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CARBON SEQUESTRATION OF FLOODPLAIN FORESTS: A CASE STUDY FROM HUNGARY, MAROS RIVER VALLEY

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Abstract. Model-based assessment of the carbon storage potential of different types of forests is an important task in the context of climate change and green infrastructure development goals. In our paper, we present the results of the calculations aimed at comparing carbon sequestration processes of floodplain forests with different ages and management intensities in the active floodplain of the Maros river (South East Hungary). These types of assessments can help in resolving the complex environmental management issues of these areas, characterized mainly by the conflicting interests of the forestry, water management and nature conservation sectors. The work was carried out using the CO2Fix3.2 model, based on the field database of a forest reserve and the forest inventory of the area. The main forest types are native and non-native willow-poplar stands, managed and non-managed hardwood forests (with pedunculate oak and elm species) and stands of invasive species. The results highlight the importance of managed forests with long rotation cycle and old-growth unmanaged forests from the point of view of carbon sequestration. They also draw attention to the necessity of incorporating these ecosystem services in the planning processes for a better environmental decision-making.

Key words: carbon stock modelling, CO2Fix, management intensity, willow-poplar forests, floodplain forests, Maros valley

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Introduction

Global climate change is of great importance among environmental issues. By now most scientists agree that greenhouse gases are among the key factors contributing to unfavourable changes in the planet's climate system (IPCC 1990, 2007). Carbon dioxide is one of the most important anthropogenic greenhouse gases and its atmospheric concentrations have increased since the 19th century, therefore the examination and understanding of the carbon cycle are becoming increasingly important. Vegetation plays a significant role in the global carbon cycle. Since plants extract carbon from the atmosphere during their photosynthesis, forests help stabilize the climate and mitigate the negative effects of climate change. The flow of carbon in the biosphere is part of a complex biogeochemical cycle. In order to set up the exact carbon-balance equation a better understanding is needed about each of the cycle's carbon binding or storing processes.

Due to the imminent dangers of global climate change, climate regulation through carbon sequestration is currently one of the most widely acknowledged ecosystem services of forests. The sequestered carbon shows up in the biomass increment and is stored in various stocks (e.g. stems, branches, foliage, roots and soil) until it returns to the atmosphere as a result of turnover or logging. Earlier it was generally thought that ageing forests should be 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 later that growth and carbon acquisition in old natural forests cannot be extrapolated from the productivity of even-aged stands (Carey *et al*. 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 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 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).

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). Although there are some studies regarding their carbon sequestration capacities (e.g. Führer and Molnár 2003, Balázs *et al.* 2008, Juhász *et al.* 2008, Kiss *et al.* 2011), the floodplain forests of Hungary have not yet been specifically studied from this respect.

Since the river regulations of the 19th century, the floodplain forests of Hungary have been constrained between the river and the flood control dams. Their development is defined by the hydrological and geomorphological environment. These controls affect the vegetation at the patch scale through soil quality (hydrology and fertility), stability of substrate and floodplain hydrology/ hydrogeology (Brown *et al.* 1997). In their natural state, floodplains are notable for their diverse habitats and vegetation. Geomorphological complexity is the key for this diversity (Harper *et al.*, 1995), but both the complexity and attendant biodiversity are only present if there is no intensive land use on the floodplain.

There are a number of unresolved problems related to floodplain forests in Hungary (Czeglédi 2004). Beside the local inhabitants, their fate is defined by three main stakeholders, acting under different regulations: nature conservation authorities, private and state forest managers, and water managers (with a high priority on flood prevention). The different priorities of these actors mean that their interests are often in conflict.

The total area of the once widespread floodplain willow-poplar woodlands in Hungary is currently approx. 21000 ha (Bölöni *et al.* 2008). Much of the stands were historically converted into meadows, farmlands or orchards, later their sites were occupied by American poplar plantations, with an uncharacteristic, weed-infected herb layer (Bartha 2001). Their high proportion is primarily due to economic reasons, because establishing such non-native plantations was more profitable, and the existing support systems were of no use in preventing this process (Dobrosi and Szabó 2001). The current legislation supports the plantation of native species wherever possible (XXXVII/2009), however, as a result of the former river regulations, the water regime is changing and that poses a considerable threat to the regeneration of the native species, which induces a further increase of the plantation area. Another serious problem is the presence of invasive plants, which slow down or prevent the regeneration of the native species. In some stands the younger generations of trees consist almost entirely of *Acer negundo* and *Fraxinus pennsylvanica* (Bölöni *et al.* 2011). Although naturalness of the species composition of the floodplain willow-poplar forests tends to be low (due to the presence of the invasive species), these forests still have considerable merits from the nature conservation point of view: due to the rapid growth and short life span of the willow and poplar species, a near-natural stand structure can form in a relatively short period of time (Bartha and Gálhidy 2007). This in turn may lead to the appearance of protected animal species.

The ecosystem services approach provides a well applicable framework for resolving the above-mentioned conflicting interests. Therefore, it is important to see how different management scenarios affect the different services. In this research we examined how different treatments affect the carbon-sequestration potential of the forests of the lower Maros valley and what would be the optimal mode of management from this point of view.

Material and methods

1. Study area

Investigations were carried out on the floodplain of the Maros river near Szeged, Hungary (Fig. 1). Most of the forests in this area are plantations of both native and non-native species. There are also a forest reserve and some stands of willow-poplar forests. The main tree species include: pedunculate oak (*Quercus robur*), white poplar (*Populus alba*), black poplar (*P. nigra*), hybrid poplar (*P.* × *euramericana*), the Hungarian subspecies of narrow-leafed ash (*Fraxinus angustifolia* ssp. *pannonica*), European ash (*F. excelsior*) and American ash (*F. pennsylvanica*), white willow (*Salix alba*) and European white elm (*Ulmus laevis*). In addition, black walnut (*Juglans nigra*), white mulberry (*Morus alba*), and sporadically hybrid plane (*Platanus × hybrida*) and common hackberry (*Celtis occidentalis*) also occur.

Eleven sample areas were selected along the Maros river from Makó to Szeged. These areas can be characterized by different species composition, age classes and management intensity (Table 1, Fig. 1).

Table 1. Management intensity and naturalness of the different forest types in our study area. Notations: 1: most natural stands with little or no management; 2: managed mixed and native stands; 3: native monocultures or non-native forests. Abbreviations: An: *Acer negundo*, Fp: *Fraxinus pennsylvanica*, Pa: *Populus alba*, Pn: *Polulus nigra*, Ul: *Ulmus laevis*, Qr: *Quecus robur*.

Age (year)	Management intensity and naturalness		
	1	2	3
0-20		A Poplar stand with native species (Pa, Pn)	B (1,2) *Populus × euramericana* plantation stands
20-50	C Willow-poplar forest at the site of an oxbow lake	D Native poplar stand mixed with American ash (Pa, Fp)	E Oak stand mixed with American ash (Qr, Fp)
50-	F (1,2,3) Forest reserve: willow-, poplar-, European white elm-dominated stands	G Riverbank protection forest (Pa, Ul, An)	H Oak stand (Qr)

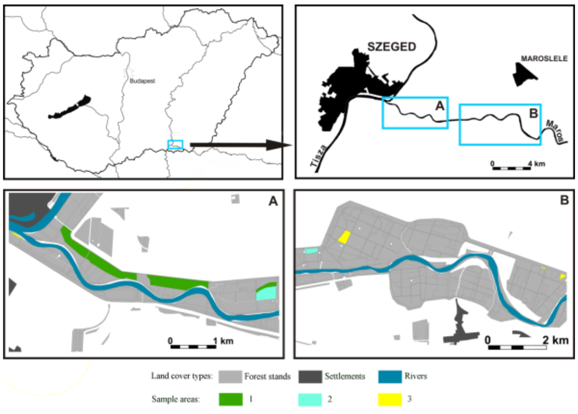

Fig. 1. Study areas along the Maros river. Notations: 1: most natural stands with little or no management; 2: managed mixed and native stands; 3: native monocultures or non-native forests.

Most of the study area on the right bank of the river is under protection and belongs to the Körös-Maros National Park. There is a strictly protected forest reserve near the mouth of the river as well. All human activity is prohibited in the core area of the forest reserve, therefore it is completely unmanaged. The stands here are 60 year-old willow-poplar forests with a slight shift towards oak-elm-ash forests, showing a diverse structure and a relatively high species diversity. The buffer zone is considered strictly protected which in theory makes it possible for forest managers to intervene. The stands in the reserve are infested with invasive species, especially American ash, which composes most of the regeneration layer. Less intensively managed stands outside the reserve include Natura2000 areas and other protected areas where management is allowed only with limitations. These stands also mainly consist of native species. Finally there are the intensively managed plantation forests, mainly of *Populus × euramericana*. One of the sample stands is situated outside the protected area, near the mouth of the river at the town of Szeged.

2. Field surveys

Each sample corresponds to a forest section, except in the reserve, which is rather diverse, and therefore it cannot be characterized properly by the usual unit of the forest inventory. The species composition and the age classes of the other stands were characterized by the data of the forest inventory. However, in different stands of the reserve, a forest structure survey was conducted in circle plots with 20 m radius, in which the position, diameter at breast height, crown class and species of each tree were recorded. The data of 3 plots in 3 different types of stands were chosen. F1 is a hollow with a few large old willow trees and lots of young American ash trees on the higher banks of the hollow. F2 is dominated by older poplar trees (both black and white) and European white elm in the second layer, and lots of smaller American ash trees. F3 is situated on slightly higher ground, which is dominated by European white elm. *Acer negundo*, together with a few older willows and lots of young American ash trees also occur in this stand.

Due to regular flooding, the soil properties of the floodplain can be considered fairly homogeneous. Soil samples were taken from a recently planted stand in order to measure the initial carbon content of the soil and to estimate the proportion of raw and recalcitrant humus forms. Measurements of the soil properties (humus content, proportion of raw and recalcitrant humus forms) were carried out according to the MSZ21470/52-83 standard.

3. Brief description of the CO2Fix model

The CO2Fix model was chosen for the analysis. 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 or species, which are assumed to exhibit similar growth. The model consists of six modules: biomass, soil, wood products, bioenergy, financial, and carbon accounting.

The biomass module converts volumetric net annual increment data to the annual carbon stock of the biomass compartment. Turnover and harvest parameters drive the fluxes from the biomass to the soil and the products module, respectively.

The model has a soil module known as Yasso (Liski *et al.* 2005) which simulates the dynamics of carbon in the soil, taking into account the decomposition of the organic matter, long term storage of carbon and its flux back to the atmosphere. Soil module inputs include litter from turnover and mortality processes and logging slash forms and the initial litter quality and the effect of climate on decomposition are also taken into account.

The fate of the harvested timber is followed via the products module. Through the decomposition of waste, this is also related to the atmosphere.

The carbon content of firewood and (after a while) of the wood products get back to the atmosphere (the latter through waste incineration); this is calculated by the bioenergy module.

The carbon accounting module follows the changes of the carbon content of the atmosphere and determines the accounting units gained in a prospective related climate policy project.

Finally, the financial module calculates the revenue based on the expenses and incomes from the management.

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. In this analysis the financial and the bioenergy modules were not used.

4. Model parameterization

Current annual increment and other yield data were taken from yield tables (Table 2). We have not found yield tables for all species, especially those that are economically less important in Hungary. Therefore data of relative or similar species were used, based on information from the literature (Veperdi 2008).

Table 2. Yield tables used in the present study.

Species	Reference
Ash (*Fraxinus excelsior*)	Kovács (1986)
Hybrid poplar (*Populus* × *euramericana*)	Halupa and Kiss (1978)
Pedunculate oak (*Quercus robur*)	Kiss *et al.* (1986)
Sessile oak (*Quercus petraea*)	Béky (1981)
White poplar, grey poplar (*Populus alba, Populus* × *canescens*)	Rédei (1992)
White willow (*Salix alba*)	Palotás (1969)

The wood density data were taken from Somogyi (2008), and in the case of hybrid poplar from Molnár and Komán (2006). For the calculation of the carbon content of wood, the IPCC default (0.5 t C/t biomass) was used. The relative growth of the branches was calculated based on branch proportion tables (Sopp and Kolozs 2000), where the values were assigned to age groups according to the tree size. Density-dependent mortality was estimated only for the non-managed stands based on the yield tables, while management mortality was defined according to expert opinion (from the state forest manager). Approximate thinning-harvest data were also provided by the local state forestry company.

The mean temperature and precipitation data were gathered from the National Meteorological Service [1], while the growing season was defined as the period from March till October. In the products module the second default dataset (low processing and recycling efficiency) was used, slightly modified on the basis of information from the state forestry company.

We have run the simulation for a period of 120 years, according to the longest rotation cycle used in the area (for oak stands). Each species were modelled separately and the results were added up for each stand after being weighted according to the species' proportion at the specific sample site. In the case of the most natural stands, we added some cohorts with time, thus simulating successional development and species changes. The time of the addition and the species of the new cohorts were based on forest inventory data and the field survey data.

Results and discussion

The results of the simulations are presented in Table 3 and Fig. 2 while Figs 3-7 and Appendix Figs 1-6 show how the carbon content changes with time in the different compartments and overall in the sample areas.

Table 3. The maximum carbon content values in the sample areas [tC/ha]. Stands highlighted with grey are not harvested.

Age (year)	Management intensity and naturalness		
	1	2	3
0-20		A: 65.11	B1: 116.13 B2: 95.04
20-50	C: 167.33	D: 105.31	E: 283.87
50-	F1: 196.31 F2: 217.55 F3: 173.39	G: 122.53	H: 236.90

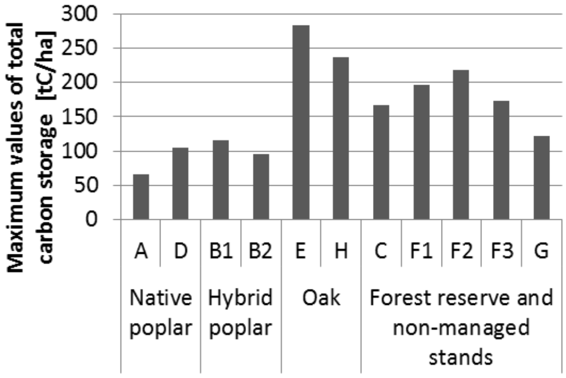

Fig. 2. The maximum carbon content values in the sample areas [tC/ha].

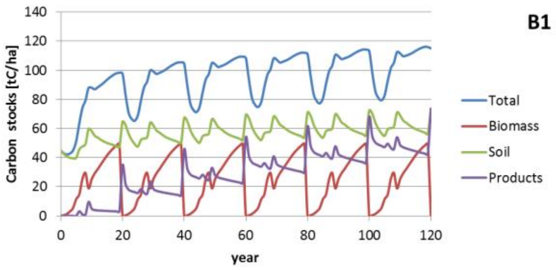

Fig. 3. Carbon stocks in the main compartments of the sample area B1 (hybrid poplar plantation stand).

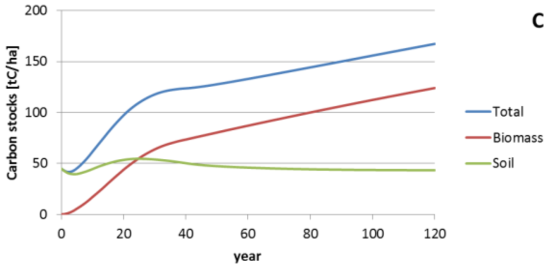

Fig. 4. Carbon stocks in the main compartments of the sample area C (willow-poplar forest at the site of an oxbow lake).

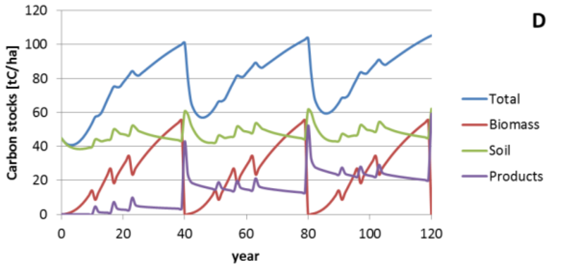

Fig. 5. Carbon stocks in the main compartments of the sample area D (native poplar stand mixed with American ash).

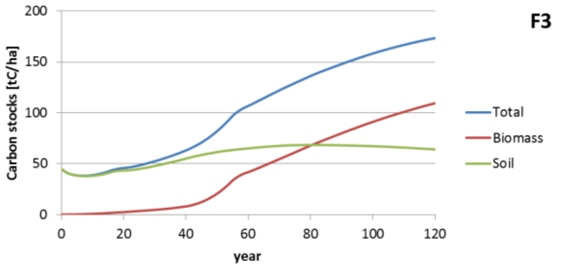

Fig. 6. Carbon stocks in the main compartments of the sample area F3 (forest reserve, European white elm dominated stand).

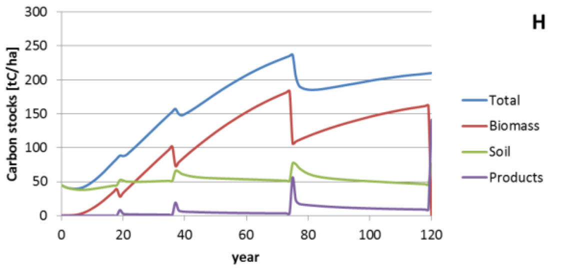

Fig. 7. Carbon stocks in the main compartments of the sample area H (oak stand).

Among the managed forests, the oak stands can be characterized by he highest carbon storage potential. Beside the species characteristics and the longer rotation cycle, the reason for this is mainly the high proportion of long-lasting products (e.g. furniture) made of oak wood.

The carbon storage potential of the hybrid poplar stands is much lower than that of the oak stands. The carbon stocks in the different compartments of the hybrid poplar stands basically reflect the management regime, since they are generally characterized by rapid growth (depending on the variety) and consequently a very short rotation cycle. It should be noted that the continuous growth of the total carbon content in the modelled results is somewhat doubtful. The modelling process in this case should be further refined by introducing soil carbon loss resulting from the soil preparation works when planting the new stands (see Somogyi *et al.* 2013) as well as a more precise parameterization of the lifecycle of the derived wood products. The continuous increase in the amount of carbon stored in the products is due to the fact that some of them are supposed to end up in landfills where decomposition is very slow. Even though this proportion has been assigned a small value (around 5%) in the model, in the case of short rotation cycle (when lots of products are produced), the carbon storage of the products added up.

According to the model, the carbon storage potential of the native poplar stands was similar, but slightly lower than in the case of the hybrid poplars. However, it should be taken into consideration, that the carbon storage potential of native poplar stands may be higher in reality: due to partial restrictions from the protected status, clear-cutting and the subsequent complete soil preparation are not allowed in these stands. Therefore, emission from the soil is probably less than in the case of non-protected stands.

In the stands of the forest reserve and the other non-managed stands, a continuously increase of the carbon storage can be clearly seen. In the case of the poplar forests, it exceeds the values of the managed poplar stands. However, the results should be further refined by introducing an increased mortality at higher ages, which were not included due to a lack of dynamics-related data.

In conclusion, the older floodplain forests can be considered significant carbon sinks. In the case of the poplar species, less intensive treatment and longer rotation cycles are more favourable from the carbon sequestration point of view, mainly due to less soil disturbance, and the generally short life cycle of the products coming from the plantations (mainly paper and packaging materials), which thus retain carbon only for a short time.

Although the low number of samples does not allow carrying out statistical comparison, the results of the simulation at the current age of the stands were compared to calculations based on the actual forest inventory data. As Table 4 shows, the results seem to be realistic, although the modelled results are generally higher, especially in the case of the oak forests. The reason for this remains to be investigated; a knowledge of the site history would be necessary (locally, the management regime can be altered or the specific stand could have been affected by factors unaccounted for – e.g. biotic or abiotic damage).

Table 4. Comparison of the carbon storage of the biomass compartment [tC/ha] based on the model results and the forest inventory

Sample areas	Age (year)	Carbon storage of the biomass [tC/ha]	
		Forest inventory	Modelled
B1	10	22.80	25.11
B2	20	37.13	39.34
D	21	37.68	31.49
E	58	117.20	177.73
H	91	110.58	134.31

Issues to be fixed and further research

Several problems occurred in the course of the analysis and especially the model parameterization. As most existing carbon sequestration models, CO2Fix can be best used to describe the processes of managed forests with few tree species. A serious drawback of the model is that the proportions of the cohorts cannot be defined, and the input data in the products module cannot be given for each cohort separately. We fixed this by creating a separate file for each species. However this makes the modelling of between-cohort interactions, e.g. competition, impossible. The final results were then weighted according to the proportion of the species in the stand. Another issue probably affecting the final results is that the soil carbon loss following clear-cutting and replanting cannot be directly included in the model.

Due to lack of data the natural dynamics of the floodplain forests could only be characterized in a limited manner and some further important additions would be required in the interest of getting more realistic results. One such addition is density-independent mortality, which in the case of floodplain forests is mainly caused by higher-than usual, longer-lasting or icy floods (or possibly biotic effects). A more precise parameterization of mortality as a function of age and regeneration dynamics should also be included. A very important aspect would be the carbon content of the shrub layer, which is currently not possible to include. In general, there is a lack of data for those tree and shrub species which are not considered economically important. The most important differences between a managed and a natural forest lie in the diversity and dynamics of the latter, therefore, simplification based on data from managed stands tends to favour such stands when a comparison is made. In the future, we plan to concentrate on refining the model, which requires further research concerning these issues.

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Appendix

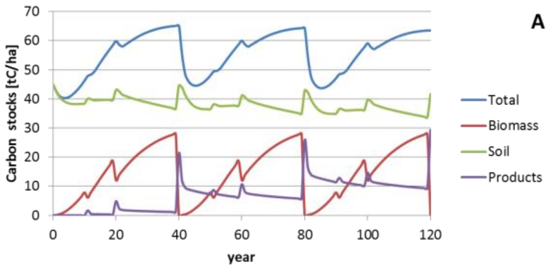

Fig. 1. Carbon stocks in the main compartments of the sample area A (poplar stand with native species).

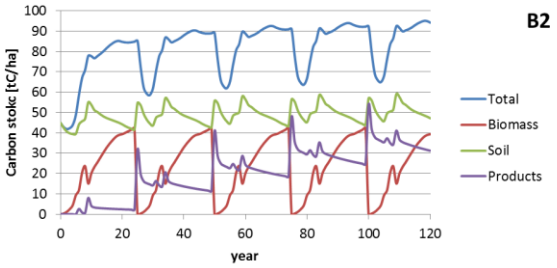

Fig. 2. Carbon stocks in the main compartments of the sample area B2 (hybrid poplar plantation stand).

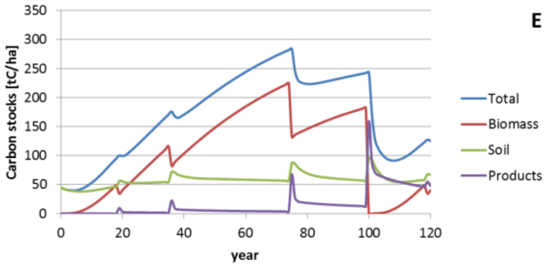

Fig. 3. Carbon stocks in the main compartments of the sample area E (oak stand mixed with American ash).

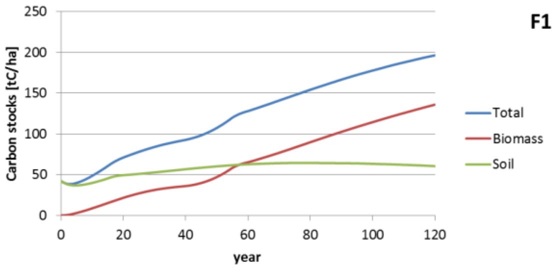

Fig. 4. Carbon stocks in the main compartments of the sample area F1 (forest reserve, willow dominated stand).

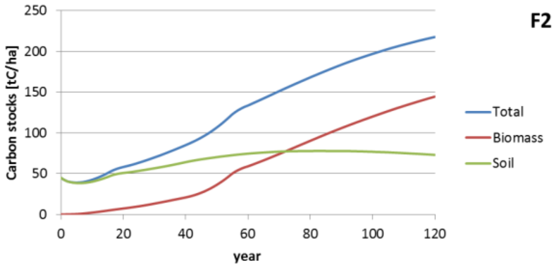

Fig. 5. Carbon stocks in the main compartments of the sample area F2 (forest reserve, poplar dominated stand).

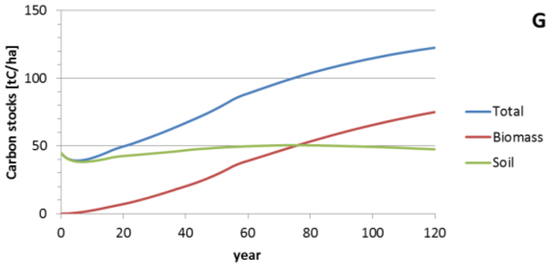

Fig. 6. Carbon stocks in the main compartments of the sample area G (riverbank protection forest).