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Aboveground wood biomass, carbon stocks and annual carbon sequestration of floodplain forests in the Danube Delta, Romania

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Abstract Intact wetlands can act as carbon sinks and mitigate increased amounts of CO_2 in the atmosphere emitted by human activities. In addition to the organic soils in reed beds, floodplain forests play an important role in the carbon storage within wetlands. In the context of the project 'EDAPHIC-BLOOM Danube' (2020-2023), actions for greenhouse gas (GHG) mitigation were developed to reduce the effects of climate change. One project part dealt with estimates of aboveground wood biomass and carbon stocks of the riparian vegetation in the Danube Delta. The different forest types were investigated in the vegetation periods of 2021 and 2022 using a plot design in which vegetation and site-specific habitat parameters such as substrate and flooding frequency were recorded. Vegetation data was used to calculate the aboveground wood biomass (AGWB) of the trees and determine their carbon stock. Furthermore, tree core samples of the dominant tree species were taken to measure annual AGWB increments for determining carbon sequestration and net primary production (NPP). In total, a carbon stock of almost 2.5 million Mg (t) is stored in the riparian forests covering an area of approximately 30,139 ha in the Danube Delta. The results show differences in AGWB and carbon stocks between natural softwood and hardwood riparian forest types and tree plantations. The individual *Populus* × *canadensis* trees in the plantations were found to have the highest annual carbon sequestration in their AGWB (0.0186 Mg year^{-1}). The natural sand dune forests, however, are the most important forest type in terms of long-time carbon storage (approximately 333,315 Mg C in the entire delta). Considering annual growth of the main tree species and the cover of the different forest types, the highest current NPP of the Danube Delta forests is found in natural floodplain forests with almost 97,750 Mg year^{-1}.

Keywords: Carbon sequestration, dendrochronological analysis, annual tree ring growth

1 Introduction

Mitigation of climate change is one of the current major challenges in the world (Chen et al., 2013). Present regulations such as the United Nations Framework Convention on Climate Change (UNFCCC) focus on the reduction of greenhouse gas (GHG) emissions as drivers of temperature rise (FAO, 2001; Gratani et al., 2017). Among anthropogenic emissions, carbon dioxide is considered as one of the most important GHG in terms of quantity (Hauck et al., 2019).

Ecologically intact wetlands and floodplains can act as carbon sinks and mitigate increased amounts of carbon dioxide in the atmosphere emitted by human activities (Cierjacks et al., 2010). Freshwater wetlands provide a potential sink for atmospheric carbon in the form of carbon dioxide and methane, depending on their age, the environmental boundary conditions such as the climate and, in the case of managed wetlands, operation (Kayranli et al., 2010). In addition to the soils, the vegetation plays an important role in the carbon cycle and storage possibilities (Gratani et al., 2017).

With the assignment of the Danube Delta as Biosphere Reserve several restoration measures were implemented (Negm and Diaconu, 2022). In this context, the project EDAPHIC-BLOOM Danube ('Ecological resizing through urban and rural actions & dialogues for GHG mitigation in the Lower Danube Floodplain & Danube Delta') was initiated (https://ddni.ro/wps/edaphic-bloom_en/). In the project, actions for GHG mitigation as well as dialogues with authorities and stakeholders in the Lower Danube region in Romania were developed (e.g., Balaican et al., 2024). The project was implemented from 2020 to 2023 as part of the European Climate Initiative (EUKI). One aspect addressed in the project was the biomass and carbon storage capacity of the riparian vegetation (Becker et al., 2023a).

Riparian forests are known to be important vegetation types in the Danube Delta. In forest biomass considerable amounts of carbon are stored and mitigation of climate change by enhancing forest carbon sequestration is promoted as low-cost option with additional other benefits (Gorte, 2009; Gratani et al., 2017). Here, we present our biomass and carbon stock calculations of riparian forests of the Danube Delta as well as annual increment and annual carbon storage of tree individuals. The methods and results are extracted from the project report (Becker et al., 2023b) including also findings from the theses by Hutschreuther (2022), Lieb (2023), and Mildt (2022).

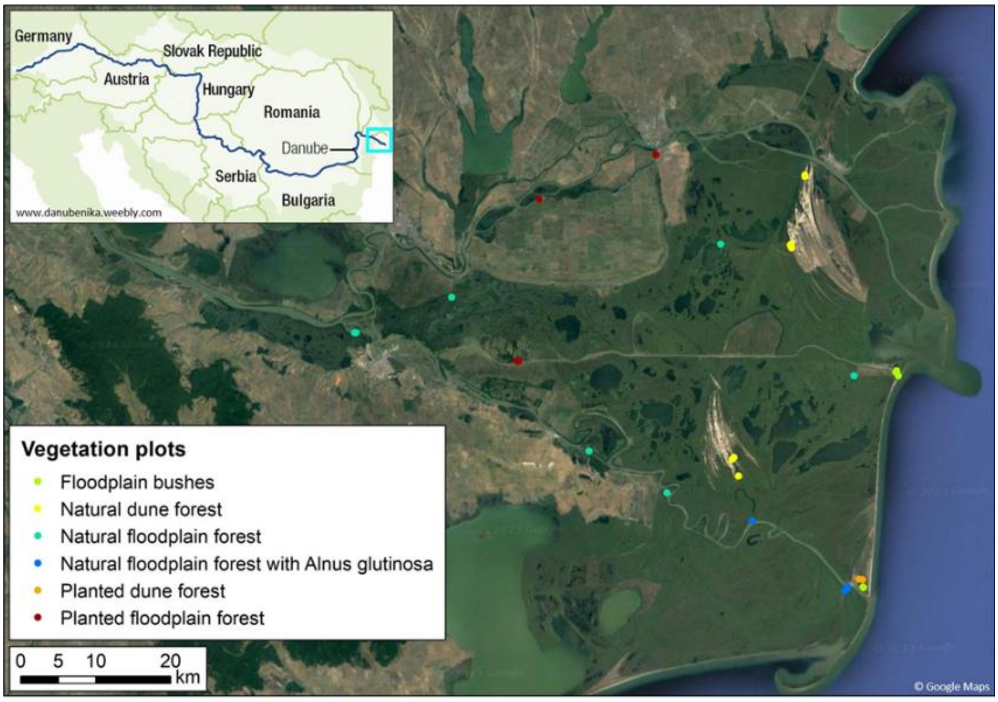

Figure 1: Forest plots used for tree biomass and carbon stock calculations across six forest types in the Danube Delta.

2 Material and methods

2.1 THE DANUBE DELTA AND ITS RIPARIAN FORESTS

At its mouth, the Danube divides into three branches that encompass the area of the Danube Delta (Kahl 2018). The total area of the Biosphere Reserve 'Danube Delta' has the size of approximately 5.800 km² in Romania and 46 km² in the Ukraine (Hanganu et al., 2002). The interplay between various morphodynamic processes of fluvial and marine origin created a mosaic of different habitats such as channels, lakes, reed beds, and riparian forests (Niculescu et al., 2015). Woody vegetation types cover about 6% of the Danube Delta (about 30,139 ha; Hanganu et al., 2002). They can be classified into riparian forests and a specific form of it, the sand dune forests, floodplain bush vegetation, and artificial plantations (**Figure 1**).

The sand dune forests are located in the Caraorman and Letea beach ridge plains. These are the two biggest beach ridge plains in the Danube Delta. Both were formed by an interplay of maritime and fluvial processes building the sites through wave influence, alluvial and maritime sediment transport and discharge with wind-induced reshaping (Hanganu et al., 2002; Rădoane and Vespremeanu-Stroe, 2017; Vespremeanu-Stroe et al., 2016). On the one hand, the areas are usually not flooded but the soils in the depressions between the sand dunes are hydromorphic influenced by fresh groundwater that flows following an East-West gradient. During high water events, the groundwater level may rise multiple decimetres above the surface. Freshwater is also supplied by rainfall. On the other hand, dry seasons cause a groundwater level decline to depths of 1.2 - 1.4 m below the surface (Hanganu et al., 2002; Pocora and Pocora, 2008), and sandy topsoils dry out quickly due to their low water retention capacity. The Letea and Caraorman dune forests developed in the humid depression zones between the dunes, form 10 to 250 m wide, elongated forest patches of varying size, oriented parallel to the dune ridges (Gâştescu, 2019; Gâştescu and Oltean, 2002; ICR, 2008; Panin et al., 2016; Pocora and Pocora, 2008). They cover a total area of 2,371 ha. *Quercus* spp., *Fraxinus* spp. and *Populus* spp. are the dominant tree species of these natural hardwood riparian forests (Gâştescu, 2019).

Other natural floodplain forests of the Danube Delta with typical alluvial dynamics grow especially on the natural riverine levees and artificial dikes alongside the main Danube branches and smaller channels (Hanganu et al., 2002; Munteanu and Curelariu, 1996). These natural floodplain forests cover an area of 13,027 ha. Willow riparian forests mostly occur on the elevated riverine levees. In most cases, extensive reed beds are adjacent to the narrow riverine levees, resulting in a gallery-like extent of the forests. *Salix alba* and *S. fragilis* are the dominant species of the softwood riparian forests. Natural floodplain forests with *Alnus glutinosa* occur on 674 ha in the Southern marine parts of the Danube Delta (Hanganu et al., 2002; Kahl, 2018). *A. glutinosa* depends on constant high water tables at sites where sandy soils are rich in organic material and/or peat. The alder forests are therefore mostly small and isolated in the Danube Delta (Hanganu et al., 2002).

Along the coast and on along the beach ridge plains of Letea and Caraorman, shrub vegetation types with *Elaeagnus angustifolia*, *Tamarix ramosissima*, and *Hippophae rhamnoides* occur. They often grow on dry elevations such as river levees. *E. angustifolia* was formerly planted in the delta by humans but spreads on its own in the meantime (Hanganu et al., 2002; Rădoane and Vespremeanu-Stroe, 2017). The floodplain bushes cover an area of 1,338 ha in the Danube Delta. Besides, they grow in areas of planted dune forests that total a coverage of 2,422 ha.

Many *Salix alba* stands have been removed and replaced by plantations of poplar species, such as *Populus* x *canadensis* or *P. canescens*. These planted monocultures or sometimes as mixed stands with remaining willows make up a significant portion of the floodplain forests in the Danube Delta (Hanganu et al., 2002; Kahl, 2018). In total, they cover an area of 10,306 ha.

2.2 FIELD INVESTIGATIONS

Structural forest biomass parameters of shrub and tree dominated vegetation types were investigated using a nested plot design. In 35 plots of 25 x 25 m size, general vegetation and habitat parameters were recorded in July 2021 and September/October 2022. These included the substrate proportions, the morphodynamic and the inundation class (Egger et al., 2015). In addition, the vegetation type and its structure-forming species were determined. The surface cover, subdivided into tree (>5 m height), shrub (0.5 - 5 m height), herb (<0.5 m height) and moss layer (<0.05 m height), as well as litter and deadwood were recorded.

In the 25 x 25 m plots, all tree and shrub individuals with a diameter at breast height (DBH) ≥ 10 cm were recorded, the individual height measured using a Blume-Leiss optical tree height measuring device, and the DBH by using a diameter measuring tape. In two (in 2022) or three (in 2021) smaller nested plots with the size of 5 x 5 m, which were placed diagonally in the larger plots, this information was gathered for all woody species with a DBH between 1–10 cm. In total, we recorded data from 36 woody vegetation plots from the sand dune forests, other types of riparian forests and floodplain bushes (**Figure 1**).

Tree core samples with a diameter of 5 mm were taken to the pith using a MoraCoretax increment corer from Haglöf from the main tree species to perform a dendrochronological, year-to-year growth analysis. Two cores per individual were taken at DBH from different angles to get a good representation of total growth and to ensure sample quality.

2.3 DENDROCHRONOLOGICAL ANALYSES

For the tree ring analyses, the core samples of ten sampled species (*Alnus glutinosa*, *Elaeagnus angustifolia*, *Fraxinus angustifolia*, *F. pallisiae*, *F. pennsylvanica*, Hybrid poplar (*Populus x canadensis*), *Populus canescens*, *P. tremula*, *Quercus pedunculiflora*, *Q. robur* and *Salix alba*) were air-dried, progressively sanded and polished. Two different approaches for the detection of tree rings were used depending on the visibility of the rings. In the first approach, the samples were scanned with the EPSON 'Expression 12000XU' scanner and analysed with the tree-ring analysis software WinDENDRO. In the second approach, the samples were analysed using the LINTAB TM 6 tree ring station of RINNTECH together with the analysis software TSAP of RINNTECH. The ring numbers and annual ring widths were then analysed with the RStudio software determining the tree age and the annual growth rates for each individual and species. The growth investigations are based on 2,430 measured tree rings represented by 108 wood samples of the ten main tree species representing the past 30 years.

2.4 CALCULATION OF TREE BIOMASS AND CARBON STOCK AND UPSCALING TO THE DANUBE DELTA AREA

For an evaluation of forest structure and assuming that older trees have larger DBH, the tree individuals were categorized by the approximate age of the individuals by dividing them into DBH classes. The DBH classes provide a rough depiction of the different life stages of the trees within the plots. Based on the assumption that trees with larger DBH tend to have higher biomass, categorizing trees into DBH classes can provide an overview of the presumed biomass in the plots. Based on the recorded data, five (partly six) DBH classes were defined:

1. 1-20 cm (1-9 cm, 10-20 cm)
2. 21-40 cm
3. 41-60 cm
4. 61-80 cm
5. ≥ 81 cm

Before estimating the aboveground wood biomass, the number of trees with DBH < 10cm from the smaller nested plots was extrapolated to the area of 25 x 25 m. Then, the total aboveground wood biomass (AGWB) for different tree species was estimated according to Cannell (1984). The formula is based on individual tree height, DBH and species-specific wood density. For the latter, literature values were used. To consider tree tapering and branching of a tree with increasing stem height, a form factor of 0.6 is added in the formula:

$V = (H \cdot G) \cdot F$

$AGWB = V \cdot D$

with V: trunk volume (m3)

H: tree height (m); measured in the field

G: trunk basal area at DBH level (m^2) calculated using field measurements

F: stand form factor (0.6)

AGWB: aboveground wood biomass (Mg, equivalent to tons)

D: wood specific gravity, wood density (g/cm3); using literature values (EOL Database; besides: Ameztegui et al., 2017; Cannell, 1984; Chave et al., 2009; Chojnacky et al., 2014; Goyal et al., 1999; Grosser, 2006; Martínez-Cabrera et al., 2009; Miles et al., 2009)

The carbon content was estimated as 50% of the AGWB as is commonly assumed for carbon estimates (Clark et al., 2001; Malhi et al., 2004; Cierjacks et al., 2010).

AGWB and carbon content were extrapolated to the extents of the different woody vegetation types on the basis of an updated vegetation map of the Danube Delta in the frame of the project (adapted from Hanganu et al., 2002).

2.5 NET PRIMARY PRODUCTIVITY OF THE MAIN WOODY SPECIES

The Net Primary Production (NPP) of plants is by definition the gross primary production by photosynthesis minus total plant respiration (Jordan, 1983; Medina and Klinge, 1983). This comprises new organic material built by the plants such as wood biomass increment and also organic material that has been lost within the investigated time interval such as litterfall (Schöngart et al., 2011; Clark et al., 2001). In forests, the aboveground NPP includes aboveground biomass increment (wood, leaves, flowers, fruits etc.), and losses by litterfall or due to consumers, emissions of biogenic volatile and leached organic compounds (Schöngart et al., 2011). The NPP is expressed as biomass unit (Mg=t) per unit soil area (m^2 or ha) and time (year; Medina and Klinge, 1983).

The NPP can be analysed by the growth rates of the dendrochronological analyses. We quantified the annual NPP of the woody vegetation types in the Danube Delta as the AGWB increment per year. The AGWB increment of an individual tree was derived by the difference between the AGWB of one tree ring with the year before. We calculated the AGWB of each tree ring using the DBH, height and wood density (see AGWB calculation above; Schöngart et al., 2011). For obtaining the tree heights of the previous years, all measured individuals of one species were plotted with their DBH against their height. Using this diagram, past tree heights were estimated using the DBH-height relationship. By this approach, the AGWB increment of each year could be estimated, spanning the period over the last three decades.

3 Results and discussion

3.1 ANNUAL RING GROWTH OF THE MAIN TREE SPECIES

The dendrochronological analysis of the 39 tree samples of the dominant species from the sand dune forests revealed tree ages between 21 and 148 years. In the rings of the last 30 years, highest mean ring growth were detected for *P. tremula* with 3.16 mm $year^{-1}$ followed by *Q. robur* with 2.33 mm $year^{-1}$ (**Table 1**, **Figure 2**).

The 69 trees sampled from the other riparian forest types were between five and 70 years old. By far the highest mean growth were measured in *P.* x *canadensis* with 7.72 mm $year^{-1}$ followed by *P. canescens* (6.85 mm $year^{-1}$) and S. alba (6.24 mm $year^{-1}$). *P.* x *canadensis* is a particularly fast-growing tree species reaching maturity at already 8 to 15 years (North Central Forest Experiment Station, 1996). This is also reflected in the double annual ring width when compared with the native *P. tremula* individuals. The shrub species *E. angustifolia* had slightly higher ring increments (4.39 mm $year^{-1}$) than the two tree species *A. glutinosa* (4.04 mm $year^{-1}$) and the alien *F. pennsylvanica* (3.43 mm $year^{-1}$).

Looking more closely at the last 30 years, in the sand dune forests no clear trend in growth rate was observed for the two oak species (Becker et al., 2023b). *Q. robur* showed a slight increase whereas *Q. pedunculiflora* had a slight decrease. The inter-annual variation was higher for *Q. robur* (e. g. for one individual in Letea forest between 1.21 mm and 9.78 mm $year^{-1}$) with maxima in 1999, 2005, and 2013. This could be due to improved water supply from higher precipitation in the catchment, which was found to be a relevant factor for tree growth in the Letea natural sand dune forest (Helfrich, 2019). This pattern was not as pronounced for *Q. pedunculiflora*. The growth rate of *P. canescens* and *F. pallisiae* were stable whereas *F. angustifolia* growth slightly decreased over the last 30 years.

In the other riparian forests, *S. alba*, *P. canescens*, and the alien *F. pennsylvanica* had positive trends of their increments over the past 30 years. However, some of the recorded individuals were rather young and not all of them covered the period of 30 years analysed in detail. *A. glutinosa* and *E. angustifolia* growth rates decreased from the very high values at the beginning of the investigated time span. Besides, also the *P.* x *canadensis* started with high growth rates at young age and had a decreasing trend to the end of the investigated time span. The latter could be influenced by the addition of several young individuals with lower growth rates.

3.2 CARBON SEQUESTRATION AND CARBON STOCK OF THE MAIN TREE SPECIES

By the measured ring widths, the annual biomass increment, and the corresponding carbon sequestration were calculated for each dominant species in the different forest types (**Figure 3**). *P.* x *canadensis* in plantations have the highest annual carbon sequestration in their AGWB with a mean value per individual of 17.68 ± 15.86 kg $year^{-1}$ followed by the oak species *Q. robur* with 12.77 ± 7.86 kg $year^{-1}$. The lowest carbon sequestrations in trees were found for *F. pallisiae* with 2.02 ± 2.03 kg $year^{-1}$ in ash poplar riparian forest and *F. angustifolia* with 2.27 ± 2.58 kg $year^{-1}$ in ash poplar riparian forest. The highest variations were in general measured for the poplar species *P. canescens* and *P.* x *canadensis*.

Table 1: Mean ring growth per year (mm $year^{-1}$) for the main shrub and tree species of the Danube Delta.

Forest type	Tree species	Mean annual ring growth (mm $year^{-1}$) and standard deviation (SD, number of measured rings)
Sand dune forest	*Fraxinus angustifolia*	1.67 ± 1.22 (168)
	Fraxinus pallisiae	1.16 ± 1.16 (348)
	Populus canescens	1.34 ± 0.86 (97)
	Populus tremula	3.16 ± 2.59 (116)
	Quercus pedunculiflora	1.54 ± 0.74 (224)
	Quercus robur	2.33 ± 1.73 (145)
Other riparian forests	*Alnus glutinosa*	4.05 ± 3.63 (365)
	Elaeagnus angustifolia	4.39 ± 3.11 (151)
	Fraxinus pennsylvanica	3.43 ± 3.02 (130)
	Populus canescens	6.85 ± 4.84 (265)
	Populus x canadensis	7.72 ± 5.77 (148)
	Salix alba	6.24 ± 4.41 (336)

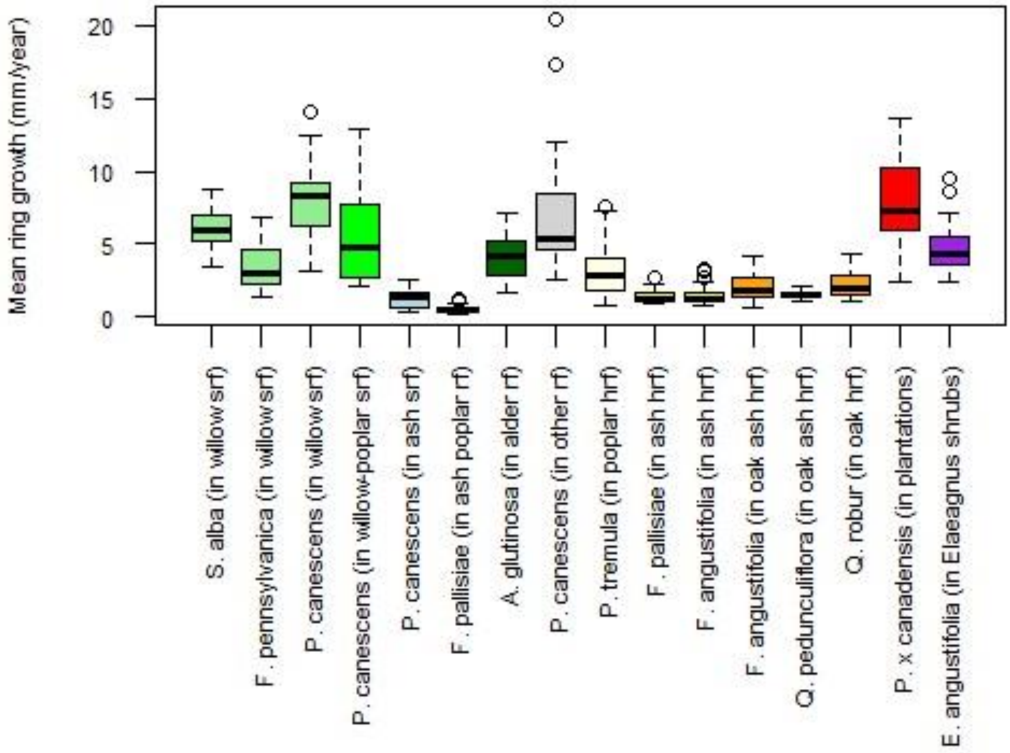

Figure 2: Mean annual ring growth of tree species of 12 different vegetation types (rf: riparian forest, srf: softwood riparian forest, hrf: hardwood riparian forest) from 1993 to 2021.

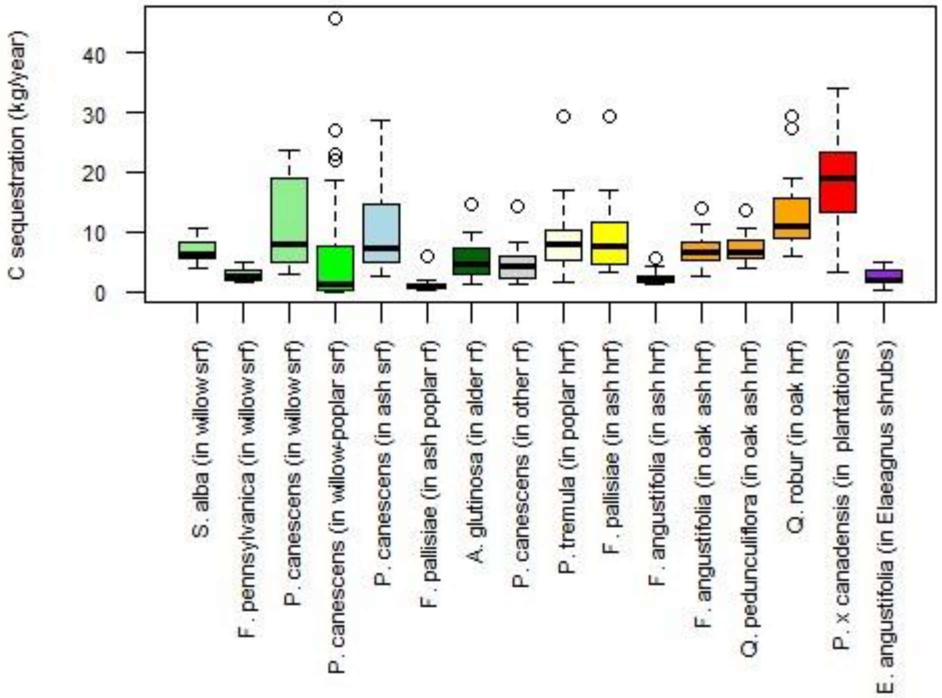

Figure 3: The mean annual carbon sequestration (Mg year^{-1}) per tree species of 12 vegetation types (rf: riparian forest, srf: softwood riparian forest, hrf: hardwood riparian forest) from 1993 to 2022.

Looking at exemplary tree samples of each forest vegetation type, it becomes apparent how the different growth strategies also determine the carbon storage (**Figure 4**). Highest carbon stock in a tree individual is found for *Q. robur* over its whole measurable life span, followed by *P. tremula* in ash poplar riparian forest and poplar hardwood forests. *F. pallisiae* has despite its long-measured life span only low increase in carbon stock. *P.* x *canadensis*, in contrast, has a fast increase in carbon stock.

These results illustrate how different forest types contribute to carbon storage and storage capacity. The natural sand dune forests are very important for long term carbon storage in particular by older oak individuals which store huge amounts of carbon over their long-life span. Although they are not of economic interest, these forests are of high ecological importance and thus protected as conservation areas and thus left to natural succession processes (Hanganu et al., 2002). The trees can reach a high age and thus store carbon over long time. This is why the sand dune forests make an important contribution in terms of carbon storage.

In the case of annual carbon sequestration over the past 30 years, all investigated trees of different sand dune forests species showed little variation in growth and carbon sequestration (results not shown here, Becker et al., 2023b). In the other riparian forest types, the most pronounced increases were found for *P. canescens* and *E. angustifolia* whereas the mean of the *P.* x *canadensis* individuals almost stayed the same.

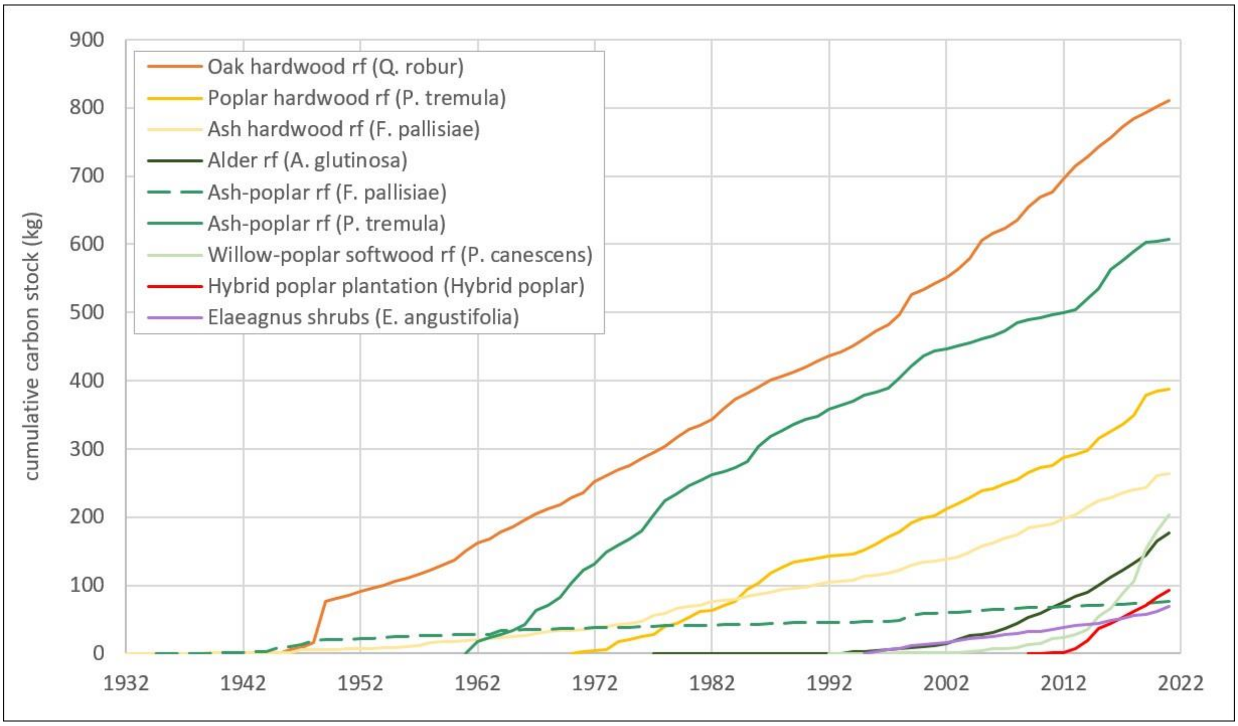

Figure 4: Mean cumulative carbon stock (kg) over the recorded life span of nine trees representing the different forest vegetation types (rf: riparian forest; Lieb, 2023).

By combining sequestered carbon in the AGWB and the mean number of individuals per hectare in 12 different forest vegetation types the mean carbon sequestration of the main tree species per hectare was estimated (**Table 3**, column 'CS per ha in Mg ha^{-1} year^{-1}'). Highest values were found for planted willow forests upstream of Tulcea with a total mean annual carbon sequestration of the two main tree species *S. alba* and the alien *F. pennsylvanica* of 6.385 Mg ha^{-1} year^{-1}. The alder riparian forests with *A. glutinosa* have an annual carbon sequestration of 3.066 Mg ha^{-1} $year^{-1}$ followed by the two investigated poplars in the plantations (*P.* x *canadensis* and *P. canescens*) with an averaged carbon sequestration of 2.917 Mg ha^{-1} $year^{-1}$ and the sand dune forests with an averaged 2.2287 Mg ha^{-1} $year^{-1}$. The values were calculated only for the main tree species which result e. g. in some natural oak sand dune forests with high tree species diversity in lower values than expected since only *Q. robur* was investigated whereas the poplar plantation consists only of investigated poplar individuals.

3.3 NET PRIMARY PRODUCTION OF THE MAIN SHRUB AND TREE SPECIES

The increment of AGWB per investigated tree ring is used as representation of the net primary production (NPP). When summarising all tree samples of one species, the highest NPP were found in *P.* x *canadensis* individuals with 35.36 ± 31.72 kg $year^{-1}$ and *Q. robur* individuals with 25.54 ± 15.72 kg $year^{-1}$ (**Table 2**). This is linked to an annual carbon sequestration of 17.68 ± 15.86 kg $year^{-1}$ and 12.77 ± 7.86 kg $year^{-1}$, respectively. The lowest values were calculated for the shrub species *E. angustifolia* with a NPP of 5.23 ± 6.27 kg $year^{-1}$ (carbon sequestration of 2.61 ± 3.14 kg $year^{-1}$).

Table 2: Annual NPP (kg year-1) as mean aboveground wood biomass increment and mean and maximum carbon sequestration (kg $year^{-1}$) per individual for the main tree and bush species of the Danube Delta.

Tree species	Annual NPP: Mean biomass increment per tree individual (kg $year^{-1}$)	Mean annual CS per tree individual (kg $year^{-1}$)	Max. NPP (kg $year^{-1}$)	Max. CS (kg $year^{-1}$)
Alnus glutinosa	10.61 ± 14.34	5.31 ± 7.17	132.52	66.26
Elaeagnus angustifolia	5.23 ± 6.27	2.61 ± 3.14	32.09	16.05
Fraxinus angustifolia	7.54 ± 7.17	3.77 ± 3.59	40.56	20.28
Fraxinus pallisiae	8.92 ± 16.91	4.46 ± 8.45	135.23	67.62
Fraxinus pennsylvanica	5.59 ± 7.37	2.79 ± 3.69	42.64	21.32
Populus canescens	18.11 ± 20.25	9.05 ± 10.13	111.45	55.73
Populus tremula	16.53 ± 18.31	8.27 ± 9.15	114.02	57.01
Populus x canadensis	35.36 ± 31.72	17.68 ± 15.86	120.29	60.15
Quercus pedunculiflora	8.17 ± 6.31	4.08 ± 3.15	42.59	21.30
Quercus robur	25.54 ± 15.72	12.77 ± 7.86	124.56	62.28
Salix alba	9.64 ± 12.56	4.82 ± 6.28	61.07	30.53

Table 3: Mean annual carbon sequestration (CS) of the tree individuals as well as the CS per plot, per hectare and for each combined vegetation type in the Danube Delta (DD) based on the dendrochronological analyses (rf: riparian forest, hrf: hardwood riparian forest, srf: softwood riparian forest). The annual net primary production (NPP, last column) is included as annual increment of aboveground wood biomass (AGWB). The values represent only the main tree species of each plot or forest vegetation type, respectively.

Forest type	Forest vegetation type	Area (ha)	Species (No. of plots)	Individuals (ind.) per plot	mean annual CS per ind. (kg $year^{-1}$)	CS for all ind. of one species in plot (Mg $year^{-1}$)	CS per ha (Mg ha^{-1} $year^{-1}$)	annual CS (Mg $year^{-1}$) and annual NPP (Mg $year^{-1}$) in DD
Natural dune forest		2,371					2.2287	5,284.8 10,569.5
	Ash hrf		*F. pallisiae* (3)	19.9	8.94 ± 11.38	0.1776	2.842	
			F. angustifolia (2)	18.6	2.27 ± 2.58	0.0423	0.676	
	Ash poplar rf		*P. canescens* (1)	21.4	9.71 ± 11.49	0.2078	3.326	

			F. pallisiae (2)	19.7	2.02 ± 2.03	0.0398	0.637	
			main tree species				3.9630	
	Oak hrf		*Q. robur* (2)	5.1	12.77 ± 7.86	0.0651	1.042	
	Oak ash hrf		*F. angustifolia* (1)	14.0	6.76 ± 3.45	0.0947	1.515	
			Q. pedunculiflora (2)	7.9	4.08 ± 3.15	0.0323	0.516	
			main tree species				2.0316	
	Poplar hrf		*P. tremula* (2)	21.3	8.27 ± 9.15	0.1761	2.817	
Planted dune forest	planted Elaeagnus shrubs	2,422	*E. angustifolia* (1)	13.0	1.84 ± 2.19	0.0239	0.382	925.1 1,850.1
Floodplain bushes	Elaeagnus shrubs	1,338	*E. angustifolia* (5)	29.4	3.19 ± 3.59	0.0032	0.0937	2,005.5 4,011.0
Natural floodplain forest		13,027					3.752	48,874.9 97,749.9
	Willow poplar srf		*P. canescens* (1)	6.0	10.13 ± 10.72	0.0608	0.973	
			main tree species (incl. *S. alba* from Willow srf)				3.743	
	Willow srf		*P. canescens* (1)	5.0	12.28 ± 10.27	0.0614	0.982	
			S. alba (5)	23.4	7.40 ± 6.73	0.1732	2.771	
			F. pennsylvanica (1)	0.3	1.82 ± 2.08	0.0005	0.007	
			main tree species				3.760	
Natural floodplain forests with *A. glutinosa*	Alder rf	674	*A. glutinosa* (4)	55.7	3.44 ± 7.170	0.1916	3.066	2,066.4 4,132.8
Planted floodplain forests		10,306						44,359.7 88,719.3
	Planted Willow forests		*F. pennsylvanica* (2)	79.3	2.98 ± 3.90	0.2362	3.779	
			S. alba (2)	25.8	6.32 ± 4.27	0.1629	2.606	
	40% of area	4,122.5	main tree species				6.385	26,321.5 52,643.0
	Poplar plantations		*P. x canadensis* (3)	13.2	17.68 ± 15.86	0.2328	3.725	
			P. canescens (2)	24.8	5.33 ± 6.67	0.1318	2.109	
	60% of area	6,183.7	main tree species				2.917	18,038.2 36,076.3
Total		30,138.5						103,516.4 207,032.7

3.4 ABOVEGROUND WOOD BIOMASS (AGWB) AND CARBON STOCK OF THE RIPARIAN FORESTS IN THE DANUBE DELTA

AGWB was calculated and summarized for all forest types and with the area shares of the Danube Delta extrapolated to the whole delta area. This results in the total AGWB of about 4,99 million Mg in the Danube Delta with a corresponding carbon stock of about 2,49 million Mg in the forest areas of 30,139 ha size (**Table 4**).

Table 4: Aboveground wood biomass (AGWB) and carbon stock of the riparian forests in the Danube Delta (DD).

Forest type	Area (ha)	Area share of DD (%)	AGWB (Mg)	AGWB (Mg ha^{-1})	Carbon stock (Mg)	Carbon stock (Mg ha^{-1})
Natural dune forests	2,371.3	0.6	666,630.9	281.10	333,315.4	140.6
Planted dune forests	2,422.2	0.6	32,485.1	13.40	16,242.6	6.7
Floodplain bushes	1,337.8	0.3	20,014.6	15.00	10,007.3	7.5
Natural floodplain forests	13,027.1	3.2	1,977,341.8	151.80	988,670.9	75.9
Natural floodplain forests with *A. glutinosa*	674.1	0.2	155,493.2	230.70	77,746.6	115.3
Planted floodplain forests	10,306.1	2.6	2,147,914.3	208.40	1,073,957.1	104.2
Sum (mean values for Mg ha^{-1})	30,138.6	7.5	4,999,879.9	150.07	2,499,939.8	75.0

The AGWB per hectare in our study was highest in the natural dune forests, however the future viability of these forests depends on changing climate and hydrological conditions. While current observations still show rejuvenation of the main tree species, the impact of climate warming hamper the growing conditions for the seedlings. Helfrich (2019) has indicated a significant temperature increase and decreased precipitation in Sulina over recent decades. The trees must therefore adapt rapidly to these shifting climatic conditions (Hutschreuther, 2022). These findings agree with climate models by Gutiérrez et al. (2021) for Tulcea County, who predict beside rising temperatures and diminishing precipitation, also a higher frequency of short-term extreme weather events. Sušnik and Moderc (2021) further underscore the escalating challenge of intensified and more frequent droughts in the Danube region, particularly impacting the East and South of the Danube Delta. These droughts pose a significant threat to young trees with shallow root systems, unable to access lower groundwater tables while simultaneously high evaporation rates.

From the other riparian forest, alder forests with *A. glutinosa* store the highest amount with about 230.7 Mg ha^{-1} AGWB and 115.3 Mg ha^{-1} of carbon. *A. glutinosa* exhibits rapid juvenile growth, whereas height and diameter growth decrease relatively quickly with increasing age (Röhrig et al., 2020). However, it can reach ages between 100 to 120 years (Schweingruber, 1993) and can therefore store carbon for a considerable amount of time. Fernandes et al. (2020) estimated a slightly higher total carbon stock of 140 Mg ha^{-1} for trees of *A. glutinosa*-dominated forests. When integrating carbon stock estimates of trees, understory (shrubs, herbs and partly decomposed litter fall) and soils they estimated a total carbon stock of 162 Mg ha^{-1} (AGWB: 324 Mg ha^{-1}).

Cierjack et al. (2010) calculated a carbon stock of 163 ± 26 Mg C ha^{-1} for softwood riparian forests in the Austrian Danube floodplains. The differences might be explained by different species composition and forest structure in these forests, but also by the more continental climate regime in Romania compared to the more temperate floodplains in the West.

4 Conclusions and outlook

Wetlands vary in their carbon cycling, sequestration and emissions depending on vegetation type, water balance and climate (Brix et al., 2001). They often can be regarded as a source for GHG on a short time scale (decades), while acting as a sink for GHG if evaluated over longer time scales (>100 years; Brix et al., 2001; Kayranli et al., 2010). This leads to the conclusion that existing valuable wetlands should be sustainably and effectively protected and that restoration measures should be implemented comprehensively and fast to achieve an early increase in carbon storage capacity.

Despite their rather small cover in the Danube Delta (about 6% in total), the woody vegetation types are important for (long-term) carbon storage. Especially when combined with the high percentage of organic soils (which account for 27% of the total area; DDNI, 2020) they can play a major role in reducing CO_2 from the atmosphere in the future. Together with about 1.9 million Mg of carbon stored in the dry reed biomass of the Danube Delta (Becker et al., 2023a,b), the area is a highly valuable site in terms of carbon storage. The total annual carbon sequestration in the Danube Delta amounts to about 1.3 million Mg (more than 103,500 Mg for forests and 1.2 million Mg for reed beds; Becker et al., 2023a,b). This corresponds to 5.8% of the 22.7 million tons of carbon emitted annually through CO_2 emissions in Romania on 2.43% of the country's land area (Statista, 2023). Although these numbers are not fully comparable, they illustrate the importance of the floodplain vegetation of the Danube Delta in the carbon cycle. However, whether wetlands function as carbon sinks or sources depends on climate change and human activity. Higher temperatures in combination with drier conditions can lead to an increase in the decomposition of organic matter and therefore to an increase in carbon emissions (Cierjacks et al., 2010). These challenges are also predicted for the Danube Delta region (Sušnik and Moderc, 2021) and will especially affect the forests of the sand dune forests due to the sensitive processes of water supply. This emphasizes the importance to protect and restore hydrological connectivity and enable flooding of wetland areas. In conclusion, conservation and restoration of natural floodplain forests within the Danube Delta should be a focus in the future, not only in terms of their role as carbon sinks but also regarding the biodiversity and multiple ecosystem services they provide.

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