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Original Articles

Florix, an index to assess plant species in floodplains for nature conservation – Developed and tested along the river Danube

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ABSTRACT

Natural floodplains are ecosystems with a diverse mosaic of habitats and site conditions, but also highly threatened due to anthropogenic pressures. Plant species occur in all habitat types and can indicate their value for nature conservation. To improve sustainable management of rivers and floodplains, several indices such as the River Ecosystem Service Index (RESI) have been developed. However, there are so far no assessment schemes for the entire range of floodplain plants. The common assessment approaches like biological integrity, achievement rates or threatened species (Red list), applying to other species groups or other ecosystems, are not appropriate in floodplains. Legal obligations and the need to restore floodplains clearly call for an index assessing the ecological value in a reference area which can be combined with a 5-scale assessment in accordance to established assessments like RESI or the Water Framework Directive.

Five typical characteristics describing vascular plants' adaptation to floodplain habitats were identified. These can be derived from published data sets available for all species in Germany. We checked these indicators for multicollinearity and selected three of them: species number, hydrodynamic indicators, nature conservation indicators. Species number highly correlate with habitat indicators and geographic occurrence. For the selected three indicators we determined thresholds to group habitats and their indicator rate to five classes (very low to very high value for nature conservation). These thresholds are valid for the river Danube and for the habitat types scrutinized in this study.

The *Florix* approach was sensitive in data sets testing active against former floodplains and protected against unprotected areas: For the entire reference region 'Danube floodplain', *Florix* values were higher in the active floodplain and in the protected areas. Only the habitat type 'water bodies' showed better scores for habitats in the former floodplain, for 'softwood forests' the status of being part of a protected area had no effect. *Florix* results were validated in two case studies differing in land use intensity. The region with dominant agricultural use showed significantly lower values than that with a higher portion of forests and grasslands.

Florix can be used for a floristic conservation status assessment at single habitat level or for the entity of a study region in comparison to a reference region. It allows to identify main pressures and to complement a habitat-type based evaluation. To achieve higher comparability, we should strive for a generalized monitoring in Europe like it is common in aquatic ecosystem monitoring.

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1. Introduction

Natural floodplains are very heterogeneous and dynamic ecosystems. Frequent flood events induce morphologic dynamics providing a variety of habitats with different soil moisture conditions in time-varying variance. These site factors lead to a very high biodiversity both of habitats and species (Ward et al. 1999, Robinson et al. 2002, Tockner et al. 2008). In the northern temperate hemisphere, the gradient of habitats spans from aquatic habitats like oxbow lakes and their riparian zone to rarely flooded hardwood forests or even xerothermic grasslands on sand or gravel deposits. Certain animal species groups can be used as indicators of the ecological status of floodplains. For instance dragonflies, ground beetles or molluscs are relatively stenoecious and occur only in certain floodplain habitats (Chovanec et al. 2005, Foeckler et al. 2017, Rumm et al. 2018, Jachertz et al. 2019). Vascular plants, in contrast, are rarely stenoecious and only very few species are restricted to floodplains (Rohde 2004) such as the pioneer species *Myricaria germanica* or *Typha minima* growing on gravelbars of alpine floodplains (Müller et al. 2019). Many characteristic species of more mature habitat types like hardwood forests or reed beds are not restricted to floodplains. Even if they have their main occurrence in floodplains, they are also found in habitats outside floodplains with comparable abiotic conditions, (e.g. *Tamus communis*, *Vitis vinifera* ssp. *sylvestris*, *Senecio sarracenicus*) (Siedentopf 2005).

Evaluating plant species is standard in assessment schemes of nature conservation and environmental planning due to the comparably simple sampling effort and the good knowledge of plants requirements (Dziock et al. 2006, Januschke et al. 2018). Nature conservation assessments in general focus on threatened or rare species, often found on nutrient-poor sites, sites with natural conditions or traditionally managed sites. Floodplains in principle are more nutrient-rich environments. But their high level of heterogeneity in relief, sediment and water dynamics also induce nutrient-poor sites. Today such sites are very rare in Central European floodplains due to prevention of morphodynamic processes, intensive land use, and anthropogenically induced nutrient accumulation. Thus, most plant species occurring in floodplains are not rare or threatened, i.e. they are not red-listed and therefore not in the current focus of nature conservation. However, Jansen et al. (2020) found that not rare, but moderately common plant species have suffered the highest declines over the last 20 years and should therefore be considered as indicators for conservation. Furthermore, for a long time nature conservation has focused mostly on the preservation of static habitats (e.g. xerothermic grassland, fen vegetation), or on the unidirectional succession towards a target habitat stage (e.g. the climax phase of hardwood forests). This is in contrast to the dynamic and multi-complex floodplain ecosystem continuously changing in abiotic conditions where high species turn-over is a common phenomenon (Stammel et al. 2021).

Both, habitat and species diversity are of great value and increasingly threatened in most floodplains (Tockner et al. 2008, Metzing et al. 2018). Straightening and damming of rivers, interrupting the longitudinal and lateral connectivity of rivers and floodplains, intensive land use, and subsequent habitat loss represent strong anthropogenic impacts on floodplains. Consequently, the loss of natural floodplains is tremendous, reaching up to 90 % of the floodplains in Europe and North America (Nilsson et al. 2005, Hein et al. 2016, BMU and BfN 2021). Given the fact that even all remnants of natural floodplains have been altered, a natural reference of pristine habitats and species diversity is largely missing in Europe. For the assessment of the ecological status of rivers, constructed reference states of aquatic indicator species were used as guiding principles (Water Framework Directive 2000/60/EC (WFD), Bouleau and Pont 2015). Koenzen (2005) and Globevnik et al. (2020) have elaborated a typology of the different floodplain types in Germany and Europe, describing their abiotic conditions and their potential vegetation types. Unfortunately these results do not allow to reckon the actual and potential occurrence of species. Obviously, the ecological assessment of floodplains requires more developed methods (Erös et al. 2019). Thus concepts like the biological integrity, reflecting the importance of species for the ecosystem (Karr et al. 1986), or an achievement rate are not suitable tools for plant species assessment in floodplains. The high number of plant species and the spatial differences in their geographic distribution make this approach hardly applicable (Stammel et al. 2017). Nevertheless, there are characteristic traits of plant species that can be assumed as typical for floodplains and therefore serve to identify indicators of an ecological or conservation status of floodplain habitats. Plant indicators of floodplains must be stress-tolerant (e.g. dynamic water levels) and/or adapted to disturbances either by tolerance or the ability to rapidly reach and colonize new pioneer sites.

The project RESI (River Ecosystem Service Index; Podschun et al. 2018, Stammel et al. 2020) aimed to evaluate all relevant ecosystem services of floodplains and rivers to improve their sustainable management. This index equally assesses the ecosystem services based on existing data on an ordinal scale from 1 to 5 to be compatible to the evaluation of the WFD. As a high performance of all ecosystem services indicates an intact ecosystem, habitats and species must be part of such an assessment. A variety of floodplain evaluation methods already exist considering distribution of habitat types (e.g. Fischer et al. 2019, González del Tanago et al. 2021), specific habitat types only (Rohde 2004), faunistic indicator species (Chovanec et al. 2005, Foeckler et al. 2017, Januschke et al. 2018), or abiotic conditions (Habersack et al. 2009, Günther-Diringer et al. 2021). However, no method is available regarding plant species for the entire gradient of characteristic habitats and land use types of floodplains. In aquatic habitats, there is a long tradition of using species as indicators of habitat quality (Kolkwitz and Marsson 1909, Karr et al. 1986, Birk et al. 2012). For aquatic species in the transition zone between aquatic and terrestrial habitats, Chovanec et al. (2005) developed and Funk et al. (2017) adapted the floodplain index for several animal groups (molluscs, caddisflies, dragonflies, amphibians, and fish). This floodplain index evaluates the hydrological connectivity of waters to the river using the occurrence of species. The need to also judge the quality of the terrestrial part of floodplains results from legal obligations like the WFD (to also include the water-influenced landscapes) and the occurrence of selected habitat types of the Habitats Directive. Other needs are to control the success of restoration measures or the impact of water management measures. However, a holistic evaluation has not yet been developed. Januschke et al. (2018) highlighted the need to integrate floodplains in the evaluation of river management and developed a method using ground beetles as indicators. González del Tanago et al. (2021) demonstrated the necessity to integrate riparian vegetation in the assessment of water bodies. Yet plant species as indicators for the value of terrestrial habitats in floodplains are not available (Dziock et al. 2006). In the US, floristic quality assessment has also been adapted to wetlands. It is a simply applicable approach using one to three attributes to rank the impact of human disturbance (DeBerry et al. 2015). However, the needed 'coefficient of conservatism', which evaluates the response to human disturbance, must be determined for each species by an expert group for each individual area. As mentioned above, such a reference state without the impact of human disturbance is difficult to depict, especially for the strongly altered floodplains in Central Europe.

Therefore, we aimed to develop a species-based multi-metric index, which can evaluate the whole range of habitat types in floodplains. The index should assess the relative habitat quality without comparing it to a reference state. The evaluation scheme should reflect and be linked to the framework of the RESI project in its evaluation scale (1 to 5) (Podschun et al. 2018). The index of the nature conservation value of floodplain habitats by plant species should be sensitive to the main drivers' changes in the flooding regime and extensive land use impact (Hernandez et al. 2015, Fischer et al. 2019, Funk et al. 2019). Further, the index should not be sensitive to geographical variation but be valid along an entire river or within its biogeographic regions. In the end, the index should summarize the high complexity of floodplain ecosystems to be understandable for non-experts (Heink and Kowarik 2010). In the following, we present the development of this index, called *Florix*. It assesses the value of a floodplain habitat for nature conservation considering all vascular plant species. These are compared to the totality of all habitats along the same river as reference region. Additionally, it can serve as an add-on for the evaluation of the habitat provision index in RESI (Fischer et al. 2019). First, the typical traits and categories for value-giving species will be defined. Secondly, the explanatory power and the informative value of these categories will be analyzed. At last, the calculation of the index will be applied and validated for different habitat types and for differently impacted floodplains both in the entire reference region and in two case studies along the river Danube.

2. Material and methods

2.1. Study area

2.1.1 Reference region

The reference region for this study is the morphological floodplain of the river Danube in the federal state of Bavaria in Germany (Fig. 1A) with an area of ca. 1,000 km^2 and a river length of 600 km. The selective habitat mapping of the Bavarian Environment Agency (LfU 2012) was used for developing and testing the new index. This mapping standard is based on an agreed list of selected habitats relevant for nature conservation in general (LfU 2012). Potential habitats were identified using aerial photographs, verified in the field and mapped in a scale of 1:5,000. Each record includes the affiliation to habitat types of the agreed list and a total species list of the entire habitat. There are almost 9,000 habitats with specific sizes ranging from 50 to > 10,000 m^2 with a total area of ca. 50 km^2 mapped. These serve as a reference for the evaluation (Fig. 1C). This reference does not represent the target status of the Danube floodplain but the state of the entire floodplain of the river section.

For many records, the habitat mapping merges several sub-areas to one larger database entry with only one species list. For the definition of thresholds of *Florix* (see 2.4), only habitats consisting of one subplot and with a size bigger than 300 m^2 and recorded in the last twenty years were selected. By this, comparability and up to date of the data could be guaranteed and the influence of the habitat size on the quality assessment could be reduced. These restrictions resulted in a selection of 1,688 habitats (out of almost 9,000). We assigned them to the following five major habitat groups according to Scholz et al. (2012): water bodies, grasslands, reed beds, softwood forests, as well as forests without softwood.

2.1.1. Distinction of land use intensity and hydrological connectivity for plausibility check

To test the plausibility and sensitivity of *Florix* to human pressures, we separated the reference region (Fig. 1B) into active floodplain (periodically inundated by the lateral overflow of the riverbanks) and former floodplain (surface flooding inhibited by man-made infrastructures like dams) (BMU and BfN 2021). 717 habitats in active floodplains and 971 in former floodplains were identified. Further, in case study 1 we distinguished habitats ‘outside the floodplain’, situated outside the morphological floodplain (sum of active and former floodplains). Additionally, the habitats were differentiated whether they are located inside (547) or outside (1,141) an area of importance for nature conservation (listed as protected area in terms of the Habitats Directive).

2.1.2. Areas for validation of Florix

To validate the assessment, *Florix* evaluation was tested for two smaller data sets within this reference data set. The location of both case

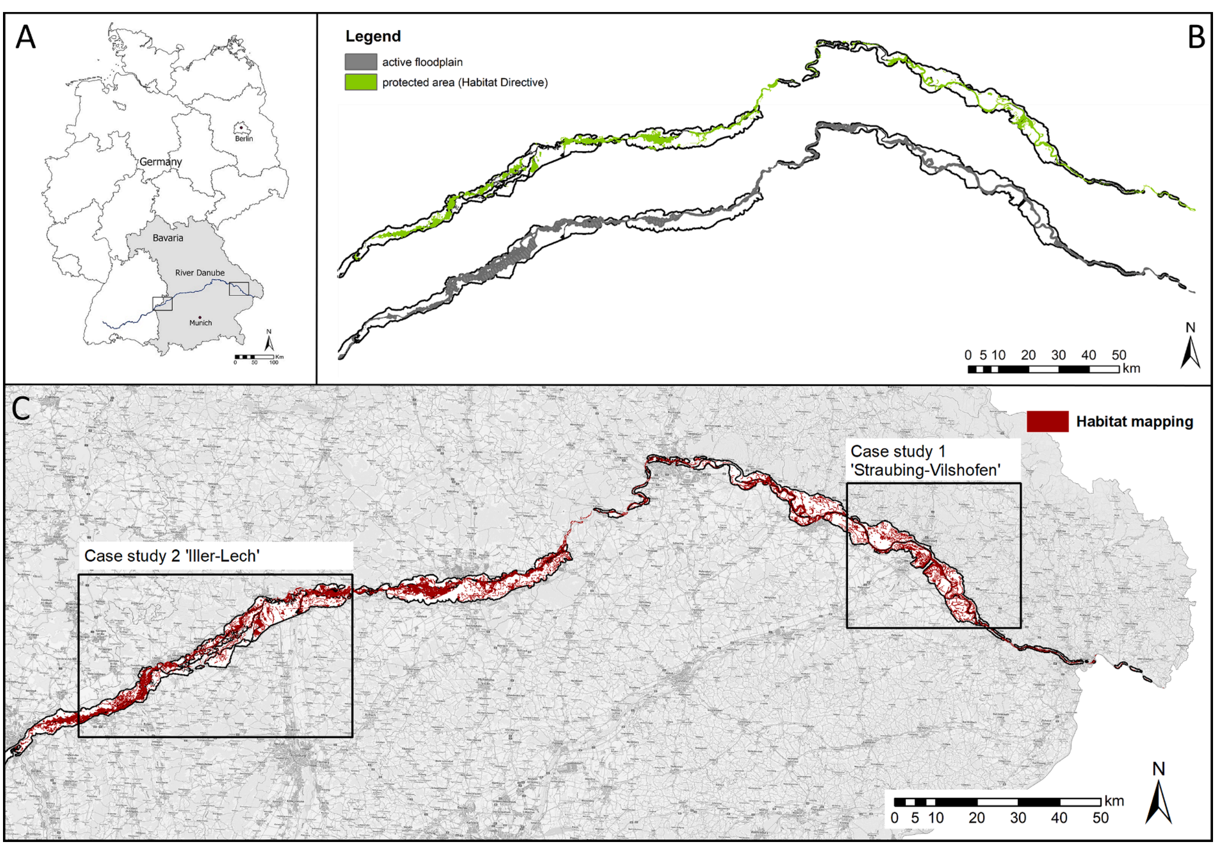

Fig. 1. Location of the study areas in Germany (A), extent of active floodplains as proxy for connectivity and extent of protected areas as proxy for land use intensity within the study area (B), and map of the study area as reference region with the location of the case studies (C), the habitats (red) used to determine thresholds for the assessment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

studies along the river, which significantly differ in their land use and connectivity to the river, is illustrated in Fig. 1A and C.

Case study 1 'Straubing-Vilshofen': not impounded, dominated by agricultural land use. Case study 1 of the Danube floodplain is located between river kilometers 2,344 and 2,259 at an altitude of 308 to 330 m above sea level. Here, the meandering, regulated, but not impounded Danube has a mean discharge of ca. 450 m^3/s. Water level amplitude reaches several meters within a year due to a pluvial-nival flow regime with both winter and summer floods (Skublics et al. 2016, LfU 2022a). To validate *Florix* in case study 1, all habitats recorded by the selective habitat mapping in the floodplain and a buffer strip of 500 m next to the floodplain were assessed. The area of these 654 habitats covers 3.8 km^2. 383 habitats are located in the morphological floodplain (50 in the active floodplain, 333 in the former floodplain). 271 are outside the floodplain in the adjacent landscape. The surrounding landscape unit called "Dungau" is an agricultural landscape with highly fertile and intensively cultivated loess plains (LfU 2011). Starting 200 years ago, the Danube has been regulated (short cuts, constant width of 130–140 m) to improve shipping, dykes were constructed to protect the arable lands against summer floods, and in 1995, the hydropower dam Straubing was launched (river km 2,321) (Stammel et al. 2018). As a consequence, only 20 % of the morphological floodplain is still considered as active floodplain, dominated by grassland (45 %) and water bodies (28 %). In contrast, the former floodplain behind the dams is dominated by arable land (34 %) and intensively used grassland (32 %) and only smaller parts are covered by forests (11 %) in both floodplain parts.

In case study 1, we tested the evaluation of habitats in the active compared to the former floodplain and to habitats outside the morphological floodplain.

Case study 2 'Iller-Lech': impounded but still connected to the river. Case study 2 is ca. 150 km upstream of case study 1 between river km 2,586 and 2,500, thus the annual mean discharge (162 m^3/s) and the mean high discharge (700 m^3/s) are significantly lower (LfU 2022b). The area of case study 2 covers the entire floodplain corridor along the river Danube between the two tributaries Iller and Lech. The selective habitat mapping identified 435 records with 234 in the former and 201 in the active floodplain. Within this 86 km stretch, there are nine dams used for hydropower generation. Preceding each dam is a retention reservoir, each with embankments of 2.5 to 5 km long dykes separating the river from the floodplain. As a result, the active floodplain in the up to 10 km wide morphological floodplain has decreased by 62 %. Land use in the studied river corridor is more evenly distributed (arable land: 29 %, grassland: 28 %, and forest: 19 %). In the active floodplain, we can find a larger amount of forests (24 %), and in spite of several hydropower dams the floodplain is regularly flooded by managed weirs.

The data set was used to compare the two case studies 1 and 2 and to show the potential of an amendment to the RESI habitat approach (Fischer et al. 2019).

2.2. Indicators of floodplain vegetation for nature conservation

Several factors have a special importance for evaluation of the riparian plant diversity as part of the habitat provisioning services in floodplains: the function as a hotspot of biodiversity, the specific dynamics of water and soil conditions, the characteristic habitat conditions, which occur (only) in floodplains, the state of threat and the spatial limitation covering only a small part of the total landscape. Thus, we identified five potential attributes, which indicate and partly summarize the adaptation of plants to the conditions of floodplains and by this underline their significance indicating the conservation status of floodplain habitats (more details and the species list with the affiliation of species to the attributes are given in Supplementary Material 1 Tab. S1 and 2):

1. Floodplain habitat indicators (FHI): Habitats typical for floodplains are affected and depending on intact hydrological connectivity between river and floodplain. A list of typical floodplain habitat types is given by Fischer et al. (2019) (see also Supplementary Material 1 Tab. S2 and 3). Species which indicate such habitats are determined as floodplain habitat indicators. Plant sociological literature of Germany and in particular of the studied Bavarian Danube area has been used to identify all potential species of this indicator: Oberdorfer et al. (1990) listed in Ellenberg et al. (1991), LfU and LWF (2020).

2. Hydrodynamic indicators (HDI): The ability to cope with regularly changing water levels, flooding as well as drought is a prerequisite to survive in natural floodplains. Species possessing this ability are determined as hydrodynamic indicators. Ellenberg et al. (1991) was used as a basis for this selection.

3. Indicators for geographic occurrence in floodplains (GeoI): Plant species are restricted to river corridors due to waterborne dispersal abilities or adaptation to the specific climate of large valleys (Burkart 2001). These species underline the ecological distinctiveness of a floodplain. The determination of an indicator for geographic occurrence along the Danube is based on literature (Burkart 2001, Siedentopf 2005). Additionally, an analysis comparable to that of Siedentopf (2005) was conducted especially for the Danube floodplains comparing the occurrences of species listed in the floristic grid mapping (see Supplementary Material 1 Tab. S1).

4. Nature conservation indicators (NCI): To evaluate the general relevance (not specific for floodplains) of species for nature conservation the conservation status given by Red Lists should be taken into account as well as political conventions on the basis of international, national, or regional laws and directives. The nature conservation indicator in our case includes regional red list species (Scheuerer and Ahlmer 2003) as well as species protected in the German Federal Nature conservation Act (§ 44 BNatschG 2009) and listed in the Federal Species Protection Ordinance (BArtSchV 2005). This includes the species protected by the European Habitats Directive 92/43/EEC.

5. Total species number (SN): As a fifth indicator, we tested whether species number not regarding any selection on adaptation to floodplains might be an indicator for a good conservation status.

2.3. Work flow of index development

The occurrence of the defined potential indicators was analyzed for all habitats in the reference region. Thresholds for the individual assessment of these indicators for the specific habitat types were defined. Then, the three most significant potential indicators were selected by correlations and finally summarized to *Florix*. Afterwards this method was checked for plausibility by comparing sites with different impacts in the reference region. The validity of the method was reviewed for two case studies. (Fig. 2).

2.4. Defining thresholds for evaluation

The index *Florix* should serve on the one hand as an independent evaluation of the species occurrence in floodplains and on the other hand as an add-on for the evaluation of the habitat provision index RESI (Fischer et al. 2019). In order to be connectable to the RESI, but also to other established indices of ecological status (e.g. WFD), the index values range from 1 (very bad) to 5 (very good). As intact floodplains (very slightly modified floodplain status) along the river Danube do not exist anymore, the evaluation is based on the comparison of the number of indicator species of a given habitat to the number of species of all habitats in the reference region along the river Danube in Bavaria. The final thresholds are valid for this specific Danube stretch, but the process to establish these thresholds can be used anywhere else where a sufficient number of habitats with species lists is available.

To define the evaluation thresholds for single indicators, all habitats

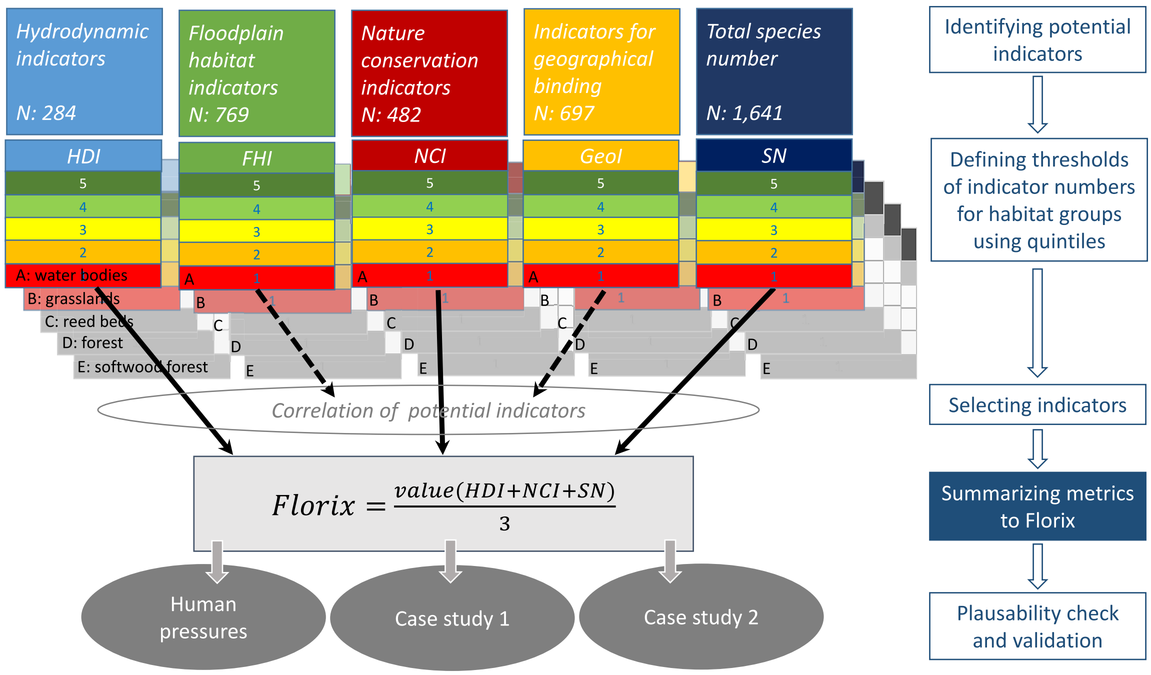

Fig. 2. Work flow of the development and testing of the multi-metric index *Florix* in the reference region along the river Danube in Bavaria, Germany; N: number of identified indicator species in the reference region.

of the reference region were grouped into five major habitat groups: water bodies, reed beds, grasslands, softwood, and non-softwood forests. To get the thresholds of the five classes 1 to 5 for each indicator and each habitat group, the values of the habitats for each indicator were sorted in ascending order, and quintiles (division into five equal groups according to the distribution of values) were determined. The same was applied for the total species number of the habitats (see in Suppl. Material Tab. S4 all thresholds for all indicators and habitat groups).

2.5. Statistical methods

In order to demonstrate the differences between the potential indicators, we analyzed and compared the number of species and their share in the total number of species at different geographical scales (total data set for all plants in Germany, reference area Danube, case studies 1 and 2). The differences between the quantity of indicators for the major habitat groups (water bodies, reed bed, grassland, softwood forest, other forests) were identified using the Kruskal-Wallis-test (non-parametric ANOVA) followed by a post-hoc Dunn's test with Bonferroni correction for pairwise comparison.

In order to reduce the redundancy of the indicators and to further increase the informative value of the selected indicators, we analyzed which indicators we can omit. To select the most significant indicators for the final calculation of *Florix*, we first calculated the mean of the evaluation values (1 to 5) of all five indicators:

$$Florix_{test} = \frac{selected\ \ values(FHI, HDI, GeoI, NC, SN)}{n(selected\ \ values)}$$

Second, the variability and collinearity of all potential indicators resulting in the value $Florix_{test}$ were tested using Spearman-rank-correlations between the single indicators, both for the absolute numbers and the evaluations (1-5). For multicollinearity the variance inflation factor (VIF) of each indicator to $Florix_{test}$ were used. In order to avoid overestimations of correlations with only five ranks the congruency of evaluation values of the indicators for each record was checked.

For validation of *Florix*, a U-Test for the reference region data set comparing the mean values between active and former floodplains and between protected and unprotected areas in terms of the habitat directive was conducted. All statistical analyses were performed using IBM SPSS Statistics 24.

3. Results

3.1. Indicator species numbers

In total, we analyzed the affiliation of 3,212 species occurring in Germany to the four potential indicator categories. 70 % of these species (2,254 species) are indicator species of any of the four described indicator groups (FHI: 788 species, HDI: 413 species, GeoI: 813 species, NCI: 1,192 species). Comparing this share with the share in the reference region Danube and the case studies 1 and 2 differences are evident (Fig. 3A): 74 % (N = 1,641) of all species are indicator species in the habitats along the entire Danube floodplain, in case study 1 even 82 % (N = 451) and 79 % (N = 883) in case study 2. Only 2.0 % (N = 81) of the German species list are indicators assigned to all of the four indicator categories. Again, higher shares are present along the Danube floodplain (4.3 % of all species, 70 species), and even higher in the case studies (case study 1: 4.8 %, 22 species, case study 2: 5.1 %, 45 species).

The indicators with the highest number of species in all analyzed regions are those of the floodplain habitats (Fig. 3B). The proportion of these indicator species is very high in the case studies (1: 65 %, 2: 57 %) and significantly higher than in the total species list (29 %) or in the reference region (47 %). A similar pattern could be observed for the indicators with geographic occurrence (case study 1: 51 %, 2: 52 %, reference region: 42 %, total species list: 22 %). Significant lower amounts in general were observed for the hydrodynamic indicators (case study 1: 25 %, 2: 22 %). In contrast, the proportion of protected species is higher in the overall species list (34 %) and on the entire Danube (29 %) than in the case studies (1: 13 %, 2: 21 %).

There are significant differences between the habitat types for the species number of all five indicators for all habitats of the reference region (Kruskal-Wallis-ANOVA $p < 0.001$, $n = 1{,}688$, FG = 4), although the standard deviation is very high (Table 1). The number of indicators of nature conservation in general is very low (mean 1.9). Only the water

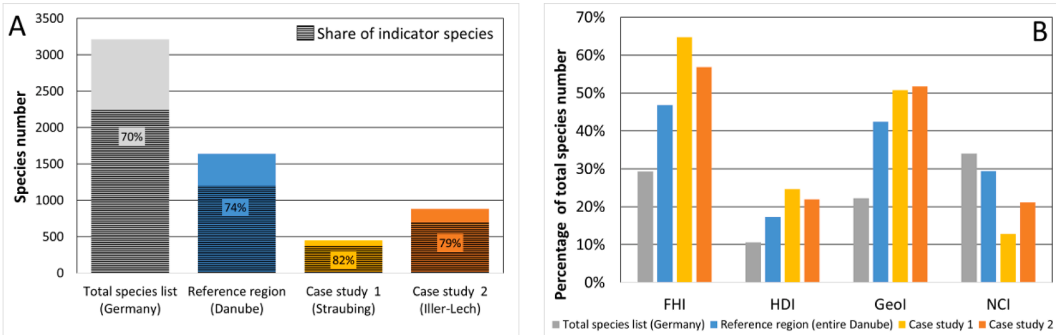

Fig. 3. A: Total species number (full color) and the number of species listed at least once as an indicator (hatched) for the entire data set, the reference region and the two case studies. B: Percentage of total species number per region for the four indicator (I) categories (FH: Floodplain habitats, HD: hydrodynamic, Geo: geographic occurrence, NC: nature conservation).

Table 1
Number of habitats, mean and standard deviation (SD) of number for the potential indicators (SN: species number, FHI: floodplain habitat indicators, HDI: hydrodynamic indicators, GeoI: geographic occurrence indicators, NCI: nature conservation indicators) of the five main habitat groups. Letters indicate significant differences between the habitat groups for each indicator (column), where equal letters mean no significant difference between two habitat groups (Kruskal-Wallis-ANOVA and post-hoc stepwise paired test).

Main habitat group	Number of habitats	SN		FHI		HDI		GeoI		NCI	
		Mean + SD	Sign.	Mean +SD	Sign.	Mean + SD	Sign.	Mean +SD	Sign.	Mean + SD	Sign.
Water bodies	226	25.5 + 22.1	ab	19.4 + 14.5	ab	8.7 + 7.3	b	15.0 + 12.6	ab	2.8 + 1.8	b
Grassland	320	29.7 + 25.2	b	20.5 + 14.3	b	6.6 + 5.4	b	14.2 + 15.1	a	1.7 + 3.8	a
Reed bed	458	18.5 + 17.1	a	14.8 + 12.4	a	7.2 + 6.6	a	10.3 + 9.4	a	1.5 + 2.6	a
Forests	599	33.9 + 26.1	c	20.2 + 15.9	b	7.8 + 6.6	b	15.1 + 13.7	b	1.9 + 2.8	ab
Softwood riparian forests	85	30.3 + 19.0	c	21.3 + 14.9	c	10.6 + 8.1	c	15.2 + 11.4	c	1.5 + 2.5	ab

bodies showed a significantly higher number of this indicator than the habitat groups grassland and reed bed. In contrast, for the other indicators reed bed habitats and water bodies (the latter not for HDI) significantly indicate the lowest numbers, whereas the softwood riparian forests show the highest numbers of indicator species for the remaining four indicators. Number of indicator species in grasslands and forests (except softwood) are in between (Table 1). This has to be taken into account when defining the thresholds for a species number-based approach of evaluation. Such thresholds have to be different for the single habitat groups.

3.2. *The final Florix - selection of indicators*

The numbers of indicators per record correlate significantly for all categories between each other (Table 2). Especially SN, FHI and GeoI have a Spearman-Rho higher than 0.9. $Florix_{test}$ (mean of all five indicator values) showed a variance inflation factor higher than 5 and very low tolerance of 0.13, 0.11 and 0.15 for SN, FHI and GeoI when testing for multicollinearity. Thus, we dropped FHI and GeoI and calculated $Florix_{final}$ only using SN, HDI and NCI.

$$Florix_{final} = \frac{value(SN) + value(HDI) + Value(NCI)}{3} \tag{2}$$

Identifying the congruency of the evaluation classes of the indicators SN, HDI and NCI per habitat, only 27.0 % of all habitats have the same values for all three indicators. There are deviations of four classes between the values of the single indicators (e.g. value 1 for NCI and value 5 for HDI) for 2.6 % of all habitats and of three classes for 10.6 %. Thus, there are many positive and negative deviations of the single indicator values from $Florix_{final}$ (Table 3). Especially the NCI differs in more than half of the habitats (856) from *Florix*, two-thirds of these values are lower than *Florix*. SN and HDI both differ in 41 % of all habitats from *Florix*.

Table 3
Deviation of values of the indicators from the calculated $Florix_{final}$ (N = 1,688).

Difference [Indicator-*Florix*]	SN	HDI	NCI
+1	432	390	248
-1	226	250	448
+2	29	25	35
-2	7	30	112
+3	1	0	0
-3	0	2	13
±0	993	991	832

Table 2
Spearman-Rank-Correlation (for all p < 0.001) between the indicator for all habitats of the reference region (N = 1688) (absolute numbers upper part and evaluation values 1-5 lower part; very high correlations (>0.9) in bold print) and collinearity to $Florix_{test}$ calculated with all five indicators. SN: Species Number; FHI: Floodplain Habitat Indicator; HDI: Hydrodynamic Indicator; GeoI: Geographical Indicator; NCI: Nature conservation Indicator; VIF: variance inflation factor.

		Number of species					Collinearity to $Florix_{test}$	
		SN	FHIs	HDI	GeoI	NCI	Tolerance	VIF
Evaluation values	SN		**0.936**	0.745	**0.906**	0.590	0.126	7.919
	FHI	**0.920**		0.844	**0.921**	0.653	0.105	9.503
	HDI	0.751	0.821		0.818	0.607	0.304	3.294
	GeoI	0.891	0.893	0.788		0.706	0.146	6.833
	NCI	0.602	0.643	0.583	0.677		0.525	1.905

3.3. Plausibility of Florix values in the entire reference region

Florix calculated for all 1,688 habitats in the reference area reached all possible values from 1 to 5. Habitats with the highest value 5 occurred least (13.6 %) while habitats with the value 2 occurred most frequent (25.4 %). Approximately one fifth of the habitats are evaluated to the classes 1 (20.5 %), 3 (21.7 %) and 4 (18.7 %).

Habitats located in a protected area have significantly higher values than those outside protected areas (*U*-test $p > 0.001$; 3.0 to 2.7) (Table 4). This is especially valid for grasslands (3.2 and 2.5) and reed beds (3.2 to 2.6), but not for water bodies and both forest types.

Comparing the impact of floodplain disconnection, habitats in the active floodplain have significantly higher evaluation values than those in the former floodplain (*U*-test $p < 0.001$; active: 3.2, former: 2.5). Except for water bodies, which have slightly higher values in the former floodplain, all habitat types show higher values in the active floodplain (grassland 3.2 to 2.5, reed beds 3.6 to 2.4, forests 3.3 to 2.4, softwood forest 3.1 to 2.4). This confirms the plausibility of *Florix*.

3.4. Validation of Florix in the case study areas

3.4.1. Case study 1: Location inside and outside the floodplain

In case study 1 that is dominated by agricultural activity in the former floodplain and the surrounding landscape, the values are relatively low (mean 1.9). *Florix* indicates differences for the location in the floodplain (Kruskal-Wallis-ANOVA n = 654, FG = 2, 14,728, p = 0.001) (Fig. 4A), but only the values "outside floodplain" (mean: 1.7 ± 0.8, N = 271) are significantly different to the others. The very small active floodplain contains only a low number of recorded habitats and the comparably low values result in no clear differences between active (2.2 ± 1.3, n = 50) and former floodplain (2.0 ± 1.0, n = 333). Differentiating between the habitat groups (Fig. 4B), clearly higher values can be observed for water bodies in the former floodplain and for softwood forests in the active floodplain. For the other habitat groups no clear differences could be observed, but the habitats outside the floodplain always show lowest values.

3.4.2. Case study 2: Comparison of habitat type quality in a river section

A positive effect of floodplain connectivity to the river on *Florix* values can be observed. In case study 2, all habitats show a higher mean compared to case study 1 (>3.0 vs 2.2; only the habitats inside the floodplain). Case study 2 achieved clearly better evaluations for all habitat groups than case study 1 (Fig. 5). In the reference region (entire Danube) each value class (1-5) is equally distributed (meaning each value ca. 20 %). In case study 2, evaluation of the grassland habitats is above this Danube average: 58 % of all habitats are in a good or very good floristic state, 13 % in a bad and only 1 % in a very bad conservation status. Also for the reed bed habitats, 46 % are in a good or very good state, whereas for the forests more than half of the habitats (57 %) are in a bad or very bad status. For water bodies and softwood forests a very good status (value 5) is relatively rare with 8 % and 5 % respectively. In case study 1, in contrast, values 1 and 2 (very bad and bad) are dominating in all habitat groups (water bodies: 67 %, reed beds: 69 %, grasslands: 72 %, forests: 74 %, softwood forests: 52 %). Thus, the results for both case studies demonstrate the validity of *Florix*.

Additionally, *Florix* values can be used to visualize the floristic conservation status of single habitats. We exemplarily plotted the habitat values against the assessment of the RESI habitat index (Fischer et al. 2019, Stammel et al. 2020) in case study 2 (Fig. 6). The calculation of the RESI habitat provision index consists of three steps: First, well-established assessment criteria (e.g., groundwater dependence, legal protection status, regenerability) are used for the evaluation at habitat type level. Second, based on specific quality characteristics (e.g. hydrological connectivity) the individual habitats are assessed. Finally, these values are aggregated within 1-km floodplain compartments weighted by their spatial expansion. The habitat index, thus, represents the value and importance of the ecological status in terms of its typical biodiversity by linking habitat types to biotic and abiotic parameters in floodplains. Fig. 6 illustrates clearly the importance of both indices: the *RESI habitat index* on the one hand demonstrates the value of an entire segment by using the quality of habitats in general (e.g. all reed bed habitats get the same value (4) in the evaluation). *Florix* on the other hand evaluates the conservation status of a single habitat using the plant species occurrence (e.g. reed beds can have a value from 1 to 5). Thus, even when the overall ecological assessment of a floodplain compartment is bad or very bad, these compartments can still contain habitats with a very good species composition and vice versa (Fig. 6).

Table 4
Mean values for *Florix* in the reference area regarding the location in protected areas (Habitats Directive) and in the floodplain (active and former).

	Habitats Directive sites			Lateral connectivity		
	inside	outside	Sign.	Active floodplain	Former floodplain	Sign.
All habitat groups	3.0	2.7	***	3.2	2.5	***
Water bodies	2.8	2.8	ns	2.6	3.0	***
Grasslands	3.2	2.5	***	3.2	2.5	***
Reed beds	3.2	2.6	***	3.6	2.4	***
Forest except softwood	3.0	2.7	ns	3.3	2.4	***
Softwood forest	2.9	2.7	ns	3.1	2.5	***

4. Discussion

We developed the multi-metric index *Florix* that is able to assess the value of floodplain habitats for nature conservation on the basis of plant species. In contrast, the concept of biological integrity or of achievement rates, which is widely used in aquatic habitats and for several species groups (Karr et al. 1986, Birk et al. 2012), can hardly be implemented for plant species on floodplains for the following reasons. 1) Due to the high degradation of the floodplains in Europe (Hein et al. 2016, BMU and BFN 2021), there are no natural floodplains which could serve as a reference for the natural species composition. 2) The species diversity of plants is much higher than that of macroinvertebrates, e.g. 1,641 species in the reference region of this study. Such a necessary individual value could not be defined for all of these species. 3) The changing dynamic conditions of flooding and morphodynamic processes in floodplains that regularly induce species turn over (Hernandez et al. 2015, Stammel et al. 2021) would lead to changing reference conditions on the same sites over the years.

Common ecological assessments of terrestrial habitats based on red list species or phytosociology are limited in the floodplain ecosystem due to its characteristic hydro- and morphodynamics and habitat mosaics, which limit clear assignments to habitat types. As floodplains are subject to various legal obligations and conflicting interests (e.g. land use, settlements, hydropower, flood protection, navigation) tools such as the river ecosystem service index RESI are needed for objective evaluation of sustainable management (Stammel et al. 2020). *Florix* aims to integrate not only habitats (Fischer et al. 2019) into RESI, but also plant species quality, which so far has only been included indirectly in habitat assessment (e.g. LfU and LWF 2020). Many assessment tools exist for rivers partly integrating floodplains, but no methods have been implemented specifically for floodplains (Funk et al. 2017, Erös et al. 2019). Thus, the presented multi-criteria index *Florix* is an important step forward. It follows recommendations to combine different metrics in order to provide more complementary information that helps understanding the structure, function and response to environmental drivers (Gallardo et al. 2011).

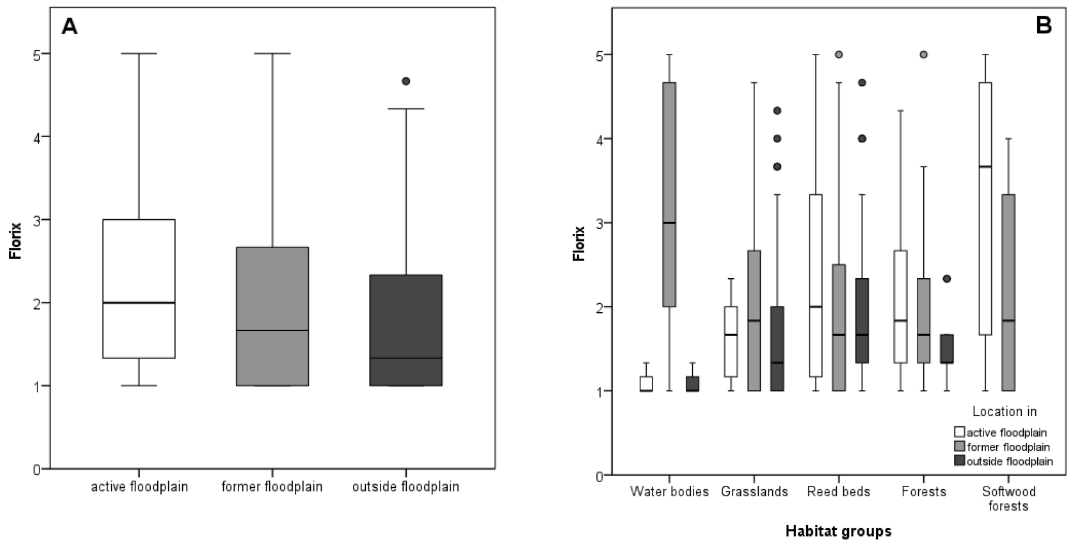

Fig. 4. Box-Whisker-plots of *Florix* results in case study 1 for the location in the floodplain (active, former, outside floodplain) A) for all habitats and B) for the grouped habitat types.

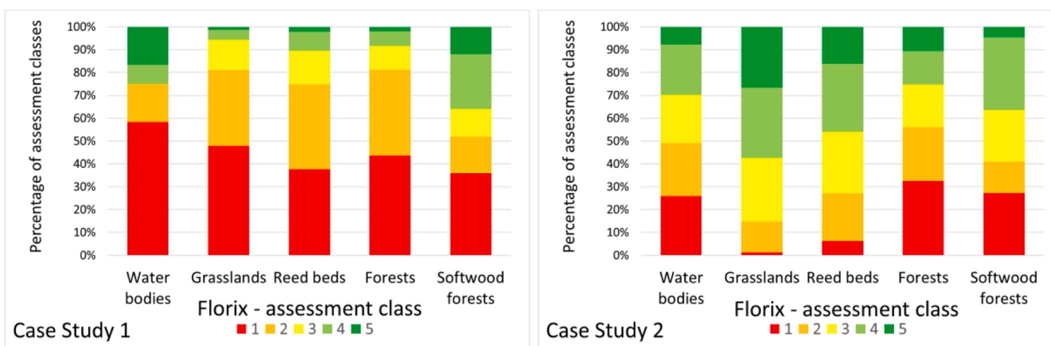

Fig. 5. Percentage of assessment classes for the recorded habitats inside the floodplain of case study 1 (left) and 2 (right), differentiated into the different habitat groups.

4.1. Meaningful plant species indicators for floodplain assessment and their thresholds

Meaningful indicators for the value of floodplains for nature conservation could be based on biodiversity, functional diversity, or rarity (Dziock et al. 2006, Funk et al. 2017). In *Florix* these three aspects were combined in a simple assessment - higher numbers of these indicators induce higher values. We identified five potential indicators, which include not only classical indicators like species number or red list species, but reflect also characteristics of ecological intact floodplains: the proxies plant sociology for abiotic site conditions, geographic occurrence for dispersal abilities, and the plant trait flooding tolerance.

All indicators show a definite correlation with the calculated multi-metrics index and with each other, as also demonstrated for other indices (Yang et al. 2018). Yet, the different indicators reflect different aspects and still influence the final value of *Florix*. Interestingly, we found species richness as a meaningful indicator. That is in contrast to observations by Kutcher and Forrester (2018) in wetlands where floristic quality assessment performed worse when species richness was integrated due to differences in the investigated plot size, but also in habitat types. We solved this issue by evaluating total species richness not of plots, but of the entire habitat, and by evaluating the habitat groups separately. In contrast to static wetlands with stable abiotic conditions (e.g. fens) evaluated by Kutcher and Forrester (2018), floodplains harbor a wide gradient of habitats (Ward et al. 1999, Robinson et al. 2002). Thus, species richness is also able to indicate the habitat variety of floodplains. Considering species richness as an indicator is in line with findings of Jansen et al. (2020) according to which especially common plant species have shown highest losses over the last decades. Focusing exclusively on rare or selected species without regarding moderately common to common species will not be sufficient to sustainably protect biodiversity. Furthermore, a requirement for developing of *Florix* was that it can be applied using five classes. A better justified classification can be achieved with a higher number of species to be assessed. Then, it can be more robustly split into five classes. Thus, for simplification, we suggest using species richness as an indicator, but it might be substituted by the floodplain habitat indicator FHI. In contrast, we cannot recommend substituting it by the species of geographic occurrence, as the criteria for selection of these species are also based on species occurrence risking a circular argument. Nevertheless, highly significant river corridor plant species (according to Burkart 2001), should instead be used as target species for restoration, but not to assess the value for nature conservation in general (van Looy and Meire 2008; Gattringer et al. 2019).

To add the aspect of threat to *Florix*, this classical nature conservation indicator should be included. The number of red list species in floodplains is low compared to the share of red list species among all plant species in Germany, depicting that most of the species occurring in floodplains are neither rare nor endangered. However, legal obligations and conventions should also be accounted for when assessing floristic diversity with a multi-metric index. This indicator showed the lowest correlations with all other indicators, adding the aspect of societal

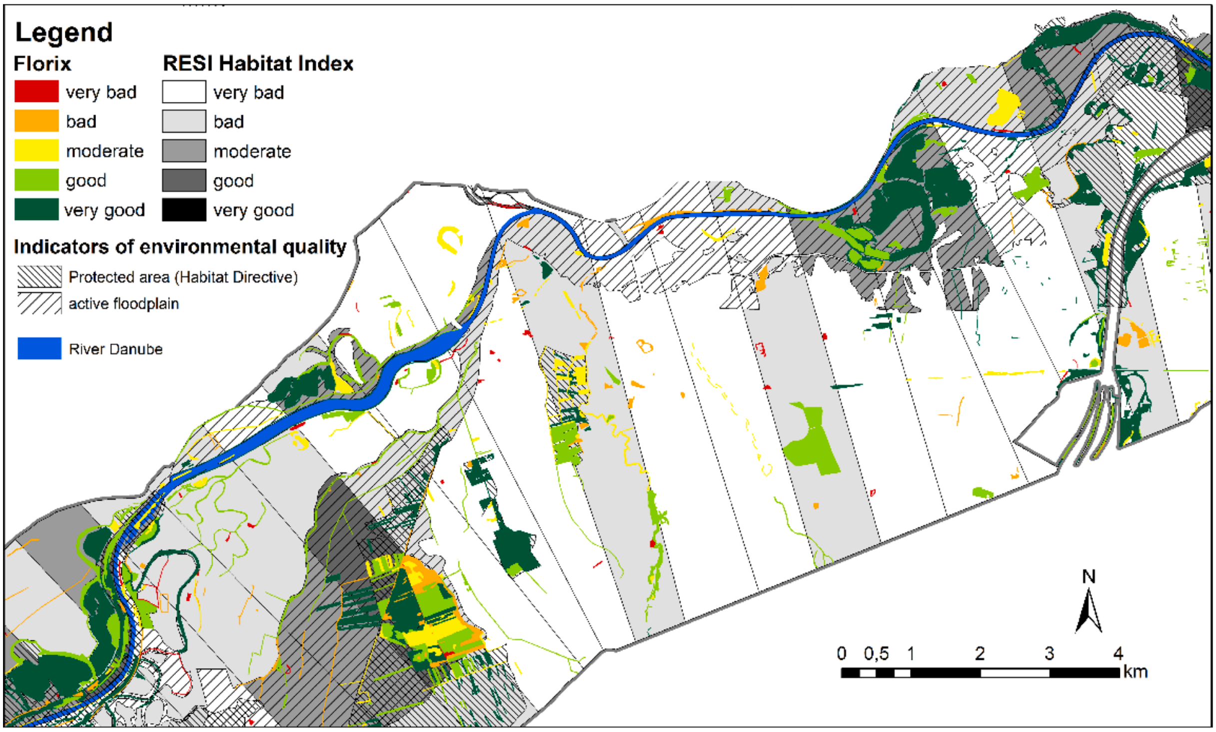

Fig. 6. Mapping of the evaluation of the habitats with *Florix* and the evaluation of the floodplain compartments with the RESI habitat index.

valuation of plant species. To complement the set of metrics we added the trait-based indicator representing the adaptation to flooding as the main driver in natural floodplains, which amplifies the significance of *Florix*.

There might be additional or substituting indicators: ruderal species indicating riverine sand or gravel banks or indicators of high nutrient availability. However, all these types of indicators represent only very special conditions of particular habitats but not the whole range of conditions of floodplains. They might be useful as additional indicators, especially as target species (Rohde 2004). Other functional plant traits like dispersal abilities (e.g. hydrochorous species) or the strategic ecological behavior according to Grime (1977) respond to floodplain specific conditions and could therefore be used to evaluate specific habitats. However, the amount of these traits varies significantly between the wide range of floodplain habitats from the gravel bank to the hardwood forest. Therefore, it is limited to use them as a general indicator for all habitat groups. Almost all types of the traits mentioned occur in the different floodplain habitats, which is documented by the fact that 74 % of all recorded plant species were identified as indicators of floodplains in this study.

Our results clearly demonstrate that there are significant differences in the number of indicators between the different habitat types. Reed beds and water bodies are known to harbor lower species numbers in contrast to forests or grassland (Ellenberg 2009). However, the different indicators show different behavior for the different habitat types, e.g. nature conservation indicators show a significantly higher percentage in water bodies than in the other habitat types. Taking these facts into account when developing *Florix*, it is important to define the thresholds for each indicator and each habitat type individually. For some floodplain types (e.g. in grassland dominated agricultural landscapes like that of the Elbe (Damm 2013)), it might be appropriate to differentiate even further in more detailed habitat types, e.g. grassland into moisture and dry grasslands as we did for forests.

4.2. Validation and application of Florix

Interruption of lateral connectivity which is severest in former floodplains is one of the main pressures on the ecological status of floodplains (Nilsson et al. 2005). Another significant pressure is land use intensification (Hein et al. 2016). *Florix* in general is sensitive to both the loss of flooding events due to the construction of dykes and the negative impact of intensive land use prohibited in nature protection areas. For both pressures, we found significantly better *Florix* values along a gradient of>500 km and over several landscape types for those areas without or with reduced pressure.

This sensitivity of *Florix* to the pressures of lateral disconnection and land use intensity was also observed at the level of habitat types, excepted for water bodies and softwood riparian forests. For water bodies, there were no differences between protected and unprotected areas, but a trend could be seen, that the value for nature conservation was even better in the former floodplain. This is in line with findings (Van Geest et al. 2005, Stammel et al. 2021) that, on the one hand, water-level fluctuation and flooding events can lead to disturbances, flushing away the occurring species from time to time, resulting in lower species richness after these floodings. On the other hand, water bodies in the active floodplain are sinks of nutrients and sediments during floods resulting in eutrophication and reduced numbers of species (e.g. nature conservation indicators) whereas this effect is less strong beyond the dykes. For softwood riparian forests, the differences between protected and unprotected areas were also not significant. This can be explained as this habitat type is not of any interest for land use, neither protected nor unprotected. The pressure on this habitat type are rather the missing dynamics as the rejuvenation of its stands depends strongly on newly developed river banks after flooding events. Therefore, softwood riparian forests depend strongly on connectivity and flooding events, as we found very strong differences between active and former floodplains in our data set.

Florix also demonstrated sensitivity when comparing different landscape types. In case study 1 (dominated by agricultural land use), low mean values and no clear differences between the values in active and former floodplain were found. This could be due to a very low number of habitats in the active floodplain. Here, the strong pressure of land use dominates over the positive effects of the well connected, but very small active floodplain (Stammel et al. 2017, Stammel et al. 2020).

However, comparing the results of the floodplain with habitats outside the floodplain, even lower values occurred indicating that the index is sensitive for floodplain specific species. In case study 2, where forests and grasslands occupy a significant area besides arable lands, the index values for all habitat types are higher than in case study 1. These differences might also be obtained by calculating an index based on habitats (Fischer et al. 2019, Stammel et al. 2020). But we could demonstrate that the assessment of single habitats by species occurrence can show relevant differences. A highly rated floodplain forest that achieves the highest rate of 5 in the RESI habitat index can reach *Florix* values from 1 to 5. By this, *Florix* adds new, site specific information to the assessment. Compared to the entire reference area, case study 2 represents for instance very good conservational conditions for grasslands, but forests and water bodies show lower *Florix* values indicating worse ecological conditions.

Even though the validation shows good results for the data along the Danube, we identified potential for development. We assume that the indicators can be transferred to floodplains of other rivers, but probably not their thresholds. This will have to be tested for other river floodplains and data sets. Additionally, the approach of using species lists reflecting the total census of a habitat bears shortcomings: up to a minimum size, the species number is highly dependent on the area size, meaning that larger habitats will often be rated better than smaller ones. However, from a conservation point of view, this is not necessarily a failure, as larger areas have a higher quality in general with larger species populations, less edge effects (Petrášová-Šibíková et al. 2017), and higher resilience. We circumvented this phenomenon by considering only habitats>300 m^2 and thus found no significant dependence of species number on area size for our recordings. However, to achieve a better comparability also for smaller habitats, a standardized method of plot survey would be required to standardize the thresholds.

5. Conclusions: How to use and apply *Florix*

Florix was successfully tested for sensitivity against anthropogenic impacts and fulfills the requirements for an index. It is simple to apply, cost-effective and understandable even for non-experts, and yet very well points the complexity of floodplains due to the three different types of sub-indicators (species number, adaptation to flooding, nature protection). It does not relate to any reference state of existing floodplains such as the one used for the WFD. As all floodplains in Germany are strongly altered (BMU and BfN 2021) using such a reference state would be based on many vague assumptions reflecting quite some uncertainty. Even if all potential floodplain-specific species identified by their characteristics are summarized in a reference list, this assessment does not produce a comparison with a reference area but with all existing habitats within a certain region. The method can easily be transferred to other regions and is therefore applicable to extensive geographical areas.

For such transfer, a database with a reasonable number of records of floristic data (at least 300 records per habitat type) should be used which is not common practice yet. A standardized recording procedure for habitat mapping could help to transfer *Florix* to a wider geographical scale and achieve comparable results for the floristic quality of floodplains. Ideally, such a procedure should be applied not only within one region, but at a national or EU wide level (comparable to the WFD monitoring). A standardized method for instance in the framework of the regular monitoring for the Habitats Directive could be used to achieve this result. Habitat types have to be differentiated when defining thresholds for the subindicators to identify the ecological quality of habitats. *Florix* can then be used, (1) to evaluate single habitats, e.g. during environmental impact assessment or monitoring of restoration projects; (2) to identify the overall value of habitats for nature conservation in a region in comparison to the reference area and by this the need to improve selected habitat types there; (3) to identify the human impacts on the habitats in a region by comparing them (e.g. active and former floodplain); or (4) to complement the evaluation of floodplains by the RESI habitat approach (Fischer et al. 2019).

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Author contributions

BS conceptualized and validated the method, performed analyses, interpretation and discussion of results together with methodological input from CF-B, CD and PH; CD, CF-B, AR, MG, PH, SK, FF and MS provided critical feedback for validation and visualisation and helped shape the article. SK created maps and supported visualisation. BS did the writing of the original draft, All authors contributed to the manuscript by reviewing and editing.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109685.

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