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RESEARCH PAPER

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# Effects of flooding duration on the occurrence of three hardwood floodplain forest species inside and outside a dike relocation area at the Elbe River

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## Abstract

Floodplain forests have become rare in Europe due to anthropogenic changes. A critical aspect of their restoration is reintroducing flooding via dike relocation, as implemented at the Elbe River near Lenzen/Germany. How forest development is influenced by dike relocation is still unclear and difficult to predict. Inside the dike relocation area at the Elbe River, most trees were planted. Due to high tree mortality, we asked if the relative elevation of the planted trees and thus the number of flooding days inside the relocation area was comparable to the prevailing flooding regime in the surrounding active floodplain. Therefore, the positions of *Ulmus laevis*, *Quercus robur*, and *Crataegus monogyna* individuals were recorded using a DGPS and merged with a digital terrain model. Subsequently, relative elevations and numbers of flooding days per year and growing season (averages for 2011–2017) were calculated. The most flooding tolerant species, *U. laevis*, occurred at the lowest sites and tolerated the highest number of flooding days, followed by *Q. robur*, and finally by the least flooding tolerant species *C. monogyna*. All three species occurred at lower sites inside the dike relocation area and were exposed to longer flooding durations compared to sites outside the area. This was due to the complex morphology of this area and its special flooding and flow dynamics, which differed from the conditions in the surrounding active floodplain. Although the mean flooding duration was within the growth range of hardwood floodplain forests (Ficario-Ulmetum), most individuals may not have established at the planted sites under natural conditions. Therefore, we recommend not relying only on plantings but also allowing natural succession. Then, species that can cope with the hydrological site characteristics may also establish in the long term.

**KEYWORDS**

dike relocation, flooding duration, flooding tolerance, floodplain forest, floodplain restoration

# 1 | INTRODUCTION

Floodplain forests are distinct, azonal vegetation communities along floodplains worldwide (Richardson et al., 2007). Due to the high variability between flooding and drought conditions as well as their small-scale heterogeneity, floodplain forests belong to the most species-rich habitats in Central Europe (Koenzen, 2005). In past centuries, many floodplain forests were cleared for settlements and agriculture (Colditz, 1994). For flood protection and to expand the European navigable waterways, dikes were constructed often near the riverbank, leading to a disconnection between floodplains and rivers (Damm, 2013). Such anthropogenic interventions changed the hydrological regime, leading to large losses of floodplains and their typical vegetation. According to the status report on German floodplains, only 1% of the natural hardwood forests in the active floodplains were left (Koenzen & Günther-Diringer, 2021). Due to the high nature conservation value of regularly flooded floodplain forests and their small area today, their conservation and restoration is an important goal of nature conservation in river landscapes (Finck et al., 2002).

Dike relocation or dike realignment is one of the most effective methods to restore hydrologically dynamic floodplains, that is, re-exposing them to periodically flooding. However, former land use in areas where dike relocation takes place is usually dominated by arable fields or cultivated grassland and thus plant communities that have not been exposed to flooding for a long time. Consequently, secondary succession takes place after changing the hydrological regime. This means that other species communities, better adapted to the new conditions, will gradually replace the existing ones.

One of the largest completed dike relocation sites in Germany, with the objective of restoring floodplain forests, is located at the Elbe River near the city of Lenzen. This nature conservation project was implemented between 2002 and 2011 (Damm, 2013). During this time, a 6.1 km long new dike was built, up to 1.3 km inland of the old dike. The old dike was not completely removed but opened by six breaches, which resulted in an area of 420 ha hydrologically reconnected floodplain (Damm, 2013). To initiate and speed up the development of floodplain forests, 77 ha of trees were also planted from 2004 to 2008.

Under natural conditions, the zonation of woody species in floodplains is mainly determined by the hydrological regime (Blom & Voesenek, 1996). Minor variations in flooding frequency and duration result in distinct differences in species composition (Kozlowski, 2002). Softwood floodplain forests (Salicetum triandro-viminalis and Salicetum albae) can be found at lower elevations with more frequent and prolonged flooding. In contrast, hardwood floodplain forests (Ficario-Ulmetum) are located at higher elevations, and are thus flooded less frequently and for a shorter time (Siebel & Bouwma, 1998).

The main problem for terrestrial plants during flooding is the shortage of oxygen (Glenz et al., 2006), which can lead to reduced plant vitality or even death (Mommer & Visser, 2005). Therefore, species in floodplain forests must be adapted to changing water levels and flooding (Glenz et al., 2006). Flooding tolerance can be regarded as a key factor for the successful establishment and development of plants (Glenz et al., 2006; Leyer, 2004). However, not all plant species are equally vulnerable to flooding. Besides the two main decisive factors flooding frequency and duration, the seasonal timing influences plant performance, as flooding has little or no effect during the winter season, but can severely affect the growth and survival of plants during the growing season due to a higher metabolic activity (Kozlowski, 1997; Siebel & Blom, 1998).

Due to the complex and unpredictable hydrodynamics in floodplains, the success of floodplain restoration projects is difficult to predict and, as in the case of the studied dike relocation area (DRA), where restoration has resulted in low survival of planted trees. Furthermore, it is known that hydrodynamics inside the DRA after opening the old dike do not correspond to the natural conditions before dike construction (Faulhaber et al., 2013), as the backflow of flooding water is comparatively slow (Krüger, 2012) and might lead to longer flooding duration inside the DRA. To increase the understanding of dike relocation and the importance of flooding durations, we assessed whether the planted trees inside the DRA were exposed to longer flooding durations than the individuals occurring in the surrounding active floodplain. Therefore, we investigated the occurrence of three hardwood floodplain forest species (*Quercus robur*, *Ulmus laevis*, and *Crataegus monogyna*) inside and outside the DRA. It can be assumed that sites at higher relative elevation will be flooded for shorter periods and less often than sites at lower relative elevation and that there are species-specific differences depending on flooding tolerance. Therefore, we tested the following hypotheses: (1) Due to its flooding tolerance, *U. laevis* occurs at the lowest elevations and is exposed to the highest annual number of flooding days, followed by *Q. robur*, and finally *C. monogyna*. (2) Species differ in their occurrence along the elevational gradient inside the DRA compared to the surrounding active floodplain and have to tolerate a higher annual number of flooding days inside than outside the DRA.

# 2 | METHODS

## 2.1 | Study site characteristics

The study area lies in the floodplain of the German lower Middle Elbe River section, including the dike relocation area near Lenzen and an area between 40 km upstream and 20 km downstream along the main river channel (Figure 1). This area belongs to the Biosphere Reserve Elbe River Landscape and is a site of pan-European importance, according to the European Habitats Directive (MLUL & LfU, 2017). The discharge of the Elbe is characterised by spring floods, with the beginning of snow melting in the Czech Giant Mountains, while summer floods are rather rare (Leyer, 2002). Phases of low water discharge usually occur between July and October. The study region belongs to a transitional climate zone between the maritime climate of Western Europe and the continental climate of Eastern

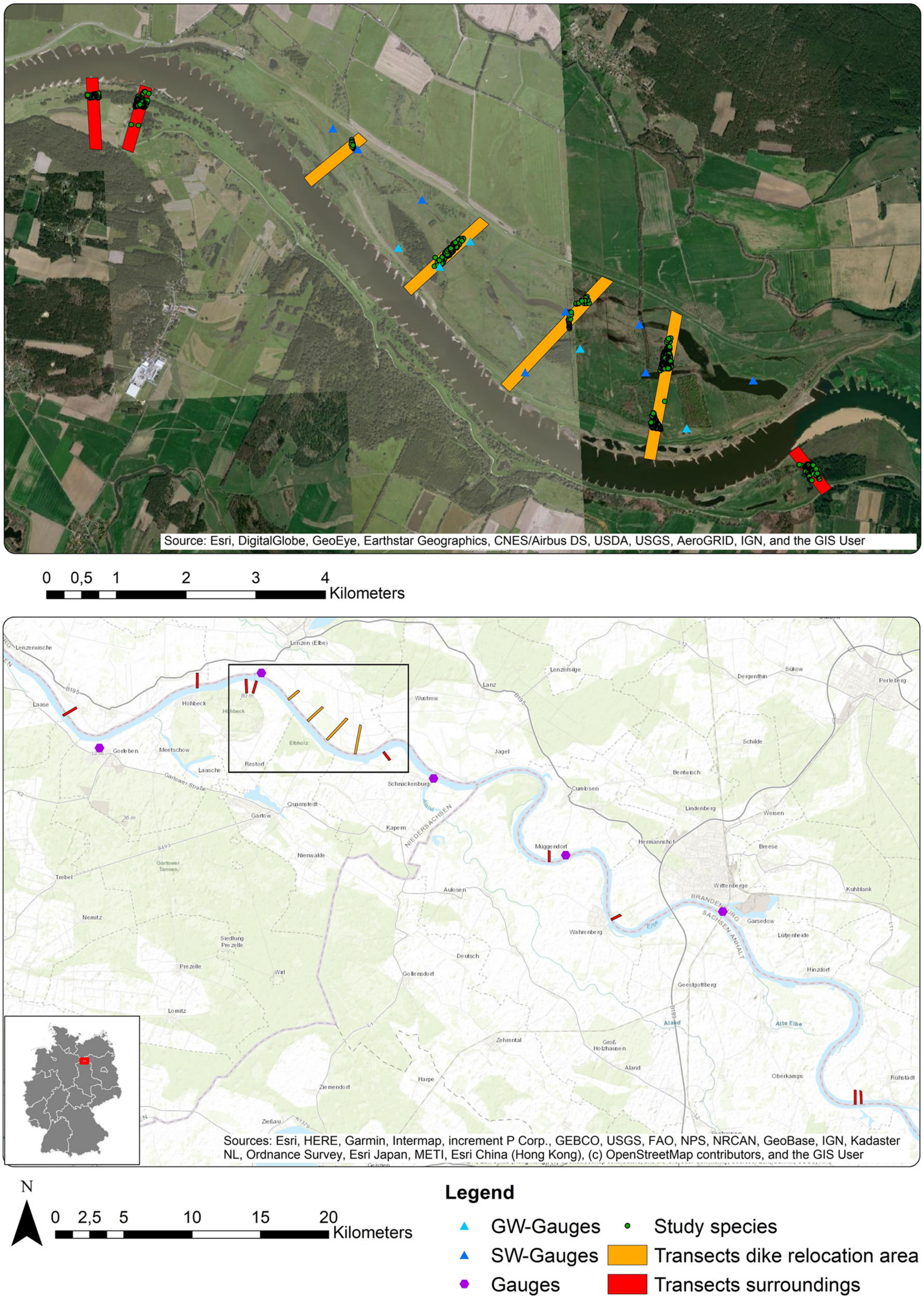


**FIGURE 1** Study area including transects, growth position of the study species in the DRA (orange) and its surroundings (red), as well as corresponding river-, GW-, and SW-gauges. DRA, dike relocation area; GW, ground water; SW, surface water

Europe. The average annual temperature was 9.7°C, and the mean annual precipitation was 607 mm in 1995–2017 (DWD, 2018).

The DRA is part of a major national conservation project in which 420 ha of hydrological floodplain were reconnected to the hydrodynamics of the Elbe River between 2002 and 2011 (Damm, 2013). To initiate alluvial forest, trees were planted on 77 ha of grassland from 2004 to 2008. Due to physical barriers, numerous flood channels, and depressions, the area is characterised by a specific and complex morphology and hydrodynamics (Faulhaber et al., 2013).

The characteristic vegetation of the area is a mosaic of fallow grassland, floodplain meadows, forb communities, and initial floodplain forests from man-made plantings. The forests consist mainly of the plant communities: Salicetum triandro-viminalis, Salicetum albae, and Querco-Ulmetum laevis. The latter is dominated by *U. laevis*, *Fraxinus excelsior*, and *Q. robur* in the tree layer, as well as *C. monogyna* and *Cornus sanguinea* in the shrub layer.

## 2.2 | Study species

The three species, *Q. robur*, *U. laevis*, and *C. monogyna*, are native to temperate regions in Europe (Caudullo & de Rigo, 2016; Meusel et al., 1965). They are typical forest species of the hardwood floodplain (Ficario-Ulmetum), often distributed in wet lowlands and floodplains along rivers due to their tolerance to periodic flooding (Jäger et al., 2017). They prefer fertile and nutritious clay soils (Jäger et al., 2017). *U. laevis* is considered the most flooding tolerant, followed by *Q. robur* and finally *C. monogyna* (Glenz et al., 2006; Kozlowski, 1997; Schmull & Thomas, 2000). Differences can be explained by the ability to react to resulting stress in morphological, physiological and metabolic terms (Glenz et al., 2006).

## 2.3 | Selection of transects

In the active floodplains of the DRA and within an area 40 km upstream and 20 km downstream of the DRA, transects were defined using ArcGIS 10.5 (Figure 1). For transect selection, information about the distribution of the target species was obtained from the administration offices of the 'Elbe-Brandenburg River Landscape Biosphere Reserve' and the 'Lower Saxony Elbe Valley Biosphere Reserve'. This ensured that the respective species were present in each transect. Each transect was 100 m wide and at a 90° angle from the centre line of the Elbe River to the dike, covering the entire elevational gradient. Four transects with a total area of 41.24 ha were defined inside the DRA, whereas nine transects with 42.94 ha were defined in the active floodplain outside the DRA (Figure 1). Since the distance between the Elbe and the dike is highly variable, approximately the same area was used instead of the same number of transects for both locations.

## 2.4 | Sampling

Sampling in the DRA and the surrounding floodplain took place once per transect either from 7th to 25th August 2017 or from 13th to 31st August 2018. The position of all individuals of the study species of greater than or equal to 2 m height (*U. laevis*, *Q. robur*, and *C. monogyna*) was recorded precisely using a DGPS (Panasonic FZ-G1 Toughpad).

## 2.5 | Calculation of the relative elevation and number of flooding days

To calculate the Elbe water levels, the nearest corresponding river gauges in Sandau (Elbe km 416.10), Wittenberge (Elbe km 453.98), Müggendorf (Elbe km 463.94), Schnackenburg (Elbe km 474.56), Lenzen (Elbe km 484.70), and Gorleben (Elbe km 492.95) were used (Figure 1). Based on these gauges, water level positions for the long-term mean runoff (MQ) for the entire study area were determined using stationary one-dimensional calculations (SOBEK), available via the river hydrological software FLYS (BfG 2013; reference period 1890–2006). As the DRA morphology is complex, 13 ground water (GW) and surface water (SW) measuring gauges inside the DRA were used to increase the precision of the river gauge data (Figure 1).

Based on the most up-to-date digital terrain model (DTM; grid size: 1 × 1 m; Brockmann et al., 2008), the relative elevation above the mean water level of the Elbe of each growth position was calculated by subtracting the water level of the Elbe from the terrain height of the DTM. Subsequently, relative elevation was used to express relative elevation above the mean water level of the Elbe.

Also, based on the DTM, the number of flooding days (number of days with water levels above the elevation surface) for the entire year (January–December) and the growing season (1st April to 30th September) for the years 2011–2017 were calculated by interpolating each measured individual from the corresponding gauges. The interpolation was carried out using inverse distance weighting (Shepard, 1968). Since no additional gauge stations were available for the sites outside the DRA, their flooding duration was calculated based on the river gauges and the derived water level positions, respectively. In this case, possible backwater effects in depressions or flood channels could not be taken into account so that the values for sites outside the DRA correspond to an idealised dynamic, that is, unimpeded, inflow and outflow of water.

## 2.6 | Statistical analysis

We analysed the relative elevation of the growing sites of the species and their number of flooding days for the entire year and growing season for the years 2011–2017 by conducting linear mixed-effect models (LMM). We used 'species' as a fixed factor and 'relative elevation', 'mean flooding days in 2011–2017', and 'mean flooding days during growing seasons 2011–2017' as response variables and included 'transect' as a random factor for the mixed effect setup (Quinn & Keough, 2002).

To compare the relative elevation and number of flooding days, the individuals inside and outside the DRA were exposed to, separate LMMs were calculated. We used the fixed factors 'species' and 'location' and their interaction and included the random factor 'transect'. As response variables, 'relative elevation', 'mean flooding days in 2011–2017', and 'mean flooding days during growing season 2011–2017' were used. Further, we analysed the years 2011–2013 separately to represent flooding conditions of normal (2012) and extreme years (2011 with extreme winter flooding; 2013 with extreme summer flooding).

For post-hoc testing, we used pairwise comparison with Tukey adjusted *p* values. Mixed-effect models were carried out using the packages 'lme4' (Bates et al., 2015) and 'lmerTest' (Kuznetsova et al., 2017). We visually assessed diagnostic residual plots to check the preconditions of the LMMs (e.g., normal distribution, variance homogeneity) (Zuur et al., 2010). The significance level for all analyses was $\alpha = 0.05$. All statistical analyses were carried out using the R software environment (R version 4.0.3, 2020-10-10; R Development Core Team, 2020).

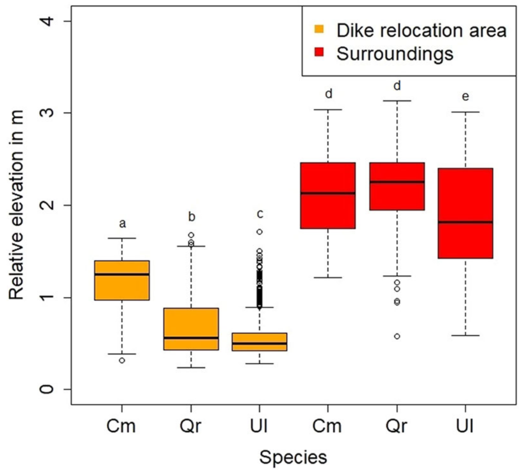


**FIGURE 2** Relative elevation in m above mean runoff (MQ) for each species inside the dike relocation area (orange) and outside (surroundings; red) (Cm = *C. monogyna*, Qr = *Q. robur*, Ul = *U. laevis*; different letters indicate significant differences between groups assessed by Tukey tests). The boxplot includes a box representing the interquartile range (25th–75th percentile), whiskers, indicating minimum and maximum values and the median

## 3 | RESULTS

Altogether, 2516 individuals were recorded in the transects (1166 of *U. laevis*, 853 of *Q. robur*, and 497 of *C. monogyna*). The relative elevation of the growing sites differed significantly between the investigated species ($t = 21.84$, 26.94, 10.44, $p \leq 0.001$) and the sites inside and outside the DRA ($t = 4.82$, $p \leq 0.001$). All occurrences of species inside the DRA were at considerably lower relative elevations than those in the surrounding active floodplain (Figure 2).

Inside the DRA, *C. monogyna* occurred at an average 1.1 m above the Elbe mean water level, followed by *Q. robur* at 0.66 m, while *U. laevis* grew at 0.57 m (Figure 2). In the surrounding active floodplain, *C. monogyna* and *Q. robur* occurred 2.1 m above the Elbe mean water level, while *U. laevis* grew at sites averaged 1.9 m (Figure 2).

Inside the DRA, there were no differences in the number of flooding days between *U. laevis* and *Q. robur*, but both showed a higher flooding duration compared to *C. monogyna* for the entire year ($t = 22.87$, 28.64, $p \leq 0.001$) and the growing season ($t = 19.75$, 24.33, $p \leq 0.001$; Figure 3). In the surroundings, U. laevis was exposed to a higher annual flooding duration than *Q. robur* and *C. monogyna*, while there were no differences between the species during the growing season (Figure 3). The range of flooding days between the different species and between the individuals of the same species, especially that of *C. monogyna*, was larger inside the DRA than in the surroundings (Figure 3).

The individuals growing inside the DRA were exposed to more flooding days than those in the surroundings in 2011–2017, namely 10–61 days throughout the entire year and 5–24 days during the growing season. In contrast, individuals in the surroundings had to tolerate 5–40 days throughout the entire year and 4–8 days during the growing season ($t = 7.26$, 6.66, $p \leq 0.001$; Figure 3).

When considering the single years 2011, 2012, and 2013, *U. laevis* and *Q. robur* again showed a higher number of flooding days than *C. monogyna* inside the DRA, while U. laevis showed a higher flooding duration than Q. robur and C. monogyna in the surroundings ($t = 28.09$, 22.10, $p \leq 0.001$; Table 1).

When focussing on the year 2011, flooding only occurred during the winter season for both locations. Regarding the entire year, there was an average of 44 flooding days for *C. monogyna* and 58 for *Q. robur* and *U. laevis* inside the DRA and about half as much for each species in the surroundings (Table 1). In the 'average' year 2012, there were counted 24 flooding days for *C. monogyna*, 45 for *Q. robur*, and 49 for *U. laevis* inside the DRA for the entire year, while there were 4, 6, and 11 outside the DRA, respectively. During the growing season, flooding occurred with an average of 18 flooding days for *Q. robur* and *U. laevis* and only for the sites inside the DRA (Table 1). During 2013, a year with extreme summer flooding, *Q. robur* and *U. laevis* were exposed to an average of 106 flooding days throughout the entire year and 62 days during the vegetation period inside the DRA, in contrast to 34 and 45, and 23 and 26 days, respectively, in the surroundings (Table 1). *C. monogyna* was exposed to an average of 72 flooding days for the entire year and 44 days for the growing season inside the DRA, while the average number of flooding days for the surroundings was 29 for the entire year and 21 during the growing season (Table 1).

## 4 | DISCUSSION

Our first hypothesis that the occurrence of the species along the relative elevation gradient and thus the number of flooding days differed according to their flooding tolerance could be confirmed. In

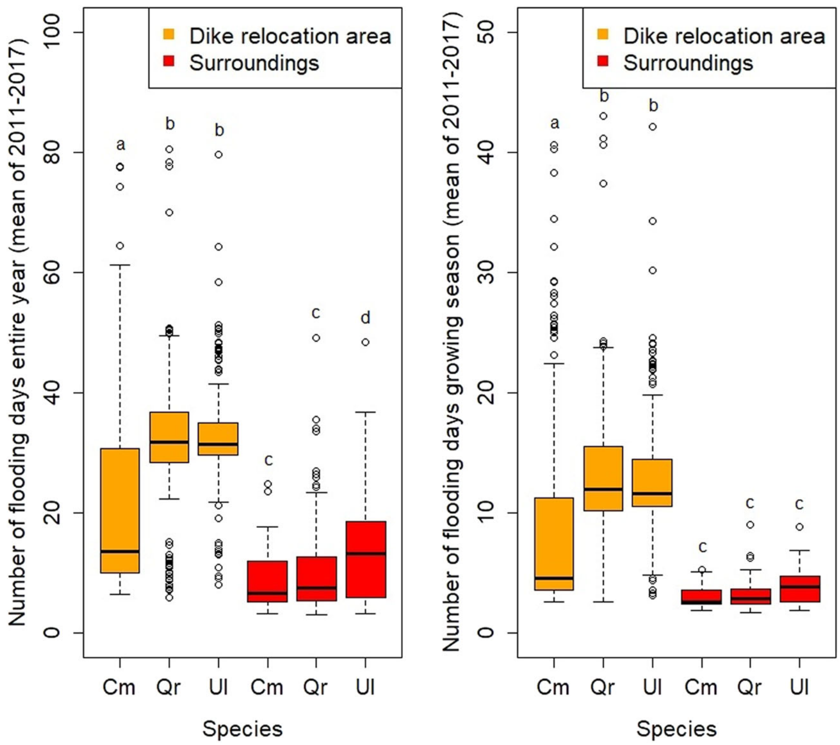


**FIGURE 3** Number of flooding days for each species for the entire year (left) (using mean values of the period 2011–2017) and during the growing season (right) inside the DRA (orange) and for its surroundings (red) (Cm = *C. monogyna*, Qr = *Q. robur*, Ul = *U. laevis*; different letters indicate significant differences between groups assessed by Tukey tests). Note the different scaling of *y*-axes. The boxplot includes a box representing the interquartile range (25th–75th percentile), whiskers, indicating minimum and maximum values and the median

**TABLE 1** Mean number of flooding days for each species for the entire year and during the growing season in 2011, 2012, and 2013 inside the DRA (left column) and its surroundings (right column) (Cm = *C. monogyna*, Qr = *Q. robur*, Ul = *U. laevis*)

| | Mean number of flooding days for the entire year | | | | | | Mean number of flooding days during the growing season | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year/ Species | Cm | | Qr | | Ul | | Cm | | Qr | | Ul | |
| 2011 | 44 | 25 | 58 | 29 | 58 | 34 | 2 | 0 | 2 | 0 | 0 | 0 |
| 2012 | 24 | 4 | 45 | 6 | 49 | 11 | 9 | 0 | 18 | 0 | 18 | 0 |
| 2013 | 72 | 29 | 106 | 34 | 106 | 45 | 44 | 21 | 62 | 23 | 62 | 26 |

general, *U. laevis* was located at the lowest sites and tolerated most flooding days, followed by *Q. robur*, and finally *C. monogyna*. In general, a flooding duration typical for Ficario-Ulmetum species to tolerate is 1 to 85 days year$^{-1}$ (Pott, 2000). At sites along the Lower Middle Elbe, *C. monogyna* and *Q. robur* were flooded on average for five and 14 days but could endure a maximum of 90 and 96 days per year, respectively, from 1964 to 1998 (Pott, 2000). In comparison, *U. laevis* reached an average of 45 days but could survive at sites flooded up to 119 days per year (Pott, 2000). Our findings were within this range; however, the averaged flooding days for *C. monogyna* and *Q. robur* were higher than the averaged values of Pott (2000). While flooding adaptation of *C. monogyna* is poorly understood, *Q. robur* and *U. laevis* are known to have the ability to form aerenchyma tissue, adventitious roots, and lenticels to avoid a lack of oxygen at the roots (Glenz et al., 2006; Heklau et al., 2019; Kramer et al., 2008).

Our second hypothesis, stating that the individuals inside the DRA were exposed to a higher number of flooding days compared to those outside, could be confirmed, too. Although the mean number of flooding days even inside the DRA was within the typical growth range of hardwood floodplain forests (Ficario-Ulmetum), the survival rate of the planted trees was very low during the control of success in 2016, in which only 7% of the planted trees were recorded (Purps, 2016). Altogether, only 10% of *U. laevis*, 3% of *Q. robur*, and 1% of *C. monogyna* survived (Purps, 2016).

The low survival rate of the planted trees was probably due to successive stress events already in the first years after the old dike's opening. In addition to flooding during winter in 2011 and 2012, an extreme flooding occurred during late summer 2013 (Purps, 2016). The study of Hall and Smith (1955) on the effects of flooding on woody plants showed that even the most flooding-tolerant species need to be unflooded for at least half a growing season to survive, which was not provided due to the summer flood 2013. As flooding is more harmful during the growing season than the dormant season (Vreugdenhil et al., 2006), flooding duration should be reported not only for the entire year but also for the vegetation period. Therefore, it is important to consider the flow regime of the respective river for future restoration measures. For example, while the Elbe, as well as the rivers Main and Neckar, are characterised by a nivo-pluvial discharge regime, in which floods primarily occur in winter and rarely in summer, the river Rhine has a nival discharge regime due to its alpine catchment area with regular summer floods (Belz, 2010).

In general, the recorded species inside the DRA were located one to two metres above the Elbe mean water level, while the investigated surrounding area was about one metre higher. Since the investigated trees need open ground and high light availability during germination and establishment (Purps, 2016), a natural tree establishment in this area seems to be principally constrained to higher sites, where the nutrient content is lower and thus a more open vegetation cover persists (Pott, 2000; Purps, 2016). Similar findings were observed in the study of Dister et al. (1992) on the River Rhine, in which successful immigration of hardwood floodplain forest species was only possible at higher, less nutrient-rich soils with a lower herb density. This is probably also a reason, why the individuals of the surrounding active floodplain established successfully at higher sites. The lower sites in this area were primarily dominated by floodplain meadows (Pott, 2000; Purps, 2016). Although open ground is ensured in plantings, establishment can still be hindered as soon as it is overgrown again.

While the first hurdle, namely germination, has already been successfully overcome in plantings, under natural reproduction germination can be limited by many factors. In addition to the species-specific environmental conditions and site characteristics needed for successful germination, seed predation can also be a limiting factor. For example, Venturas et al. (2014) showed that *U. laevis* could only regenerate in mast years, when conditions were optimal, while in nonmast years, postdispersal predation provided almost no chance for *U. laevis* to regenerate (Venturas et al., 2014). While the establishment of a single tree could be a very rare event, the natural regeneration of hardwood floodplains can be a very slow process, due to many influencing factors and only occurs over decades (Mosner et al., 2009; Reif & Gärtner, 2007).

Although the relative elevation of the individuals at both locations varied by about one metre, the number of flooding days inside the DRA fluctuated over a wider range than outside. This can be explained by the complex morphology of the terrain and its particular flooding and flow dynamics that differ from the conditions of the active floodplain in the surroundings (Faulhaber et al., 2013). When the water level rises, the water first enters the area from downstream, that is, against the flow direction of the Elbe main river channel, before it finally flows through the whole area from upstream at high water levels. This and the fact that the old dike is a considerable barrier, where the water can only exit at the six breaches, leads to a slow backflow into the Elbe (Krüger, 2012), increasing the already higher number of flooding days due to the lower elevation. A slower backflow was also documented for the reconnected floodplain 'Kühkopf-Knoblochsaue' at the Rhine River, where the dike broke in 1983 and was not fixed again (Dister et al., 1990). Further, for the study area at the Elbe River, the soil consists mainly of well-permeable sands and gravel sands, which leads to the fact that the groundwater level often depends directly on the river (Montenegro, 2013). Therefore, flooding duration is also influenced via soil and groundwater balance (Krüger, 2012). While the water remains inside the DRA, it flows back comparatively quickly in the surrounding active floodplain. This illustrates how important geomorphological processes are in addition to ecological and hydrological aspects.

## 5 | CONCLUSION

In summary, the studied species occurred at different elevations according to their specific flooding tolerance and were generally exposed to a higher number of flooding days inside than outside the DRA. Although, the mean flooding duration was within the typical range of hardwood floodplain forests, the success of tree plantings depended largely on the hydrological situations in the year of the plantings as well as the subsequent years. As plantings are often costly and do not guarantee successful regeneration, we recommend not relying exclusively on plantings but also allowing natural succession, even if it takes a long time. Then, species that can cope with the hydrological site characteristics would establish in the long term. To gain a better understanding of the interacting processes in floodplains, long-term monitoring programs should be carried out, ideally, every 5–10 years over 10–15 decades, as a hardwood floodplain forest requires a development period of 100–150 years or longer (Bierhals et al., 2004; Scholz et al., 2012). Only then it will be possible to provide better predictions and possible solutions for future restoration measures.

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