the typical dimensions (dbh and height) of the appropriate yield class. Each species for each yield class was handled in a separate model and the results were added up for each plot after being weighted according to the species composition. Therefore interactions between the cohorts were not (directly) included in the model (correction number was left at the default: 1). For rare species without yield information we used the parameters of the most similar commercial species, mainly pedunculate oak.

Turnover rates were defined on the basis of the paper of Wutzler and Mund (2007). As the products module was not used, the amount of harvest and mortality due to logging were not considered – the status of the area ('forest reserve') means that active management is limited to its buffer zone.

As described in the introduction, the mortality rate parameter was earlier found to be a critical point of the parameterisation. In order to find the best approach, we ran the model

with 3 different mortality settings. In the first case ('no mortality') we set the mortality rates to 0 as is the model default. In the second case ('yield table mortality') we used the volume of trees proposed for removal in the yield tables, supposing that since thinning aims to optimize growth, the volume of wood proposed for removal would be similar to that lost to mortality in a natural forest. This means relatively high, although continuously decreasing rates. In the third case (3) we used the species-specific mortality statistics calculated from our own dataset for the examined beech stands for the period between 2006 and 2015. In this case for stands younger than 50 years, mortality rates were set to 0.

3. RESULTS AND DISCUSSION

3.1 Model results

When estimating the actual carbon content of the stands based on the survey data, we got on average 188 t ha^{-1} for the 100–105-year-old stands and 148 t ha^{-1} for the 70–75 year-old ones (Fig. 2). Of the 13 plots examined, 18AO had to be omitted; shortly after the baseline survey, a gap formed in the vicinity of the plot, where most of the trees (representing 87% of the volume in 2006) died by the autumn of 2015; thereore the amount of carbon stored in the remaining living biomass is much lower at this plot than at others around it. Although the C content of living biomass at the plot increases with stand age, other factors (e.g. species composition and local mortality) also influence its value.
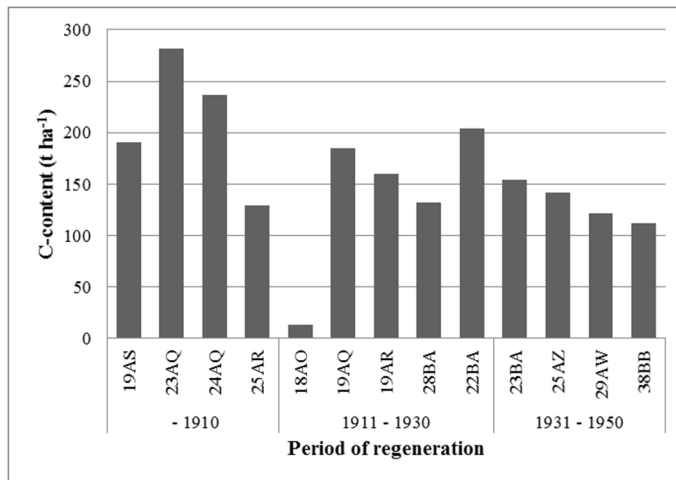

Fig. 2 C-content of the biomass (t ha^{-1}) at the plots estimated using survey data from 2015. Dates show the time of the last stand regeneration based on forest inventory data

Since most of the stands in the reserve have been subject to management in the past, their natural development has only recently begun and their structure retains traces of earlier human impact (Tanács et al. 2007). Therefore the amount of biomass (and carbon) stored in the stands was expected to be between those of managed stands and naturally developed forests. Führer and Jagodics (2009) carried out detailed measurements in a managed beech forest at a high-quality site and as a result found the C-content of the living biomass to be

292 t ha^{-1}. Juhász et al. (2008) measured and estimated the C-content of an old-growth natural beech forest (Kékes-Észak forest reserve) and got 231 t ha^{-1} as a result. Our results are typically lower than both, however the stands in our survey are younger and the site is less favourable. 2 of our plots (23AQ and 24AQ) show values that are similar to the above-mentioned results, these are situated in a rather remote part of the study area, where stands with the most natural structure can be found (Tanács 2011).

Fig. 3 shows the model results together with the reference values. All those calculations where mortality is included tend to underestimate the carbon content, except in the case of plot 18AO, where locally mortality was extremely high in recent years and regrowth has not occurred yet. Calculations without including mortality seem to give the best estimations for the carbon content of the biomass. The reason for this could be that the loss of a dominant tree also means modified light conditions resulting in the accelerated growth of the surviving individuals around it. Whereas it is possible to include mortality in the model, it is not possible to directly include the effect of the resulting increased growth. The average difference between the model results and the reference values is -8.38 t ha^{-1} (25.8 t ha^{-1} if the absolute values are averaged), which means an average -2.69% of the reference values (15.44% for the absolute values).
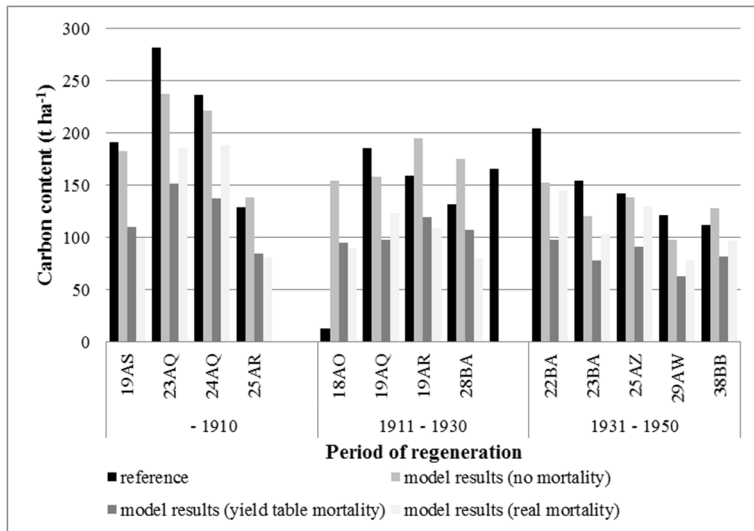

Fig. 3 The carbon content of the biomass (t ha^{-1}) at the plots using different mortality settings in the model

As the averages show, the no-mortality model results are in most cases also lower than the reference values (see also Fig. 4). One reason for the underestimation could be that the yield tables applied were created on the basis of national-level data; no matter how carefully the yield class is chosen, in most locations the actual growth rates are different. This is especially true in the extremely diverse karstic environment where growing conditions may significantly change within very short distances (Tanács 2011). Also, the yield tables contain data for monospecific stands whereas interactions between species could result in increased growth rates (such an effect was demonstrated in another Hungarian forest reserve for beech by Veperdi (2010)).

In some cases the model with the 'no-mortality' setting overestimates the carbon content of the biomass, usually for those plots where the proportion of hornbeam is high (Fig. 4).

Since in these forests hornbeam generally forms a second crown layer, overshadowed by the bigger beech trees, its growth is considerably slower than it would be in a monospecific stand such as those represented by the yield table. Mortality is higher among the suppressed individuals (Tanács and Barta 2014) but the disappearance of a small tree from the second crown layer probably does not generate so much excess light as to induce faster growth in the vicinity.
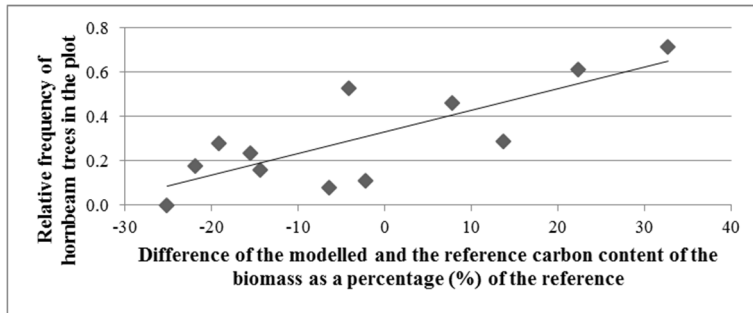

Fig. 4 The effect of species composition on the performance of the 'no mortality' model

4. CONCLUSIONS

Hungarian forests are considered important carbon sinks (Somogyi 2008); in fact, they are the only significant sinks in the greenhouse gas balance of Hungary (Kis-Kovács et al. 2011). As climate mitigation becomes a more and more pressing issue, the role of forests as carbon sinks will increase even further and management decisions will need to increasingly take this into account. Carbon sequestration models can be useful tools in planning future management strategies, but only if they are properly calibrated for the ecosystem in question. In our study we used data from the literature and other publicly available data for the parameterisation of the CO2Fix model and compared the model results to reference estimations based on data from a field survey carried out in autumn 2015 in some beech and hornbeam-dominated stands of Haragistya-Lófej forest reserve. Due to the less favourable site conditions, effects of earlier management and the age of the stands the actual carbon content of the biomass was found to be somewhat lower than expected in a near-natural beech forest. We also examined the effect of using different mortality settings on the results. The model with 'no mortality' settings was found to give the best results in almost all the plots, however the performance was species-dependent. The higher the proportion of hornbeam is at the site, the higher the chance that the model overestimates the carbon content. This draws attention to the fact that growth is much affected by the status of the individual within the canopy (expressed e.g. by the crown class) therefore the model performance could perhaps be further enhanced by taking this into account as well.

It is important to note that empirical data (even appropriate yield tables) for setting up even a relatively simple carbon sequestration model are scarce even for the most researched

tree species and forest types and there are several of these (usually economically less important) for which practically no data are available.

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