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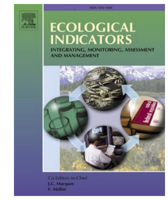

Topographical factors related to flooding frequency promote ecosystem multifunctionality of riparian floodplains

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ABSTRACT

Various ecosystem functions provided by floodplains depend on a natural river activity and floodplain morphology. Therefore, anthropogenic alterations of rivers modify their flooding regimes and may affect the provisioning of numerous ecosystem functions. Restoration projects, which aim at reestablishing natural processes of floodplains, require a better understanding of the ecosystem's ability to simultaneously provide multiple functions (multifunctionality) and how this relates to the environmental template.

Here we investigate the relationship between environmental drivers and ecosystem multifunctionality. We focus on 24 ecosystem functions, representing five ecosystem services provided by floodplains of the Mulde River: plant productivity, biodiversity provisioning, retention of sediments, nutrients and pollutants. These functions were measured on 74 plots located on three well preserved floodplain sites of the Mulde River. We described synergies and trade-offs between single functions using correlations and calculated quantitative measures of ecosystem multifunctionality, quantified as the number of functions provided above either 50% of maximal functioning, or 75% of maximal functioning. We then explored relations of multifunctionality with two environmental factors, which also affect the probability of flooding i.e., the hydrological distance and the distance to the water table.

Although numerous functions related to sedimentation processes were positively correlated to each other, they traded off with functions related to biodiversity provisioning. This advocates the application of a holistic measure of ecosystem functioning. Multifunctionality indices decreased with an increase of both distance to the water table and hydrological distance, with effects of the distance to the water table being most strongly negative. These findings imply that ecosystem multifunctionality is highest at sites which are flooded regularly. We conclude that restoration attempts which shorten hydrological distance and distance to the water table, like removal of artificial embankments or reconstruction of side channels, may have a positive effect not only on single functions, but also on overall ecosystem multifunctionality. We also advocate the application of a multifunctionality measure to facilitate management and restoration of floodplains.

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1. . Introduction

Riparian floodplains harbor a high biodiversity (Shiel et al., 1998; Ward et al., 1999) and provide an exceptionally broad range of ecosystem functions and services (Tockner and Stanford, 2002). For instance, they play a vital role in water purification (de Sosa et al., 2018), sediment and nutrient retention (Brunet et al., 1994; Venterink et al., 2006), as well as in habitat provisioning (Tockner and Stanford, 2002; Tomscha et al., 2017; Hanna et al., 2018). Despite their undeniable importance, floodplains are among the world's most threatened ecosystems (Tockner and Stanford, 2002).

The ability of floodplains to provide multiple ecosystem functions (González et al., 2017) is underpinned by a mosaic of environmental conditions, such as floods and groundwater fluxes, which are themselves shaped by floodplain topography *i.e.* elevation, distance to the river or terrain roughness (Doble et al., 2006; Thonon et al., 2007) and by the presence of secondary channels and hollows (Jung et al., 2004; Acreman and Holden, 2013). Anthropogenic structures like dikes, artificial embankments or run-off-river hydropower plants affect both the river channel and floodplain topography, reduce the frequency and intensity of floods and prolong low water periods (Nilsson and Berggren, 2000; Petts and Gurnell, 2005; Gumiero et al., 2012; Kuriqi et al., 2020; Kuriqi et al., 2021). Consequently, alterations of hydro-geomorphological conditions simultaneously threaten numerous functions provided by floodplains (Poff and Zimmerman, 2010; Leigh et al., 2012). For instance, reduced frequency and amplitude of flood events can decrease primary production (Robertson et al., 2001), affect nutrient cycling (Baldwin and Mitchell, 2000; Schönbrunner et al., 2012) and facilitate invasions of exotic species (Bren, 1992; Catford et al., 2011; Catford et al., 2014). Despite this, it remains unclear whether and to what extend topographical drivers which facilitate water relations on floodplains can affect the simultaneous provisioning of multiple ecosystem functions by floodplains *i.e.* ecosystem multifunctionality (Kremen and Ostfeld, 2005; de Sosa et al., 2018).

Approaches quantifying and mapping the provisioning of multiple functions by floodplain systems can provide valuable information for riparian restoration and conservation projects which aim at reestablishing natural ecosystem processes (Gilvear et al., 2013; Funk et al., 2019; Funk et al., 2021). They can be used to prioritize areas for conservation (Gilvear et al., 2013; Funk et al., 2019; Gilby et al., 2020), establish a reference point for restoration (Harris, 1999), or to assess efficiency of restoration measures (Bunn and Arthington, 2002; Schindler et al., 2014). Furthermore, the need for a joint restoration of various ecosystem functions and services is increasingly recognized by policy makers and addressed in legal guidelines, such as the environmental and water policy in Europe (European Union, 2000; European Union, 2007; European Commission, 2011).

Even so, attempts to simultaneously increase provisioning of multiple functions may prove challenging, especially if the target functions differ in their responses to environmental drivers (Bunn and Arthington, 2002; Bennett et al., 2009), or trade off with each other (Cord et al., 2017; Chen et al., 2021). While synergies between functions imply a mutual improvement of multiple functions in response to management, and are generally desired, trade-offs (negative correlations) pose a challenge for landscape management (Howe et al., 2014; Cord et al., 2017). For instance, riverine conservation often trades-off with production of food or hydropower (Kuriqi et al., 2020; Liang et al., 2021). The presence of trade-offs requires choices between alternative ecosystem functions, which cannot be increased simultaneously (Turkelboom et al., 2015; Deng et al., 2016). Although management and restoration of riparian areas requires a holistic perspective of ecosystem functioning, our understanding of relations between ecosystem functions and of mechanisms underpinning their provisioning is still limited (Bennett et al., 2009; Landuyt et al., 2016; Dade et al., 2018). Similarly, relations between drivers and functions are rarely reported by studies assessing relationships between ecosystem services (Dade et al., 2018). The most straightforward way of exploring floodplain multifunctionality is a spatial assessment of the provided functions (Holland et al., 2011; Tomscha et al., 2017; Salata and Grillenzoni 2021). It allows to capture patterns on a scale usable by humans and highlights areas suitable for conservation. This is often done by investigating the spatial drivers of each function separately (Felipe-Lucia and Comín, 2015; Funk et al., 2019; Demeter et al., 2021). However, analysing each function separately makes it difficult to identify overall levels of ecosystem services (Bradford et al., 2014), especially if some ecosystem functions trade-off (Byrnes et al., 2014). Consequently it may hinder interpretation and communication of mechanisms driving ecosystem multifunctionality (Manning et al., 2018) and lead to implementation ofineffective and environmentally or financially costly policy and management (Kremen and Ostfeld, 2005; Spake et al., 2017). Measures of ecosystem multifunctionality overcome these limitations, as they make it explicit how different functions contribute to an overall measure of ecosystem multifunctionality. Such methods can also help to find potential conflicts caused by e.g., restoration efforts, and help to balance opposing objectives (Kuriqi et al., 2020).

In this study we apply The Ecosystem Multifunctionality Threshold Index (EMTI) to estimate multifunctionality of riparian floodplains, a system of high potential multifunctionality and high demands of restoration and management. The applied index provides a quantitative estimation of the ecosystem multifunctionality, allows to explore relations between environmental drivers and different levels of multifunctionality (Byrnes et al., 2014) and can be extrapolated on a landscape scale (Van der Plas et al., 2018). This aggregative measure provides a simple way to summarize overall ecosystem functioning and visualize trade-offs (Allan et al., 2015; Manning et al., 2018). Here we adapted this tool to describe the complex relationship between floodplain topography and its multifunctionality. Our objective was to investigate how floodplain multifunctionality responds to two main topographical drivers of natural water level variation *i.e.* the distance to the water table (vertical) and hydrological distance to the river (horizontal). To our knowledge, despite the growing need to address floodplain multifunctionality and its drivers, this approach was previously not used in such a context. A mechanistic understanding will help to describe the effect of restoration of the natural floodplain topography, by removal of artificial embankment or reconnecting side-channels (Addy and Wilkinson, 2021) on floodplain multifunctionality. As a study system, we use the floodplains of the Mulde River and a set of ecosystem functions that is considered important from a restoration perspective (Schulz-Zunkel et al., 2017). We focus on 24 ecosystem functions, which we assigned to five categories: retention of sediments, retention of nutrients, retention of pollutants, biodiversity provisioning and plant productivity. We used these functions to calculate two ecosystem multifunctionality measures that differ in the thresholds at which ecosystem functions need to be provided to contribute to ecosystem multifunctionality. We hypothesized that ecosystem multifunctionality will decrease with an increase of both distance to the water table and hydrological distance, as this reduces the likelihood of flood events that are crucial for floodplain functioning.

2. . Materials and methods

2.1. Study area

Our study was conducted on floodplains of the Mulde River - a tributary of the Elbe River in Germany (Fig. 1). Its catchment, covering approximately 7600 km^2, includes to a large part a mining district of the Ore Mountains/Erzgebirge in the southern part of East Germany. Extraction and processing of various metals and minerals occurred along the river since the 13th century (Müller et al., 2000; Klemm et al., 2005; Overesch et al., 2007). Although the industrial plants have been closed, their wastelands and sewage discharge facilities remain until today and increase the loads of inorganic pollutants in the Mulde River (Kowalik

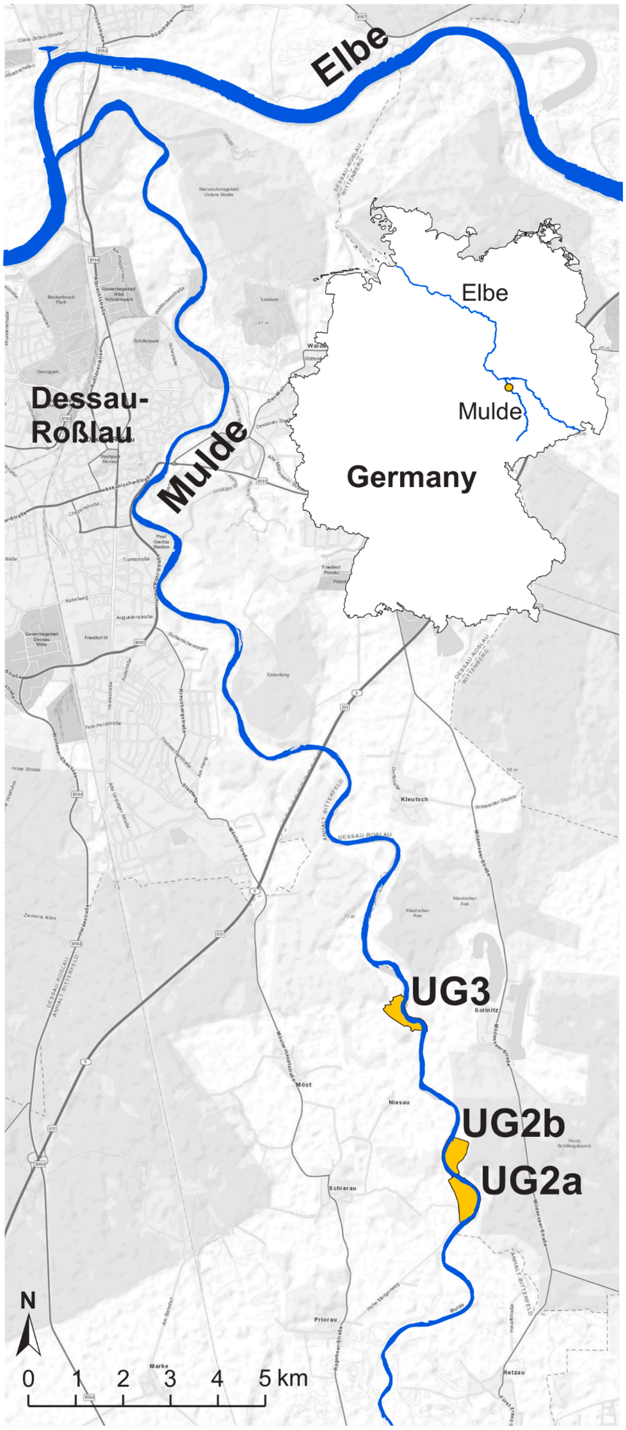

Fig. 1. Location of the three study sites: UG2a, UG2b, UG3 on the banks of the Mulde River, situated in Central Germany. Names of the plots are consistent with the project Wilde Mulde—Revitalization of a wild river landscape in Central Germany (https://bexis.ufz.de:4434/, Note S1).

et al., 2003; Klemm et al., 2005) and consequently the catchment of the Elbe River (Overesch et al., 2007; Schulz-Zunkel and Krueger, 2009).

Large parts of the river course with their floodplain areas were designated as nature reserve “Lower Mulde/Untere Mulde” (1961) or as landscape conservation area (1957) and integrated into the extended UNSECO (United Nations Educational, Scientific and Cultural Organisation) Biosphere Reserve “Middle Elbe/Mittlere Elbe” after 1990 (Jurgeit et al., 1997; Funkel et al., 2003). Additionally, the lower Mulde River is protected as the SAC/FFH (Special Area of Conservation/Fauna-Flora-Habitat) area “Lower Mulde floodplain/Untere Muldeaue” (DE4239302) and contains a large number of habitat types protected according to Annex 1 of the Fauna-Flora-Habitat Directive/Fauna-Flora-Habitat Richtlinie (FFH-D/FFH-RL; European Commission, 1992). Despite the relatively natural character of the Mulde River floodplains, their hydromorphological dynamics are altered along large sections mostly by bank stabilization constructions (Puhlmann and Rast, 1997). These areas are currently undergoing restoration in the framework of the project Wilde Mulde—Revitalization of a wild river landscape in Central Germany (Schulz-Zunkel et al., 2017). This project aims at restoring numerous processes and functions of the ecosystem. This justifies the need of applying an aggregative multifunctionality metric which summarizes the levels of multiple ecosystem functions. Because of the historical background of the Mulde River, some of the ecosystem services, like sediment or pollutant retention are of special interest. Although water-related ecosystem services are an important part of river functioning (e.g., Liang et al., 2021), in other river systems other functions and services may be emphasized (e.g., Perosa et al., 2021). Therefore, although the EMTI can be applied in various settings, direct comparison of multifunctionality measures across studies should be undertaken with caution (Garland et al., 2021).

We selected three study sites, located in the active floodplains of the lower Mulde River (Fig. 1; Table S1). On these sites we established 74 plots, where in 2017 we carried out inventories of all vascular plants and sampled vegetation biomass and sediments (see Note S2 for sampling and data preparation details). Sampling took place after a spring flood, which occurred in the same year. Water level variations and discharge similar to the ones observed in 2017 were regularly recorded in the lower Mulde River (Fig. S1). The collected data was then used to specify ecosystem functions provided by the floodplains in the lower reach of the Mulde River.

2.2. *Ecosystem functions*

Considering the historical and environmental background of the Mulde River floodplains described above, we used 24 ecosystem functions, which are related to five ecosystem services: retention of sediments, retention of nutrients, retention of pollutants, biodiversity provisioning and plant productivity (Table 1, Note S2). These services are considered as indicators of restoration success by the restoration project Wilde Mulde—Revitalization of a wild river landscape in Central Germany: Wilde Mulde (Schulz-Zunkel et al., 2017).

Sedimentation mechanisms, as well as properties and quality of sediments such as grain size or chemical composition, differ for sediment deposition on the soil surface and on the vegetation (Kretz et al., 2020; Kretz et al., 2021a, Kretz et al., 2021b, Kretz et al., 2021c). Consequently, we distinguished between sedimentation on these two surfaces when defining all functions related to sedimentation (Table 1). For instance, sediment retention was represented by two functions: amount of sediments deposited on sediment traps underneath the vegetation (a standardized floodplain surface) and on the vegetation itself (Table 1).

Nutrient retention on floodplains is driven primarily by sedimentation mechanisms (Venterink et al., 2003; Venterink et al., 2006). However, it is also affected by the accumulation of nutrients in the tissue of the riparian vegetation (Kiedrzyńska et al., 2008). Therefore, we characterized nutrient retention using the amounts of nitrogen and phosphorus present in sediments captured on sediment traps and on vegetation, as well as their content in plant biomass (Table 1; Note S2).

Inorganic pollution caused by the metal extraction industry is especially relevant in the context of the Mulde River. Accordingly, to represent pollutant retention, we focused on historically important metals, in particular mercury (Hg), lead (Pb) and arsenic (As; Schulz-Zunkel and Krueger, 2009) as well as metals, whose hydrous oxides control retention of other trace metals in soil, for example iron (Fe) and aluminum (Al; Rate et al., 2000; Trivedi and Axe, 2000). Amounts of

Table 1
Functions used to calculate multifunctionality indices, along with the ecosystem service they contribute to and a weight used to equalize the importance of each ecosystem service. All abbreviations are explained in the Note S1. Details on the ecosystem functions are available in the Note S2.

No.	Ecosystem function	Unit	Definition	Ecosystem service	Weight
1	Amount of sediments on vegetation	g/m^2	Sediments deposited on vegetation	Sediment retention	15
2	Amount of sediments on traps	g/m^2	Sediments deposited on traps	Sediment retention	15
3	Nitrogen in sediments on vegetation	g/m^2	Nitrogen in sediments on vegetation	Nutrient retention	5
4	Nitrogen in sediments on traps	g/m^2	Nitrogen in sediments on traps	Nutrient retention	5
5	Phosphorus in sediments on vegetation	g/m^2	Phosphate in sediments on vegetation	Nutrient retention	5
6	Phosphorus in sediments on traps	g/m^2	Phosphate in sediments on traps	Nutrient retention	5
7	Nitrogen in biomass	mg/g	Nitrogen in mg per kg biomass	Nutrient retention	5
8	Phosphorus in biomass	mg/g	Phosphate in mg per kg biomass	Nutrient retention	5
9	Hg in sediments on vegetation	mg/kg	Mercury in sediments on vegetation	Pollutant retention	3
10	Al in sediments on vegetation	mg/kg	Aluminum in sediments on vegetation	Pollutant retention	3
11	Fe in sediments on vegetation	mg/kg	Iron in sediments on vegetation	Pollutant retention	3
12	Pb in sediments on vegetation	mg/kg	Led in sediments on vegetation	Pollutant retention	3
13	As in sediments on vegetation	mg/kg	Arsenic in sediments on vegetation	Pollutant retention	3
14	Hg in sediments on traps	mg/kg	Mercury in sediments on traps	Pollutant retention	3
15	Al in sediments on traps	mg/kg	Aluminum in sediments on traps	Pollutant retention	3
16	Fe in sediments on traps	mg/kg	Iron in sediments on traps	Pollutant retention	3
17	Pb in sediments on traps	mg/kg	Lead in sediments on traps	Pollutant retention	3
18	As in sediments on traps	mg/kg	Arsenic in sediments on traps	Pollutant retention	3
19	Plant biomass	g	Dry weight of biomass collected on plots	Productivity	30
20	Species richness	–	Number of plant species on plots	Biodiversity	6
21	Abundance of neophytes	% cover	Species origin based on Biolflor (Kühn et al., 2004)	Biodiversity	6
22	Abundance of species endangered in Germany	% cover	Based on Red List Germany (Ludwig et al. 1996)	Biodiversity	6
23	Abundance of species endangered in Saxony-Anhalt	% cover	Based on Red List Sachsen-Anhalt (Frank et al. 1992)	Biodiversity	6
24	Abundance of species related to rivers	% cover	based on species connection to the river (Siedentopf 2005)	Biodiversity	6

accumulated metals were measured both in sediments deposited on sediment traps and on vegetation (Table; Note S2). Metals can be stored in floodplains for hundreds of years (Meade, 1982; ;(James, 1989) Miller, 1997) reducing or even ceasing their release into the river basin (Martin 2000). However, geomorphic activity *e.g.* high frequency of high and low flows may favor remobilization of stored metals (Martin, 2000). In this study, we consider storing pollutants on the floodplain as an ecosystem function, as it decreases the high level of inorganic pollutants in the catchment of the river Elbe (Förstner et al., 1990; Schulz-Zunkel and Krueger, 2009).

Riparian areas provide habitats for numerous species (Shiel et al., 1998; Ward et al., 1999) many of which are highly specialized and do not occur in other areas (Sabo et al., 2005). This ecosystem service is especially important from the perspective of nature conservation (Jurgeit et al., 1997; Funkel et al., 2003). In our study is represented by five functions: plant species richness, abundance of plant species endangered in Germany (Ludwig et al., 1996) and in Saxony-Anhalt (Frank et al., 1992), abundance of plant species characteristic for riparian corridors *sensu* Siedentopf (2005), as well as abundance of recently introduced alien plant species (neophytes; Table 1; Note S2). The latter function is considered a negative indicator of ecosystem functioning and consequently we included it in the analysis with a reversed value.

Plant productivity was based on a single ecosystem function *i.e.* plant biomass (Table 1; Note S2).

All the variables were collected in 2017 on 74 plots located on the 3 study sites in the active floodplain of the Mulde River, or in some cases imputed with the MICE algorithm (Van Buuren and Oudshoorn, 1999). The detailed description of methods used to sample and estimate all of the variables used in this study can be found in the appendix (Note S2; Fig. S2).

2.3. Multifunctionality indices

We estimated multifunctionality based on the above described functions for each of the study plots using the Ecosystem Multifunctionality Threshold Index (EMTI). The EMTI is defined as the number of functions, which exceed an *a priori* chosen threshold value. For each ecosystem function, the threshold is defined as a percentage fraction of the ‘maximum’ observed function across all plots (Byrnes et al., 2014). To avoid effects of outliers (Zavaleta et al., 2010), this ‘maximum’ was estimated as 95% of the maximal observed function value. We then calculated multifunctionality indices based on thresholds of 50% and 75%, which reflects counts of the number of functions exceeding the respective thresholds. For example, if the highest observed plant biomass value across all plots was 1000 g m^{-2} then plant biomass contributed 1 unit to the 50% multifunctionality index, if the biomass exceeded 50% x 0.95 × 1000 g m^{-2} = 475 g m^{-2}. Similarly, it contributes 1 unit to the 75% multifunctionality index in plots, if plant biomass exceeds 75% x 0.95 × 1000 g m^{-2} = 712,5 g m^{-2}.

Both indices were calculated using all 24 functions, grouped in five ecosystem services, as described above. The number of functions differed within the ecosystem services, leading to a potential over-representation of categories with more functions (Table 1). To correct for this, we calculated weighted threshold indices, where we applied a weighting of the functions within each of the categories. This way, each functions’ contribution to ecosystem multifunctionality (if the threshold level was exceeded) was W, where W = 1/N and N is the number of functions representing a given ecosystem service. As a result, each ecosystem service was equally important.

2.4. Topographical variables

We used two topographical variables, the distance to the water table (W_distance) and the hydrological distance to the river (H_distance), as predictor values in our analysis. The distance to the water table was measured as the vertical difference between the elevation of a given plot and the annual mean elevation of the groundwater (Note S2). Hydrological distance was the horizontal length of the surface flow path, between each plot and the river (Fig. S3). Hydrological distance was defined as the length of the surface flow path the water needs to reach the stream, and was derived from a stream network, calculated using the flow accumulation approach on the digital elevation model (DEM) of the floodplain area (Schwanghart and Scherler, 2014). To inspect the role of these variables for the hydrological regime, we used them as predictors of the presence of the flood in 2017, the annual standard deviation of the groundwater level and the duration of the flood in 2017 (Table 2).

2.5. Statistical analysis

In the first step of the analysis, we investigated relations between single functions to identify potential synergies and trade-offs among them. As the functions used in our study were measured on different scales, were often not normally distributed and relations between them were not always linear, we used Spearman's rank coefficient (ρ). This method is commonly used for testing association between two continuous variables, when the assumption that the underlying distribution is bivariate normal is violated. In absence of ties in the data, Spearman's rank coefficient turns values are closer to the desired coverage rates than Kendall rank correlation coefficient (Puth et al., 2015).

To test the effects of topographical drivers on ecosystem multifunctionality, for each of the EMTIs we fitted a generalized linear mixed effect model (GLMM) with distance to the water table, hydrological distance and their interaction as fixed terms and site identity as a random term. We selected GLMM instead of other approaches, like generalized estimating equations (GEE) and generalized additive mixed effect models (GAMM) because of its flexibility and because of a straightforward interpretation of the model predictions (Pekár and Brabec, 2018), which may facilitate its application. All variables and interactions used in the models had a strong support (ΔAIC2 ≤ 2; Anderson and Burnham, 2004), therefore we did not remove them from the model. To avoid problems with model convergence, we Z-transformed each of the fixed terms. The model diagnostics indicated that a Poisson error distribution, with a log-link between response and explanatory variables was best suited to our count data. We used the fitted models to predict and map values of multifunctionality on the three study sites.

To find out how the effects of topographical variables that we related to ecosystem multifunctionality might be mediated by effects of flood properties, we explored relations between distance to the water table and hydrological distance with inundation occurrence and duration of the study sites during a spring flood in 2017, as well as with annual groundwater fluctuation, represented by standard deviation of the groundwater levels, measured in 2017. The duration of the flood was measured only on 24 plots, where the flood occurred in 2017. Due to data deficiency, the groundwater standard deviation was calculated only on sites UG2a and UG2b. To test the effects of topographical drivers on the duration of flood and groundwater fluctuations, we used linear mixed effect models, while presence of a flood was analyzed with a generalized linear mixed effect model with a binomial error distribution and a logit link. In case of flooding duration, we additionally applied a parametric power transformation (Sakia, 1992) to satisfy the assumption of a homogeneity of residual variances.

All analyses were conducted in R (R Core Team, 2019). The hydrological distance was calculated with MATLAB 2016 (Mathworks, 2016).

3. . Results

3.1. Relations between single functions

The analysis of correlation patterns between ecosystem functions revealed strong correlations between functions representing pollutant retention, nutrient retention and sediment retention (Fig. 2; Table S2). The strongest correlations occurred between the different functions representing pollutants retention (0.91 ≤ ρ ≤ 0.99; Fig. 2; Table S2). In contrast, the weakest correlation among these functions was exhibited by amounts of nitrogen and phosphorus in plant biomass (0.06 ≤ ρ ≤ 0.28; Fig. 2; Table S2).

Ecosystem functions representing biodiversity provisioning were also correlated with each other with an exception of the abundances of neophytes and species endangered in Germany (−0.05 ≤ ρ ≤ 0.82; Fig. 2; Table S2). Abundance of species endangered in Germany and the abundance of species endangered in Saxony-Anhalt, as well as the abundance of riparian species traded-off with indicators of all other functions with an exception of plant biomass (−0.44 ≤ ρ ≤ 0.08; Fig. 2; Table S2).

Plant biomass, the only function representing plant productivity, was the one function least associated with other functions in this study (-0.177 ≤ ρ ≤ 0.077; all $p > 0.05$; Fig. 2; Table S2).

3.2. Relations between drivers and flooding parameters

Distance to the water table had a negative effect on presence of the flood event as well as on flooding duration, although it weakly increased the groundwater annual standard deviation (Table 2). The hydrological distance also had a negative, but weaker, effect on the presence of a flood event (Table 2), while it had no significant effect on the duration of the a flood event (Table 2). In contrast to the distance to the water table, hydrological distance had a negative effect on groundwater annual standard deviation (Table 2).

3.3. Relations between the EMTI and environmental drivers

Distance to the water table along with hydrological distance and their interaction explained between 64% and 85% of the total variance

Table 2
Effect of distance to the water table (W_distance) and hydrological distance (H_distance) on the presence of the flood, annual standard deviation of the groundwater level, and duration of the flood as observed in 2017. The groundwater standard deviation was calculated only on plots UG2a and UG2b. Duration of the flood was calculated only on plots where the flood occurred in 2017. The table contains information about coefficient estimates (Estimate), standard errors (Std.er.), values of *z* and *t* statistics, as well as *p* values. For every model the number of observations, marginal and conditional coefficients of determination (marginal R^2 and conditional R^2), Akaike criterion (*AIC*) of the most parsimonious models and a difference in *AIC* between the full and the most parsimonious model (Δ *AIC*) are presented.

	Presence of flood				Groundwater annual standard deviation					Duration of flood				
	Estimate	Std.er.	*z*	*p*	Estimate	Std.er.	*D.f.*	*t*	*p*	Estimate	Std.er.	*D.f.*	*t*	*p*
Intercept	−3.206	1.446	−2.217	**0.027**	0.582	0.004	0.975	130.096	**0.006**	0.765	0.029	3.345	26.680	**<0.0001**
H_distance	−1.712	0.825	−2.074	**0.038**	−0.020	0.003	46.038	−6.145	**<0.0001**	0.012	0.009	19.732	1.251	0.225
W_distance	−5.018	1.637	−3.064	**0.002**	0.007	0.003	46.100	2.233	**0.030**	0.226	0.013	20.007	17.090	**<0.0001**
Observations	74				50					24				
AIC	34.300				−188.320					−72.309				
ΔAIC	1.500				11.441					13.595				
marginal R^2	0.837				0.435					0.8267				
conditional R^2	0.887				0.453					0.943				

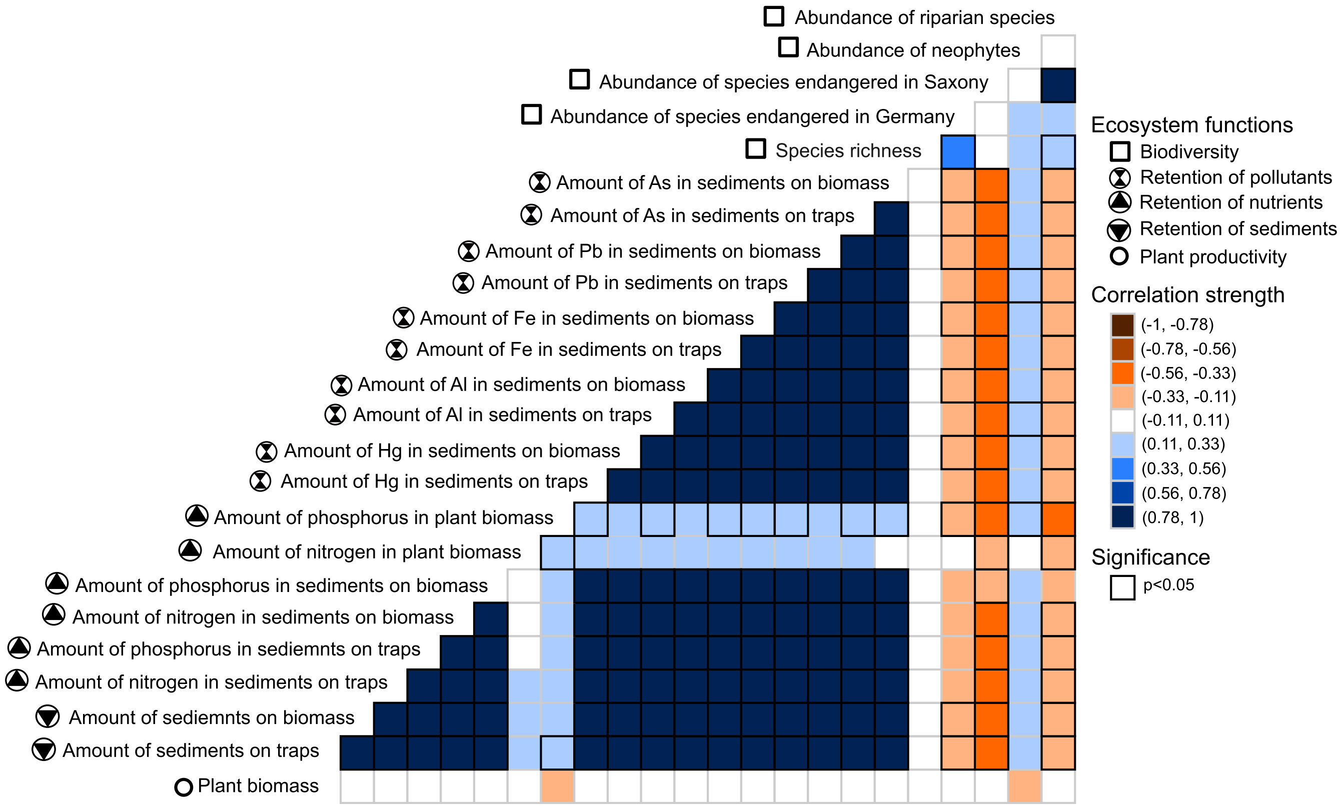

Fig. 2. Relations between single functions used to calculated multifunctionality indices represented by Spearman'srank correlationcoefficients (ρ). Strength and direction of correlations is represented by colors. Significance is represented by black border lines.

across the four applied EMTI indices (Table 3). Increase of both of these distances significantly decreased all of the EMTI indices, while their interaction remained non-significant (Table 3; Figs. 3 and 4). Similarly, the negative effect of the distance to the water table on all of the EMTI indices was stronger than the effects of the hydrological distance (Table 3; Fig. S4).

4. . Discussion

Our results show that both vertical distance to the water table and horizontal hydrological distance are important drivers of multifunctionality. It is well known that floodplain topography regulates many aspects of flooding, like inundation duration, flow depth and water velocity (Florsheim and Mount, 2002). In case of the Mulde River floodplains, distance to the water table as well as hydrological distance proved to be good predictors for the occurrence of flooding and groundwater standard deviation, as measured in 2017. Nevertheless, distance to the water table was the only variable affecting flooding duration. This prominent effect of distance to the water table is not surprising, as elevation is one of the highest-ranking variables used for predicting flood susceptibility (Choubin et al., 2019). The role of elevation in shaping flooding parameters also has consequences for the functioning of floodplain ecosystems, such as sedimentation (Asselman and Middelkoop, 1995; McMillan and NOE, 2017). The hydrological distance represents a flow path of water from the channel to the floodplain and can be linked to the floodplain connectivity (Heiler et al., 1995; Bracken and Croke, 2007). An increase of this distance can result in a longitudinal decline of sediment deposition along the path (Middelkoop and Van Der Perk, 1998; Kretz et al., 2021c). Patterns of sediment retention can in turn modify abiotic and biotic conditions, by affecting nutrient dynamics (Tockner and Stanford, 2002) and diaspore deposition (Leyer, 2006). Our findings highlight the importance of both distances as environmental drivers of hydrological conditions in the lower Mulde River floodplains and imply that they can be used in

Table 3
Test statistics of the linear models used to investigate effects of distance to the water table (W_distance) and hydrological distance (H_distance) on the number of ecosystem functions exceeding thresholds of 50% and 75% of the maximal multifunctionality. The table shows degrees of freedom (*D.f.*), values of Wald X^2 test (X^2) and *p* values (*p*) for each main effect and their interaction. Significant *p* values ($p < 0.05$) are highlighted in bold. The table contains information about number of observations, marginal and conditional coefficients of determination (marginal R^2 and conditional R^2) and Akaike criterion (*AIC*) of respective models.

	Multifunctionality 50%						Multifunctionality 75%					
	No weighting			Equalized			No weighting			Equalized		
	D.f.	X^2	*p*	*D.f.*	X^2	*p*	*D.f.*	X^2	*p*	*D.f.*	X^2	*p*
W_distance	1	100.616	**<0.0001**	1	410.426	**<0.0001**	1	81.170	**<0.0001**	1	32.160	**<0.0001**
H_distance	1	7.127	**0.007**	1	4.984	**0.025**	1	5.186	**0.022**	1	334.780	**<0.0001**
W_distance^{x}H_distance	1	0.032	0.857	1	0.013	0.911	1	2.896	0.090	1	1.499	0.221
Observations	74.000	74.000	74.000	74.000								
Marginal R^2	0.657	0.794	0.647	0.858								
Conditional R^2	0.683	0.900	0.675	0.899								
AIC	394.721	1009.245	347.331	923.902								

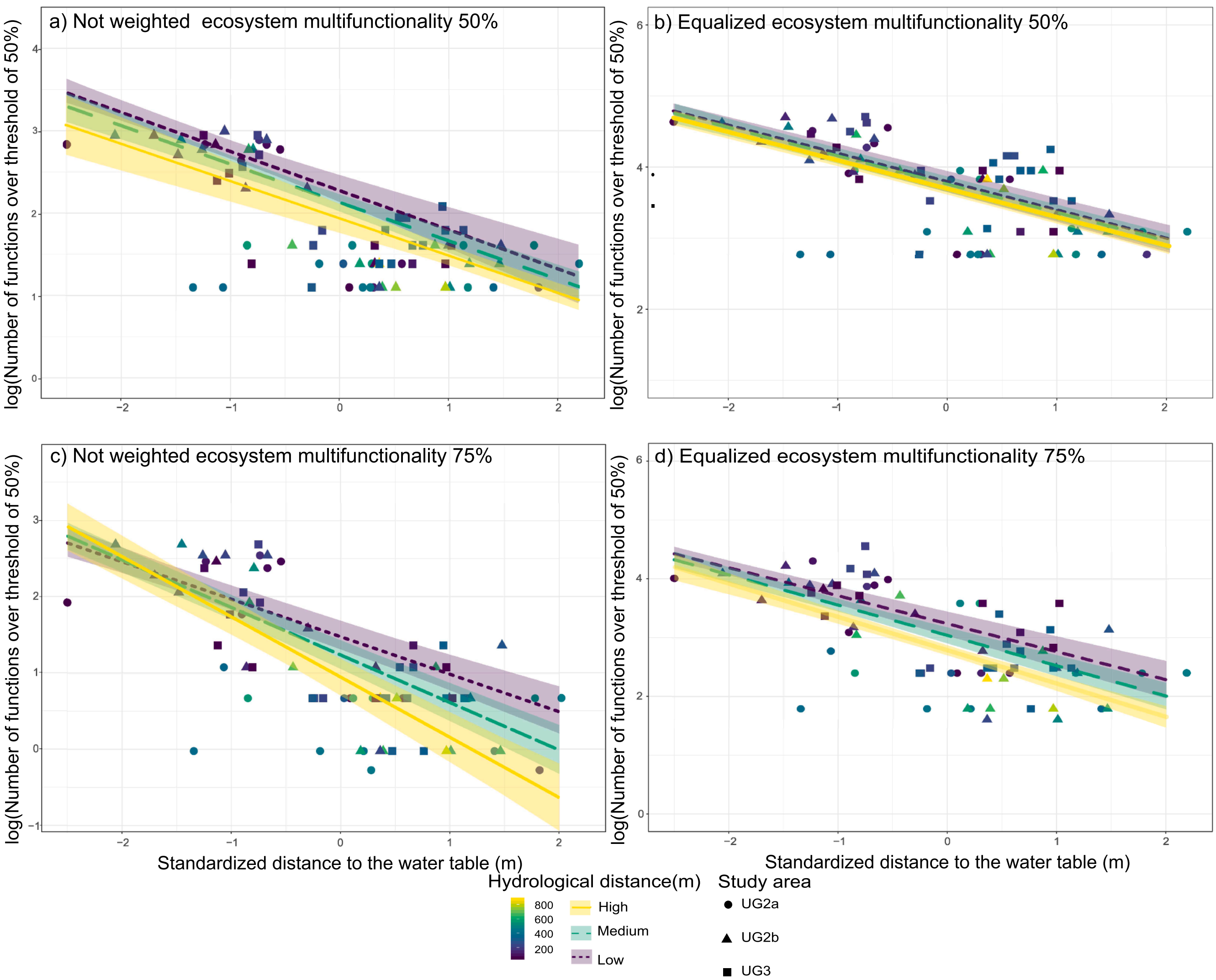

Fig. 3. Effects of the distance to the water table and hydrological distance on the multifunctionality indices. Panels illustrate: a) not weighted EMTI 50%, b) equalized EMTI 50%, c) not weighted EMTI 75%, b) equalized EMTI 75%. Lines represent fitted values with 95% confidence intervals.

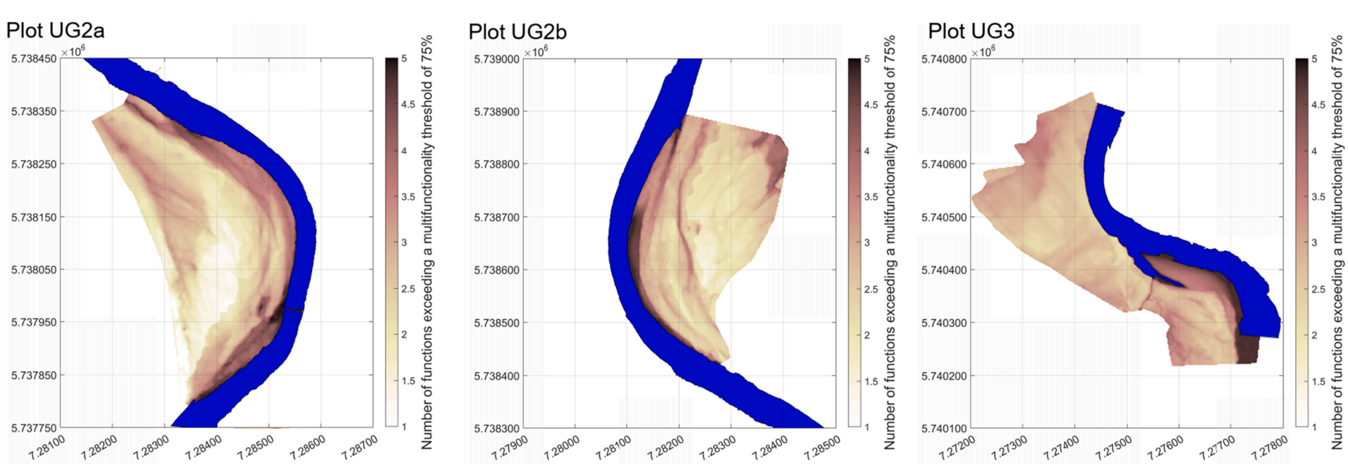

Fig. 4. Spatial extrapolation of a multifunctionality index: equalized EMTI 75% on the study sites. Number of functions exceeding the threshold of 75% is represented by colors. Names of the plots are consistent with the project Wilde Mulde—Revitalization of a wild river landscape in Central Germany (https://bexis.ufz.de:4434/).

situations when detailed information on flooding characteristics are not available. Here we focused on these two distances, because the floodplain morphology (and thereby these measures) was modified by the applied restoration measures. We have shown that these two measures are at least good predictors of the occurrence and duration of site inundation during the recent flood of 2017. The presence of floods is however driven by a very complex combination of physical processes. Therefore, accurate predictions of these events often require sophisticated methods (*e.g.* Mosavi et al., 2018; Liu et al., 2020; Nachappa and Meena 2020). In these cases, predictions may be improved by machine learning or deep learning algorithms (Liu et al., 2020; Motta et al., 2021; Pham et al., 2021).

During our study, we observed a single flood event. Although data collected at the gauging station Priorau in years 2005–2020 (Fig. S1) indicate it was not a unique event, predictions for the future need to consider the fact that flooding events may be less frequent (Palmer et al., 2009). For instance, the relationship between floodplain morphology, a measure of flooding characteristics *e.g.* length of inundation and multifunctionality can be modelled with structural equation models (SEM). However, detailed and well replicated information on these variables may not always be available (Wolf et al., 2013). Finally, the relationship between ecosystem functions and their drivers are often dynamic (Garland et al., 2021). Therefore, measurements should ideally be repeated after a meaningful period of time. On the floodplains of the River Mulde this was not possible due to ongoing restoration measures. However, a new survey in the future can provide important insight into how current restoration measures have altered floodplain morphology, flood dynamics and, as a consequence, ecosystem multifunctionality.

The ecosystem multifunctionality of the Mulde River floodplains decreased with an increase of both topographical variables consistently across both of the considered thresholds. This demonstrates the importance of topography irrespective of how exactly multifunctionality is defined. The main strength of threshold indices, like EMTI is their ability to summarize multifunctionality into a single value. Its main weakness is the arbitral choice of functions and thresholds (Garland et al., 2021). Although these features allow more flexibility, they also limit possibilities to synthesize results and compare findings between river systems, unless the same ecosystem functions and multifunctionality index are used. Here we selected thresholds of 50% and 75%, as we were interested in average and above-average levels of ecosystem functioning. However, if a broader scope is needed, it is possible to apply multiple thresholds ranging between 0 and 100% (Byrnes et al., 2014). Our results allow to select the most suitable locations for restoration of floodplain multifunctionality on the basis of information obtained from elevation models (Benda et al., 2011; Schulz and Schröder, 2017). Furthermore, according to our findings, restoration projects aiming at increasing hydrological connectivity by reconnecting side channels or removing of artificial embankments (Tockner et al., 1999; Reckendorfer et al., 2006)., can improve the functioning of the floodplain system. These findings stay in agreement with other studies, that also found that connectivity increases the provisioning of floodplain functions (McMillan and Noe, 2017; Jakubínský et al., 2021). Nevertheless, as the interactive effect between the distance to the water table and hydrological distance was not significant, we conclude it is not possible to mitigate the negative effect of increased elevation by shortening hydrological distance.

Studying ecosystem multifunctionality can be especially useful in the presence of trade-offs between ecosystem functions (Cord et al., 2017; Manning et al., 2018; Giling et al., 2019). Here, we observed negative correlations, mostly between ecosystem functions related to biodiversity provisioning and sediment, nutrient and pollutant retention. The applied measure of ecosystem multifunctionality allows to explore different scenarios and examines the consequences of various ecosystem conditions Because of a high number and diversity of provided functions, trade-offs are relatively common in floodplain ecosystems (Sanon et al., 2012; Butler et al., 2013; Howe et al., 2014; Tomscha and Gergel, 2016). Their occurrence is often associated with objectives of restoration and flood protection (Pahl-Wostl, 2006). In our study, strong positive correlations occurred between ecosystem functions representing retention of sediments, nutrients and pollutants (Fig. 2; Table S2), which is probably because all these functions increase with flood-driven sedimentation. Measures of multifunctionality often implement closely related functions (Garland et al., 2021), although it may lead to up-weighting of some aspects of functioning and cause a bias in the multifunctionality measure (Manning et al., 2018). In our study, we partly overcame this problem by down-weighing the impacts of closely related ecosystem functions that contributed to the same ecosystem service. The many strong synergies we found between ecosystem functions likely reflect the importance of sedimentation for many of these functions, which is crucial for the functioning of floodplains (Bridge, 2009). Sedimentation is not only spatially restricted to flooded areas, but it is also linked with numerous ecosystem services like nutrient deposition, or water quality control (Venterink et al., 2006). Restoring the natural sedimentation processes is a frequent motivation for river revitalization projects (Venterink et al., 2006; Kiedrzyńska et al., 2008; Kronvang et al., 2009). Because of the industrial and agricultural history of the Mulde River (Klemm et al., 2005; Overesch et al., 2007), retention of sediments, nutrients and pollutants became especially important in context of restoration project Wilde Mulde—Revitalization of a wild river landscape in Central Germany (Schulz-Zunkel et al., 2017). Because of that, we did not include some ecosystem functions and services which may be important in other river systems e.g., cultural ecosystem services (Riis et al., 2020). Consequently, our results should not be indiscriminately implemented in other systems. To mitigate the effect of a potential overrepresentation of function indicators related to sedimentation, we applied a weighting scheme which equalized their importance in the analysis. This approach, however, did not affect our results, what highlights their consistency. Although here we used weighting to equalize values of functions, it is possible to apply it to represent the importance of particular ecosystem functions and services to management objectives or to address preferences of local stakeholders (Allan et al., 2015, van der Plas et al., 2018). Although this approach can facilitate decision making in complex ecosystems such as floodplains (Metcalf et al., 2010), it requires consultations with local stakeholders and decision makers.

5. . Conclusions

The consistent, negative relation between ecosystem multifunctionality and topographical drivers, namely distance to the water table and hydrological distance demonstrates their importance for provisioning of multiple ecosystem functions and services. As these two distances are also good predictors of flooding parameters, our approach can be helpful in situations where detailed information on water level is not available. Our findings imply that restoration projects aiming at improving floodplain connectivity, through *e.g.* removal of artificial embankments or reconstruction of side channels, may have a positive effect not only on single functions, but also on ecosystem multifunctionality, a holistic measure of ecosystem functioning.

In this study we explored a potential application of the ecosystem multifunctionality threshold index to summarize floodplain functioning. Our choice of ecosystem functions and services is specific for the floodplains of the Mulde River. Consequently, the presented findings describe local conditions and should not be extrapolated to other systems. Nevertheless, the EMTI can be adapted in various settings and on a large scale (e.g. Van der Plas et al., 2018). Our study was conducted on a relatively small area, which was relevant for the applied restoration measures. It may however be beneficial to use the EMTI to characterize multifunctionality of the whole river catchment (Li et al., 2020). Similarly, application of the EMTI to summarize functioning of aquatic and terrestrial zones of rivers is a promising avenue of research, as it may provide a profound perspective of river functioning (Holland et al., 2011). Finally, ecosystem functions can be weighted to construct predicted scenarios, corresponding with perspectives of different stakeholders (Van der Plas et al., 2018). These scenarios can for example compare the outcomes or river management suggested by different stakeholders' groups and thus reveal synergies and trade-offs. Additionally, applying a higher number of multifunctionality thresholds can be used to explore various degrees of ecosystem functioning. We consider the ecosystem multifunctionality threshold index as a useful tool, which facilitates modeling and prediction of floodplain multifunctionality.

Declaration of Competing Interest

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

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Data availability

Data will be deposited in the iDiv Data Repository (https://idata.idiv.de) and will get a DOI.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108312.

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