limits) the negative impacts of human activity. Nature-based solutions such as restoring a morphologically diverse river channel, reconnecting floodplains, or managing more sustainably areas adjacent to the water offer the opportunity to not only targeting a singular issue, (e.g. water quality), but also to look for solutions integrating several societal demands. Thus, these types of solutions aim at improving the ecological status of rivers and floodplains and at the same time enhancing services the ecosystem provides for human well-being. In this regard, the IDES Tool has shown in the pilot areas that the functional approach of ES assessment facilitates integrating the various interests in a multidimensional view. This enables stakeholders to better understand and appreciate the perception of others, and to jointly develop site-specific integrative concepts. Availability of a new, common assessment procedure, as it is the IDES Tool that takes almost all relevant ES into account, is favouring incorporating the ES concept into spatial and socio-economic planning and decision-making. The IDES approach harmonised between the Danube river basin countries will enable water managers and planers of different levels designing ES based, integrative and transparent decision-making processes. This will foster the application of the ES approach and result in multipurpose and sustainable solutions. At the local and regional levels, where water management projects are realised, the detailed assessment of ES based on the available local data may help to convince land users and land owners as well as all relevant stakeholders to apply measures in order to increase the ES availability in their floodplain territories. Chances for a successful implementation of restoration projects increase when stakeholders and their ideas and perceptions are integrated into the planning process. At the national or basin-wide level the assessment of ES and the multifunctionality of floodplains will serve more the conceptual and strategic planning, by identifying potentials and deficits and comparing scenarios. The IDES Tool may be effectively implemented to adapt river-floodplain systems that formerly had been modified to maximise one or a few societal benefits to the more sustainable and more diverse societal requests and legal requirements of the 21st century. For that purpose, we recommend here to implement the IDES Tool also at Danube-wide and national levels in addition to the positive experiences at local level.

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Aboveground biomass and carbon stock of the riparian vegetation in the Danube Delta

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Abstract

Intact wetlands can act as carbon sinks and mitigate increased amounts of greenhouse gases in the atmosphere following climate change. In addition to organic soils, the riparian vegetation plays an important role in carbon storage and cycling within wetlands.

In the context of the project 'EDAPHIC-BLOOM Danube', the riparian vegetation in the Danube Delta was investigated. Preliminary results show differences in aboveground biomass and carbon content between softwood and hardwood riparian forests and artificial poplar plantations. The aboveground biomass in the reed beds is much lower per plot, but due to their huge extension, they are very important for carbon storage.

Introduction

In terms of climate change, the mitigation of greenhouse gas (GHG) emissions is very important. Hereby, carbon dioxide is considered the most important GHG among anthropogenic emissions. Ecologically intact wetlands and floodplains can act as carbon sinks and mitigate increased amounts of carbon dioxide in the atmosphere following climate change (Cierjacks et al. 2010). In addition to the organic soils (Wilson et al. 2016) for example in reed beds, floodplain forests play an important role in the carbon storage within wetlands.

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. In the project, actions for GHG mitigation as well as dialogues with authorities and stakeholders in the Lower Danube region in Romania are developed. The project with Romanian and German partners is part of the European Climate Initiative (EUKI) of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). It is managed by the Danube Delta National Institute for Research and Development (DDNI) in Romania. One aspect addressed in the project is the carbon storage capacity of floodplain vegetation.

The Danube Delta

The Danube originates in southern Germany and crosses ten countries on its way in a predominantly south-eastern direction. After about 2,850 km it flows into the Black Sea in Romania where its average discharge is about 6,500 m^3/s. Its catchment has a size of 817,000 km^2 (Jungwirth et al. 2014).

Close to the river mouth, the Danube divides into three branches (Chilia, Sulina, and Sf. Gheorghe branch) that encompass the area of the Danube Delta (Kahl 2018). The total area of the Biosphere Reserve 'Danube Delta' is about 5800 km^2 in Romania and 46 km^2 in Ukraine (Hanganu et al. 2002). The area is characterized by a dry continental climate. Summers are very hot with maximum temperatures up to 40 °C, while winters are very cold, even up to minus 25 °C. The annual mean temperature in Sulina City close to the Black Sea is 11 °C. The month with the highest precipitation is June, while February and March have the lowest values. The annual mean precipitation in Sulina City is 350 mm (Kahl 2018).

The complex interplay between various morphodynamic processes of fluvial and marine origin led and still leads to continuously evolving landscapes in the delta. It contains a mosaic of different habitats such as channels, lakes, reed beds, dune fields, and lagoons (Niculescu et al. 2015). The aquatic and marshy vegetation make up most of the Danube Delta. The reed beds cover about 44% and are mostly dominated by the Common Reed *(Phragmites australis)*. This species has a wide ecological amplitude and builds reed beds in the Danube Delta ranging from floating peat islands ('plaur') to almost permanently shallow inundated areas without a frequent supply of fresh river water to areas with high Danube water circulation and high siltation rates. The other two dominant species of the marshy areas are Reedmace (mostly the Lesser Reedmace, *Typha angustifolia)* which grows especially in the fluvial delta areas with high siltation. The marine part of the delta is dominated by Sedge marshes (*Carex* spp.; Hanganu et al. 2002).

Floodplain forests cover about 6% of the Danube Delta. The larger part (about 5%) is covered by softwood floodplain forests that occur on the natural riverine levees and artificial dikes alongside the main Danube branches and smaller channels (*fig. 1*). The most important softwood forest types are White Willow *(Salix alba)* floodplain forest, Common Alder *(Alnus glutinosa)* floodplain forest and artificial Poplar plantation. Between the fluvial and the fluvial-maritime part of the Danube Delta on the former seashore area, sand dune areas developed due to an interplay of fluvial and aeolian processes. In the two areas of Letea and Caraorman, hardwood floodplain forests on the sand dunes cover about 1% of the delta area (Hanganu et al. 2002; Gâştescu 2009). The dominant species of these sand dune forests are *Quercus pedunculiflora, Fraxinus angustifolia,* and *Fraxinus pallisiae.* The woody vegetation types also comprise small stripes of shrub vegetation along the seashore, for example with *Elaeagnus angustifolia, Tamarix ramosissima,* and *Hippophae rhamnoides* (Hanganu et al. 2002).

Figure 1. A typical sequence of a channel with an associated gallery forest on the higher riverine levees and adjacent reed beds in wide areas with lower elevations (picture: G. Egger).

Methods

In three field campaigns in 2021 and 2022, we collected vegetation data in plots that were distributed over the Romanian part of the Danube Delta (*fig. 2*). In addition, samples of organic soils were taken in the plot surroundings to analyse soil organic carbon and related parameters (Nichersu et al. 2022).

For the floodplain forests and shrub vegetation, tree and bush individuals were measured in nested plots. In the 25 on 25 m plots, all tree and shrub individuals with a diameter at breast height (DBH) above 10 cm were recorded with the species, individual height, and DBH. In three smaller nested plots with 5 on 5 m size, this information was gathered for all woody species with a DBH of 1 to 10 cm. Additionally, tree core samples were taken from the main tree species to perform a year-to-year growth analysis. Besides, vegetation and habitat parameters such as vegetation type, vegetation cover in different layers, grain size, and estimates on flooding and morphodynamics were recorded. In total, woody species in 36 plots were measured. Using the field data, the aboveground woody biomass (AGWB) of the trees and shrubs was calculated using the species-specific allometric formula of Cannell (1984). The carbon content was estimated using 50% of the AGWB (Clark et al. 2001; Malhi et al. 2004).

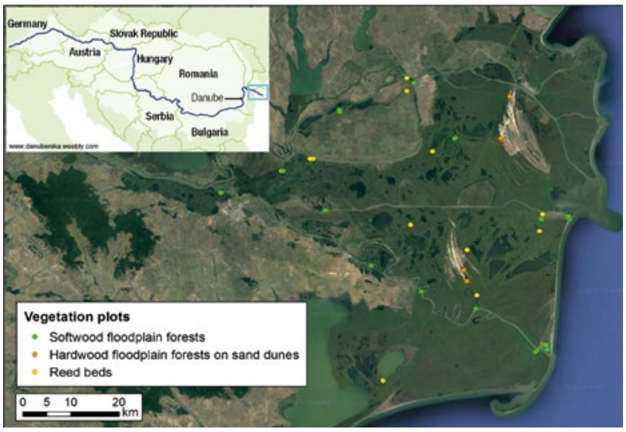

Figure 2. Plots for the different main vegetation types in the Danube Delta (picture: G. Egger).

The reed beds were sampled using a plot design at the end of the vegetation period (September and October 2021). Again, general vegetation and habitat parameters such as vegetation type, grain size, and inundation in plots of 5 on 5 m size were recorded. In total, 28 plots in different reed vegetation types were documented. In each plot, the aboveground reed biomass together with the litter was harvested on 0.5 on 0.5 m, weighed and 10% of the homogenised sample was dried and the dry weight was determined. To measure the carbon content, the dried samples were ground and the carbon and nitrogen determined using a Euro EA Element Analyzer. As no Carex-dominated plots were measured, they were assumed to be one third of the reed biomass. The field and laboratory results were used together with a vegetation map of the Danube Delta (Hanganu et al. 2002) to upscale the findings on the whole delta area.

Results

The main tree species recorded in the floodplain forests were *Quercus robur, Quercus pedunculiflora, Fraxinus angustifolia, Fraxinus pallisiae, Populus canescens, Populus x canadensis, Salix alba,* and *Alnus glutinosa.*

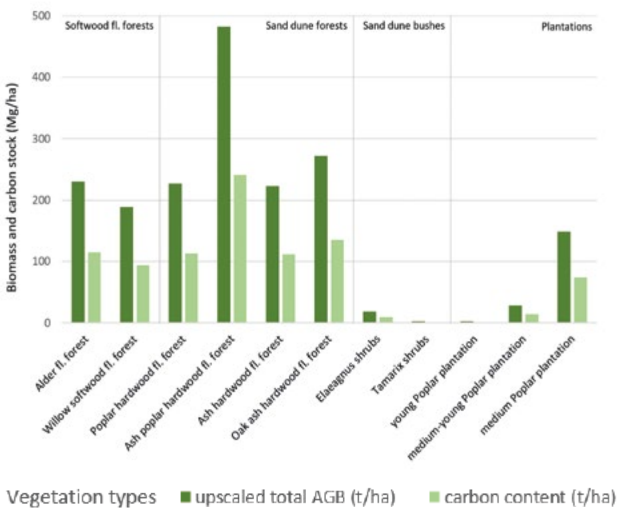

Figure 3. Aboveground woody biomass and carbon stock (in Mg/ha) of the different woody vegetation types in the Danube Delta.

For the softwood floodplain forests, the *Alnus glutinosa* dominated type had the highest aboveground wood biomass (AGWB; usually given in megagrams (Mg) which is equivalent to tonnes (t)) with an average of 230.2 Mg/ha and a corresponding carbon stock of 115.1 Mg/ha (*fig. 3*). The seven willow dominated plots had an average AGWB of 188.9 Mg/ha, but with a large variation between plots.

For the hardwood floodplain forests in the sand dune areas, the ash-poplar-dominated plots had the highest AGWB with 481.9 Mg/ha and a corresponding carbon stock of 241.0 Mg/ha. The other sand dune forests had similar AGWB values ranging from 223.3 Mg/ha for ash-dominated forests, to 227.3 Mg/ha for poplar-dominated forests followed by 271.7 Mg/ha for oak-ash-dominated forests.

Regarding the artificial poplar plantation, the AGWB and carbon stock is highly dependent on the plants' age. The values range from 3.0 Mg/ha for about 5-year-old poplars to 149.0 Mg/ha for poplars of 20 to 35 years.

In the shrub vegetation close to the Black Sea the AGWB is about 18.6 Mg/ha for *Elaeagnus angustifolia*-dominated sites and about 2.8 Mg/ha for *Tamarix ramosissima* shrubs.

The *Phragmites australis*-dominated reed beds had a maximum of 115 kg dry aboveground reed biomass in one plot (5 on 5 m). In general, the medium dry biomass was 18.3 Mg/ha, 23.1 Mg/ha on salinised soils, and 24.8 Mg/ha in plots on plaur (peat; *tab. 1*). The medium carbon content of the *Phragmites australis* aboveground biomass was 43.2% and 0.8% of nitrogen. When combining these results with the area of each *Phragmites australis*-reed type the resulting dry biomass is 4.2 million Mg and the carbon stock is more than 1.8 million Mg in the whole Danube Delta.

The other two reed bed species had a smaller aboveground biomass with 15.6 Mg/ha for Reedmace and 5.5 Mg/ha for Sedge vegetation. The laboratory analysis revealed for Reedmace a medium aboveground carbon content of 43.3% and nitrogen of 0.5% and for Sedge a medium aboveground carbon content of 41.9% and nitrogen of 0.9%. This results for Reedmace in a total aboveground biomass of more than 215,000 Mg with more than 93,000 Mg of carbon in the Danube Delta. For the sedge vegetation, the aboveground biomass is more than 96,000 Mg and more than 40,000 Mg of carbon in the Danube Delta.

Discussion and conclusions

The forest vegetation of the Danube Delta has different roles in carbon sequestration and storage. The sand dune forests store quite high amounts of carbon in their biomass. Besides, oaks are rather long-living trees and as many old and tall individuals of *Quercus pedunculiflora* were recorded it can be said that they are important for long-term carbon sequestration (Hutschreuther 2022). In the softwood forests,

Reed type	Dry biomass (Mg/ha)	Area (ha)	Dry biomass in Danube Delta (Mg)	C stock (Mg)	N stock (Mg)	Carbon stock (Mg/ha)
Common Reed vegetation *(Phragmites australis)*	18.3	83,523	1,527 841	660,027	12,222	7.9
Common Reed vegetation on plaur	24.8	82,268	2,041 114	881,761	16,329	10.7
Common Reed vegetation on salinised soils	23.1	27,394	633,895	273,843	5,071	10.0
Sum Common Reed reed beds	22.1	193,185	4,202 850	1,815 631	33,623	9.4
Reedmace vegetation (*Typha* spp.)	15.6	13,819	215,417	93,275	1,077	6.7
Sedges vegetation (*Carex* spp.)	5.5	17,603	96,602	40,476	869	2.3
Sum reed beds	18.2	417,792	4,514 869	1,949 383	35,569	4.7

Table 1. Biomass (aboveground dry biomass) and carbon stock of the different reed bed vegetation types in the Danube Delta.

Populus canescens and *Salix alba* are important regarding the short-term storage of carbon since they sequester relatively large amounts of carbon within a relatively short period while *Fraxinus pennsylvanica* allows for more long-term carbon storage. *Alnus glutinosa* occupies an intermediate position (Mildt 2022).

The riparian vegetation of the Danube Delta will probably undergo some changes related to human impact and climate change. Trees dieback was observed especially for the sand dune forest over the last years. This vegetation type is highly dependent on the groundwater supply. The effects of climate change are increasingly exposing these forests growing on the dune formations to the two stressors of drought and artificial channel digging. Besides, the sand dune forests are grazed by feral horses (Posthoorn & Tudor 1999). This may affect the build-up of AGWB and carbon sequestration in the coming years. In the field, the rejuvenation of the main tree species could be observed. But the management and water supply will determine the future development.

One possibility to increase future carbon storage in the Danube Delta would be to restore drained areas that are now used for agriculture. Since carbon sequestration in soils is seen as a main means of reducing GHG emissions to the atmosphere and especially the management of agricultural soils has a huge impact on the carbon storage in the soils, adapted management or restoration measures could enhance the GHG mitigation (Nichersu et al. 2022). In addition, the preservation of the existing forests or reforestation of natural floodplain forests is important to store carbon over a long time span. Besides, since the reed beds store also considerable amounts of carbon and are important for the peat formation in wet sites and the preservation of the organic soils they should be preserved.

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