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Research Article

Perseverance of management is needed – Efficient long-term strategy of *Reynoutria* management

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Abstract

One of the most problematic invasive species in Europe are knotweeds from genus *Reynoutria* (*Fallopia*) which have significant negative impact on the native communities as well on human activities. Therefore, they are a target of many control programmes. Due to their high regeneration potential, their management is problematic, and only chemical treatment is reported to be sufficiently effective.

The aim of this paper was to describe and analyse the patterns of *Reynoutria* invasion under long-term chemical treatment with glyphosate-based herbicide in The Morávka river floodplain, Czech Republic. The data covers 17 years of management which started with the European project "Preservation of alluvial forest habitats in the Morávka river basin". We focus on (i) assessment of *Reynoutria* distribution during long-term management, (ii) analysis of the change of distribution according to the habitat, and (iii) discussion of the optimal management strategy based on the long-term data.

Distribution data was obtained using GNSS field mapping. Before the start of the study in 2007, *Reynoutria* stands covered 29% of the study area (96.9 ha). As a result of systematic whole area chemical management, the extent decreased to 19.6% (65.3 ha) in 2009, and even reached 14.5% (48.2 ha) in 2013, three years after its end. Due to implementation of local chemical management in the following years, the area of *Reynoutria* was maintained at similar level, with minimum value 41.8 ha in 2018 and a slight increase in recent mapping in 2023.

Beside the extent, the structure and coverage of invaded sites was analysed. There was a clear trend of fragmentation of larger polycormons with high coverage into many smaller and less dense ones as a result of chemical spraying. The average size of *Reynoutria* stand decreased from 0.61 ha in 2007 to half in 2013 (0.32 ha) to 0.15 ha in 2023. Testing of the effects of time, habitat, and biotope did not reveal significant differences of changes of extent and abundance over different environments (forest, open, bare ground), which indicates that there are no differences in reaction to management in the studied habitat and vegetation types.

Our study provides a robust and unique overview of the invasion, reinvasion, and suppression dynamics for an important invasive species. If herbicide management is used, chemical treatment must be quite long-term as even three years of intensive glyphosate foliar spray application was not sufficient for the complete eradication of *Reynoutria*.

Therefore, we propose the following procedure for effective chemical management of *Reynoutria*:

1) In largely infested sites, the first step is to reduce the distribution of *Reynoutria* stands to isolated polycormons. This phase can last 3–5 years.

2) After reaching the state of sparse distribution of *Reynoutria*, we recommend herbicide application only in periods of every 3–5 years depending on the local context and rate of regrowth.

3) At sites exposed to soil disturbances, where the soil is contaminated by fragments of *Reynoutria* rhizomes, there is a need to apply herbicide immediately to target newly resprouting individuals.

Key words: *Fallopia*, GNSS, knotweed, long-term management, mapping, neophyte, protected area, Roundup

Introduction

The spread of non-native plant species has a negative impact on the conservation of native communities and is one of the most serious threats to ecosystem biodiversity (Pyšek et al. 2020; IPBES 2023). Invasibility and the level of invasion differs among different habitat types (Chytrý et al. 2005) and is generally the highest in riparian stands and riverbanks (Chytrý et al. 2009; Pyšek et al. 2010; Fristoe et al. 2021). In terms of invasion ecology, floodplains exhibit most of the characteristics that support invasion of non-native species: strong diaspore introduction, frequent disturbances, and major human impact (Richardson et al. 2007).

One of the most problematic invasive neophytes in the Czech Republic are species from the genus *Reynoutria* (syn. *Fallopia* sp.) (Pyšek et al. 2022). *Reynoutria* sp. have a significantly negative impact on the native communities, including soil environment (Hejda et al. 2009, 2021; Pergl et al. 2023). Their first spread into wild nature was reported in the territory of today's Czech Republic in the late 19th century (Mandák et al. 2004). Due to the negative impacts of *Reynoutria* on native species, it is desirable to carry out their control programmes especially in environmentally valuable locations, as their total mass eradication is practically impossible (Delbart et al. 2012; Cottet et al. 2015; Halas et al. 2018). *Reynoutria* is managed mechanically, chemically or by a combination of both methods. Mechanical treatment is not very effective in the long term (Scott and Marrs 1984; Jones et al. 2020a; Bzdega et al. 2022; Kadlecová et al. 2022); chemical treatment using a Glyphosate active ingredient is reported to be the most effective (Kadlecová et al. 2022; Hocking et al. 2023). Biological control on *Reynoutria* is tested, but not yet very effective (Shaw et al. 2011). The effectiveness of less common methods such as plastic sheet covering, stem injection, digging or ploughing varies largely and there are many regional guidelines targeted on practical use, even in regional languages (see e.g., Child and Wade 2000; Mantzou 2008; Csiszár and Korda 2017; Bzdega et al. 2022) which are the useful source of information for local managers. Long-term efficiency of these methods such as hot water/steam and/or covering by a plastic sheet is not available, and their efficiency in the short run is suspicious (Jones et al. 2020a; Dusz et al. 2021). The study by Mantzou (2008) provides a comprehensive list of methods with their cost available mostly for human-made stands, but again without any longer efficiency evaluation. It has to be kept in mind, that there can be regional/country restrictions on use of herbicides.

Even though the use of herbicides is mostly rejected by the public compared to mechanical methods, application of herbicides leads to more effective control of *Reynoutria* and can therefore lead to a less negative overall effect on the environment in terms of its pollution (Pergl et al. 2020a; Hocking et al. 2023).

The wide and frequent use of herbicides can be linked to a negative effect on surrounding ecosystems through a direct effect on pollinators, the effects on non-target organisms, and the effects of herbicide residues in the soil and water. Therefore, there is a continuous effort to minimize the use of herbicide applied by spraying. Unfortunately, for large *Reynoutria* stands the foliar spraying is the only effective management, and therefore we need to identify ways to limit the amount of used herbicide.

The effectiveness of management of invasive species depends largely on the level of invasion. Several studies have shown that the success of eradication depends on time, extent, abundance and regulation of the propagule pressure (Pluess et al. 2012). Even though there are continuously invested financial and human-labour resources to manage the invasive species, the effectiveness of individual projects at a large-scale perspective is under-evaluated. However, the need for prioritization of management is needed at different regional scales and also at the level of species, as some species can be tolerated due to high management costs, low effect of management and low environmental risk (Pergl et al. 2016). Such assessments rarely exist. Long-term data is scarce as most of the projects are limited to a duration of approximately 3–5 years (Kettenring and Adams 2011; Pergl et al. 2020b).

As *Reynoutria* is one of the most problematic species in Europe, there have been many projects devoted to developing efficient and sustainable control methods (Kadlecová et al. 2022). One was the European project "Preservation of alluvial forest habitats in the Morávka river basin", which took place in 2007–2010 (LIFE-Morávka 2007; Barták et al. 2010). The main objective of this was to suppress the population of *Reynoutria* in the study area. It was the largest continuous coordinated control programme of this species in the Czech Republic at the time.

Distribution of *Reynoutria* can be mapped relatively easily by the methods of aerial photographs (Martin et al. 2018) or by the methods of direct field mapping (Blahuta et al. 2016). Currently, a common mapping method is the use of Global Navigation Satellite System (GNSS) based on the use of Global Positioning System (GPS) (Teunissen and Montenbruck 2017). Negrea et al. (2022) used their own spectral UAV (Unmanned Aerial Vehicle) data combined with in-situ measurements to estimate the expansion potential of *Reynoutria japonica* with the Inverse Distance Weighted (IDW) method being used for interpolation. Jovanović et al. (2018) observed Southeastern Europe for *Reynoutria* niche modelling. For the purpose of data collection, Moore et al. (2006), Molitoris (2013), Jovanović et al. (2018) used GPS measurements. Dyrmann et al. (2021) used neural network classification for Camera Assisted Roadside Monitoring to observe invasive alien plant species (including *Reynoutria*).

Based on the outlined context of invasion of *Reynoutria* and the possible management options, our study (i) assesses the distribution of *Reynoutria* in the Morávka riverside during long-term management, (ii) analyses the change of distribution according to the habitat, and (iii) discusses the optimal management strategy based on the long-term data.

Material and methods

Study area

The study area of 334.1 ha is located in northern Moravia between the municipalities of Frýdek-Místek and Vyšní Lhoty (the outermost municipality), covering the floodplain landscape in the vicinity of the Morávka River (river kilometre 1.1–11.5) in the elevation range 298–380 m (Figs 1, 2). Orographically, the territory belongs to the Sub-Beskydy Highlands. The Morávka is a watercourse of the third

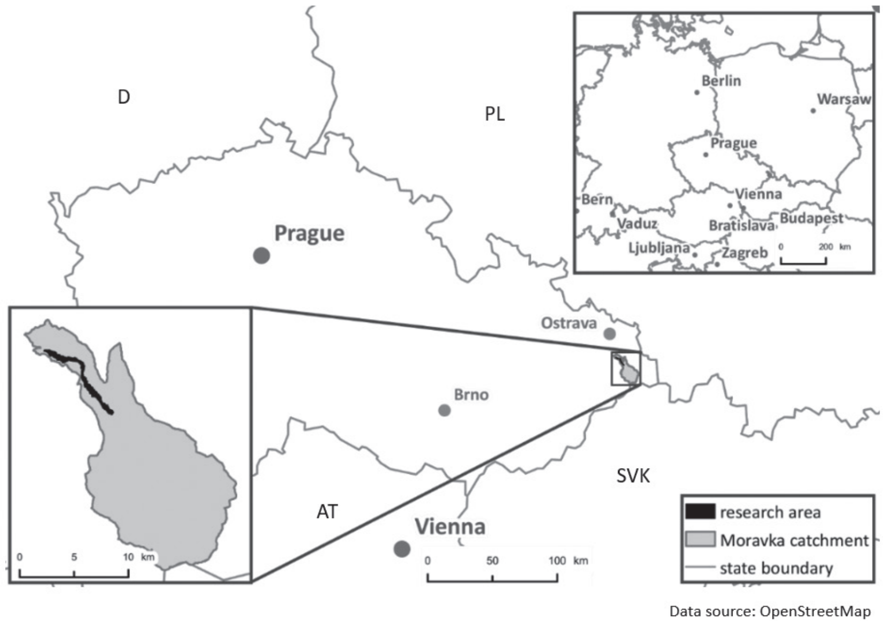

Figure 1. Study area.

order, belonging to the Odra River catchment and the Baltic Sea drainage basin. The Morávka is a rightward tributary of the Ostravice River; its total length is 29.4 km and it has an average annual flow at its mouth of 3.7 $m^3.s^{-1}$.

The Morávka River (Fig. 2, Suppl. material 4) drains the north-western part of the Moravian-Silesian Beskydy, part of the flysch zone of the Outer Western Carpathians (Chlupáč 2002). The bedrock is built of rhythmically alternating positions of claystones and sandstones. The Morávka River forms extensive accumulations of gravel alluvium in its floodplain, in which, especially during major floods, it changes its watercourse (Škarpich et al. 2013). The Morávka floodplain represents the most extensive area in the Czech Republic in which the river is still wild. In order to protect the remaining fragments of the originally up to 300 m wide riverbed, a complex of several protected areas: the Profil Morávky Natural Reserve, the Niva Morávky Natural Reserve, and the Skalická Morávka National Natural Reserve, have been gradually declared part of the Niva Morávky European Site of European Importance. Since the beginning of the 20th century, systematic modifications have been carried out in order to stabilise the riverbed. One of the most major interventions in the fluvial regime of the Morávka was the construction of the weir and the Žermanice Reservoir inlet in Vyšní Lhoty (1953–1964) in river kilometre 11 and the Morávka Waterworks (1961–1967) in river kilometre 19 (Škarpich et al. 2013).

The study area (Fig. 2) has been determined to respect the floodplain forest boundary. It includes the protected sites the "Profil Morávky" (49.6 ha) and the "Niva Morávky" (74.6 ha) Natural Reserves and most of the "Skalická Morávka" (102.0 ha) National Natural Reserve. It therefore covers a larger part of the Special Area of Conservation (SAC) the Niva Morávky (total area 367.4 ha). The protected areas are maintained by the Nature Conservation Agency (NCA) of the Czech Republic and the Regional Council of the Moravian-Silesian Region (RCMSR).

The vegetation cover of the floodplain involves mostly floodplain forests and naturally similar habitats, including gravel bars and floodplain. In the more remote parts of the floodplain there are human settlements and arable land.

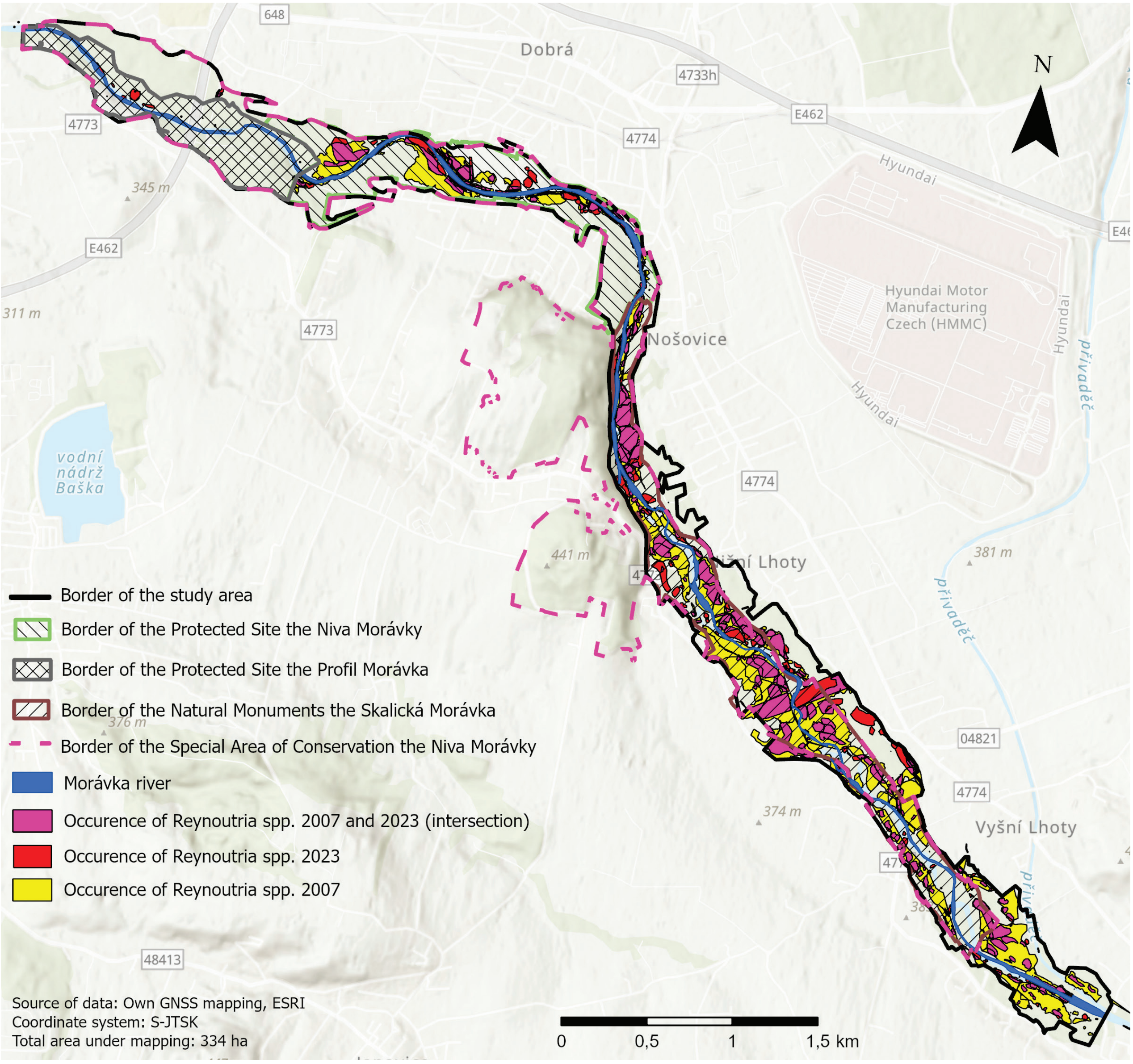

Figure 2. Study area in detail.

The species composition of the floodplain forests roughly corresponds to the natural potential vegetation of bird cherry-ash woodland (*Pruno-Fraxinetum*), which in places on the valley slopes change to Carpathian sedge oak-hornbeam woodland (*Carici pilosae-Carpinetum*) or wet oak-beech woodland (*Carici briz-oidis-Quercetum*) (Neuhäuslová et al. 1997). According to the 2018 Corine Land Cover (CLC) database (Feranec et al. 2016), the structure of the study area was as follows: 83.7% deciduous forest, 16.1% grassland, mainly meadows, and 0.3% other land. The structure of land cover has undergone substantial changes during the 20th century. While in the first half of the 19th century the area was mainly made up of gravel deposits, there was a significant increase in forest land during the 20th century (Trnčák 2012; Škarpich et al. 2013).

The first record of *Reynoutria* in the study area of the Morávka riverside comes from the 1940's (Talpa 1948), and today all the three species of *Reynoutria* genus occur here. The large-scale invasion of *Reynoutria* was probably conditioned by several circumstances. These circumstances included the recurrent disturbances by floods, which in the Morávka floodplain, unlike many other Czech rivers, can be manifested over a relatively wide area of the river floodplain, and in particular the change in the hydrological regime and regulation of the Morávka flow channel. Old aerial photographs (1950s) and older maps (imperial copies of stable cadastre from the first half of the 19th century) show that many of today's floodplain forests and non-forested parts were used as pastures with solitary trees (Trnčák 2012; Škarpich et al. 2013).

Study species

Invasive knotweed from genus *Reynoutria* (*Fallopia*) growing in the Morávka river basin includes *Reynoutria japonica* (native to Japan), *Reynoutria sachalinensis* (native to East Asia) and their hybrid *Reynoutria ×bohemica*. They are perennial, up to 3 m tall, shrub-like herbs that often form connected, impenetrable stands. Within their primary range, *Reynoutria* grows naturally and secondarily in nutrient-rich environments, e.g., near rivers, on young lava flows in alpine environments, and in ruderal vegetation (Beerling et al. 1994; Forman and Kesseli 2003; Mandák et al. 2004). *Reynoutria* negatively affects the species diversity of plant communities (Bímová et al. 2004; Gerber et al. 2008; Maurel et al. 2010), but also the diversity of fauna (Gerber et al. 2008). Their dense and interconnected stands prevent light penetration to the leaves of native herbs (Beerling et al. 1994; Siemens and Blossey 2007), which are mostly of a smaller size.

Reynoutria species reproduce mainly vegetatively within the introduced range. Nevertheless, there are reports of repeated crossing between the species, which is indicated by higher genetic diversity in the stands (Mandák et al. 2005; Suda et al. 2010; Bzdega et al. 2016). The study area around Morávka River was identified as one of the hotspots of such hybridization (Suda et al. 2010). Therefore, although we are aware of possible different reactions of individual *Reynoutria* species and even genotypes to management (Bailey et al. 2007), we were not able to discriminate individual taxa/genotypes for the purpose of our work and consider all *Reynoutria* only at genus level.

The control of *Reynoutria* in the study area

In the study area, the European project "Preservation of alluvial forest habitats in the Morávka river basin" (LIFE-Moravka 2007) was carried out in 2007–2010. The main objective of the project was to suppress the *Reynoutria* population in the study area. It combined mechanical and chemical treatment throughout the study area.

The control of *Reynoutria* was done with a 7–10% solution of the herbicide Roundup Biaktiv in years 2007 to 2010 (glyphosate-based herbicide). The herbicide was applied with a backpack sprayer predominantly in August and September. In locations with high *Reynoutria* coverage, *Reynoutria* was cut mechanically before herbicide application whereas regenerating plants were treated with a backpack sprayer. With regard to the elimination of environmental risks in the proximity of the Morávka reservoir, foliar spraying was replaced by injecting of herbicide directly into the stems of *Reynoutria* in this area; a 20–30% concentration was used. The application of herbicide was done once or twice each season depending on the success of the first treatment (Barták et al. 2010; Halas et al. 2018). Throughout the project duration (2007–2010), this systematic whole area chemical management was carried out every year in the entire study area.

After the end of the LIFE project, which significantly reduced the surface area of the stands, different parts of the study area were treated locally, in different years, depending on financial resources and conservation needs. Most of the study area consists of nature reserves whose authorities (RCMSR and NCA) have continued with chemical treatment using a 4–7% solution of the Roundup Biaktiv herbicide applied by a backpack sprayer. The first application took place after GNSS mapping in 2013 over the entire area of all nature reserves (226.2 ha). In the Niva Morávky Natural Reserve and the Profil Morávky Natural Reserve (124.2 ha), further chemical spraying was carried out in 2014, 2017 and 2019–2023. In the Skalická Morávka National Natural Reserve, the application was carried out once a year for three years, in 2016–2018 on river kilometre 9.4–10.6 (treated area 46.0 ha), and in 2020–2022 on river kilometre 5.5–9.4 (treated area 60.0 ha). The area from the southern boundary of the Skalická Morávka National Natural Reserve to the Žermanice Reservoir inlet was repeatedly chemically treated by the Povodí Odry (Odra River Basin Authority).

Reynoutria is also found in the upper parts of the watercourse below the Morávka Reservoir and above it up to river kilometre 21.1. This poses a risk for the introduction and distribution of *Reynoutria* rhizomes and repeated further spread. At the same time, repeated irregular chemical control took place in these parts as well.

Data

In-situ measurement by GNSS

Data on the occurrence of *Reynoutria* was obtained using GNSS field mapping. For the purpose of our mapping, we used the GPS system. GPS mapping was conducted in the study area in 2007 prior to the start of management, in 2009 during management, and in 2013 prior to the start of local management. In 2015, 2018, and 2023, it continued during local management. The GPS mapping was done in early summer (June and July) before the application of herbicide. In 2007 and 2009, a TOPCON FC-100 PDA was used in combination with a Navilock BT-338 external GPS module. In 2013, 2015, 2018, a JUNO 3D device by Trimble with an integrated GPS antenna was used. In 2023, we used a Xiaomi Redmi 7 smartphone with an integrated GPS antenna. All measurement methods used were autonomous. The error in this type of measurement is in the order of units of metres (Blažek and Švec 2010; Tomaštík et al. 2017; Teunissen and Montenbruck 2017). For the field mapping, ArcPad software (ESRI 2022) by ESRI was used. And in 2023 we used the mobile application Field Maps (ESRI 2023). These applications allow mapping of both the geometric and attribute components of the data. A project was created in ArcPad and Field Maps software in which attributes and a mapping form were defined. The attributes listed in Table 1 were recorded as part of the mapping.

The measurement was carried out in such a way that a mapper walked around the perimeter of each *Reynoutria* polycormon. During the mapping, a polygon edge was automatically recorded every second from the GPS in the ArcPad app. This created areas of different sizes and shapes. *Reynoutria* was mapped so that the mapped areas were homogeneous in terms of the defined parameters: Coverage, Vitality, Moisture type and Vegetation cover type (see Suppl. materials 1, 3). For point occurrences, *Reynoutria* was defined as a point and the radius was entered into the attribute, which were then used for creating the circle polygon.

Table 1. Mapped variable attributes.

Monitored attribute type	Monitored attribute category
Coverage (%)	0.01–0.1; 0.11–1.0; 1.1–10.0; 10.1–50.0; 50.1–100
Moisture type	dry; normal; wet
Vitality	low; average; high
Vegetation cover type	forest; open stands; bare ground habitats

During the mapping, we recorded the coverage percentage of *Reynoutria* according to selected coverage intervals, assessed *Reynoutria* vitality and habitat moisture according to selected criteria (Table 1). Vitality was defined by three categories, that is, plant size, vegetation compactness, and signs of plant damage due to chemical treatment were assessed (see Suppl. material 2). Plants with high vitality were massive, reaching more than 3.0 m in height, and often formed continuous stands. *Reynoutria* that were considered as average plants were up to ca 2.5 m tall. Plants relatively short, spindly, often with deformed leaves and usually isolated were mapped as stands with low vitality.

The moisture-type attribute was categorized according to relief, land cover, and vascular plant species representation. Areas with lowlands, oxbow lakes, pools, clay soils were mapped as wet habitats. Normal habitats were located on flat relief without frequent influence of flood waters, away from river channels and pools. Normal habitats were characterised by loose, organic soils, lacking wetland and xerophytic plant species, whereas mesophilic herbs were common. Dry habitats were mapped on elevated sites, mainly on gravel bars, accompanied by a dry coarse-grained substrate (see Suppl. material 3). The vegetation cover type was grouped into: forest, open stands (meadows, grasslands, sparse shrubby vegetation) and bare ground habitats (mostly gravel river stands).

Due to the high dynamics of changes in the relief and course of the channel in the Morávka floodplain, we vectorised the Morávka river in the years that most closely corresponded to each year of mapping based on archival aerial photographs and orthophotomaps.

Auxiliary data

Aerial photographs and land cover datasets were used as auxiliary data. The Corine Land Cover (CLC) database was used for the land cover data, the orthophoto Web Map Service (WMS) layer and Base topographic map of the Czech Republic at a 1:10 000 scale WMS by State Administration of Surveying and Cadastre in the Czech Republic was used for the aerial photographs.

Orthophoto

The Orthophoto is a map service by State Administration of Surveying and Cadastre in OGC (Open Geospatial Consortium) WMS 1.3.0 (https://geoportal.cuzk.cz/(S(zwhj1uzsovk24saxpcdkjjfy))/Default.aspx?lng=EN&mode=TextMeta&side=wms.verejne&text=WMS.verejne.uvod&head_tab=sekce-03-gp&menu=311). The Orthophoto is derived by orthorectification from the aerial photographs product. The product has spatial resolution within 0.2 m. Data is available in JPEG with JGW (world file) in several coordinate systems: S-JTSK, ETRS89-TM33N a ETRS89-TM34N. The temporal resolution of the dataset is two years.

Base Map of the Czech Republic at 1:10 000

The base topographic map of the Czech Republic at a 1:10 000 scale (ZTM 10) is a map service provided by State Administration of Surveying and Cadastre in OGC WMS 1.3.0 (https://ags.cuzk.cz/arcgis1/services/ZTM/ZTM10/MapServer/WMSServer?). The ZTM 10 includes planimetry (settlements and individual objects, hydrology, communication networks, administrative and cadastral boundaries, boundaries of protected areas, height and planimetric control points, soil surface, vegetation), altimetry (terrain steps, contour lines) and lettering.

Corine Land Cover (CLC)

The CLC is an open dataset for land cover of European countries provided by the Copernicus Programme. Data is available for download from 1990, 2000, 2006, 2012, and 2018. Datasets are in the vector and raster format with 100 m Minimum Mapping Width (MMW) and the minimum mapping unit (MMU) is 25 ha. Data is distributed over 44 thematic classes. Datasets are downloadable at Copernicus website https://land.copernicus.eu/en/products/corine-land-cover.

Data processing

Geodata was processed in ArcGIS and QGIS. It was then analysed in SPSS Statistics and Statgraphics software. From the geometric component of the *Reynoutria* polygons, we calculated their surface area. After we finished data processing, a script using the ModelBuilder tool in the ArcMap programme was created. The script successively created 19 buffer zones increasing in 20 metres up to a distance of 380 metres from the Morávka River. For each buffer zone, the cumulative surface area of the areas invaded by *Reynoutria* was calculated (see Table 5).

Before the core tests the normality of the *Reynoutria* stand size data was tested in the Statgraphics programme using the Kolmogorov-Smirnov test. Normality was tested for each year under study. The normality of *Reynoutria* stand sizes for each year was not confirmed. In all years examined, the p-value was less than 0.001.

Furthermore, we carried out statistical testing of the significance of the difference between surface area sizes without *Reynoutria* in the studied years at regularly increasing distances from the Morávka River as part of spatial data analysis. Areas without *Reynoutria* were calculated from the difference between the total size of the buffer zone and the area with *Reynoutria*, always for a specific distance from Morávka. The change of size patterns of stands with *Reynoutria* over time was tested by Friedman test. This test was selected as the used variables were colinear and normality tests were not significant (Gibbons and Chakraborti 2010).

Since these were categorical variables, we calculated a Chi-square test of independence between the selected pairs of attributes. To perform the calculation well, we aggregated the attributes Area and Coverage. Aggregation was performed to meet the Chi-square test criterion that the smallest expected frequency had to be equal to or greater than 1. Also, the maximum 20% of the areas could have an expected frequency less than 5 (Greenwood and Nikulin 1996). Thus, the aggregated values of the attributes Area and Coverage were obtained. For the Area attribute, two interval values of 0.01–0.07 ha and 0.08–8.10 ha were created. Aggregation of the Coverage attribute produced area categories of 0.01–1.00% and 1.01–100.00%.

To ascertain the effect of biotopes and type of vegetation on the pattern of change of extent of *Reynoutria* polygons over time, linear models (R. 4.3.1) were used. The extent was taken as dependent variable, levels of abundance were 0.05, 0.50, 5.00, 25.00, and 75.00. To analyse the effect of time we specifically analysed the significance of interactions with years.

Results

Detected changes in the distribution of *Reynoutria*

The following numbers of *Reynoutria*-invaded areas were mapped in each year of GPS mapping: 2007, N = 160; 2009, N = 171; 2013, N = 149; 2015, N = 352; 2018, N = 530; 2023, N = 345. Analysis of data collected between 2007 and 2023 (Fig. 3, Table 2) shows that in 2007 *Reynoutria* covered 29% of the total surface area of the area under study (96.9 ha). Due to chemical treatment, the total area size decreased to 19.6% (65.3 ha) in 2009. In 2013 (3 years after the end of systematic whole area chemical management), the *Reynoutria* area size was 14.5% (48.2 ha) and from this year on, a switch to targeted local management of *Reynoutria* stands was made. In 2015, the *Reynoutria* area remains at similar levels as a result of partial chemical treatment. The area size increased by 0.9 ha to 49.1 ha. 2018 saw a decrease in the *Reynoutria* area size to 41.8 ha. The area reduction was due to repeated local management. Surprisingly, in 2023, the size increased to 52.6 ha and there was a return of *Reynoutria*, although partial chemical treatment was continued. We attribute the increase in the area size to the passage of 5 years since the last chemical treatment in part of the Skalická Morávka National Natural Reserve and other parts of the study area.

As a result of *Reynoutria* management, the structure and coverage of *Reynoutria* stands also changed, as shown in Fig. 4 and Table 2. While in 2007, stands with coverage above 50.1% (50.5 ha) covered the largest area, no *Reynoutria* stands with such high coverage were recorded in 2013. In 2015, these stands reappeared and covered an area of 0.6 ha. In 2013, *Reynoutria* stands with a coverage of up to 0.1% occupied the largest area, but in 2015 there were already stands with coverages of 1.1–10.0%. In 2018, although there was an overall decrease in total area size, surprisingly the largest area of *Reynoutria* stands were already in the 10.1–50.0 coverage category. In 2023, total area size of *Reynoutria* increased again and the most prevalent stand category was the 0.11–1.00% coverage category.

Table 2. Area size of invaded areas of *Reynoutria* and their proportion in the study area by coverage intervals. The data in bold show the highest values of the area of *Reynoutria* in a given year.

	Total area size and proportion of areas with *Reynoutria* in coverage intervals (ha) and (%)											
	2007		2009		2013		2015		2018		2023	
Coverage (%)	**ha**	**%**	**ha**	**%**	**ha**	**%**	**ha**	**%**	**ha**	**%**	**ha**	**%**
0.01–0.1	–	–	8.1	2.4	**24.4**	**7.3**	4.7	1.4	5.3	1.6	10.1	3.0
0.11–1.0	–	–	17.9	5.4	15.0	4.5	18.1	5.4	8.9	2.7	**18.4**	**5.5**
1.1–10.0	22.7	6.8	**30.7**	**9.2**	8.9	2.7	**19.6**	**5.9**	8.9	2.7	12.7	3.8
10.1–50.0	23.7	7.1	6.4	1.9	–	–	6.1	1.8	**13.2**	**4.0**	7.1	2.1
50.1–100.0	**50.5**	**15.1**	2.2	0.7	–	–	0.6	0.2	5.4	1.6	4.4	1.3
Invaded area (ha)	**96.9**	–	**65.3**	–	**48.2**	–	**49.1**	–	**41.8**	–	**52.6**	–
Invaded area (%)		**29.0**		**19.6**		**14.5**		**14.7**		**12.5**		**15.8**

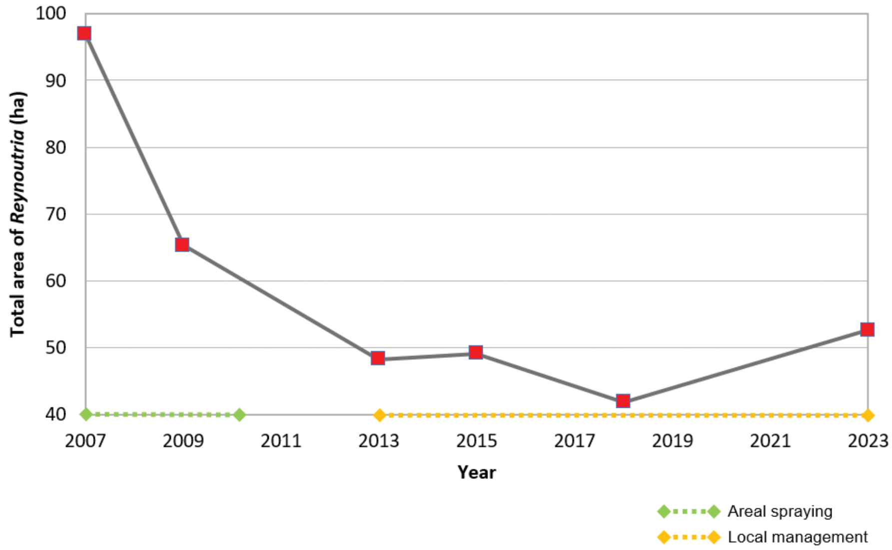

Figure 3. Development of the total area size invaded by *Reynoutria* in the study area between 2007–2023.

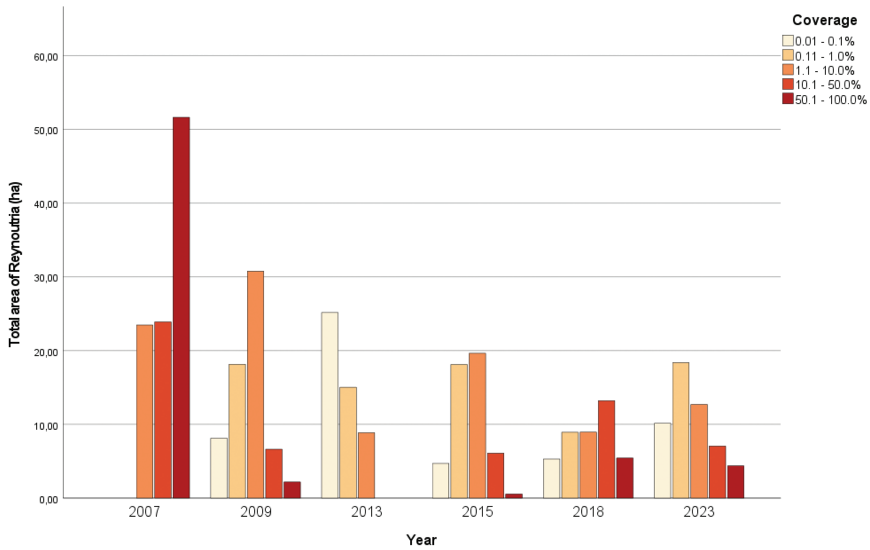

Figure 4. Changes of the area size invaded by *Reynoutria* by coverage intervals.

In addition to the changes in *Reynoutria* coverage, the average area of each stand has also decreased with time elapsed since herbicide application (Figs 5, 6). The graph shows that most areas are less than 1 ha in all years under study, and except for 2007, the largest invaded areas are up to 3.2 ha in size. The average area size decreased from 0.61 ha in 2007 to 0.38 in 2009, to 0.32 in 2013, to 0.14 ha in 2015 and to 0.08 ha in 2018. However, the average area size increased again to 0.15 ha in 2023, which is comparable to 2015. After the end of systematic whole area chemical management in 2010, the fragmentation of *Reynoutria* areas increased. This was evidenced by both the 2015 and 2018 mapping (Table 3). There was a slight increase in the total area of *Reynoutria* in 2015, and an increase in the area of stands with higher *Reynoutria* coverage (Figs 5, 6), although this decreased in 2018 due to local management. However, the trend of fragmentation was still evident. By 2023, the fragmentation trend was no longer confirmed and there was an increase in average area size, although chemical control was ongoing in part of the area.

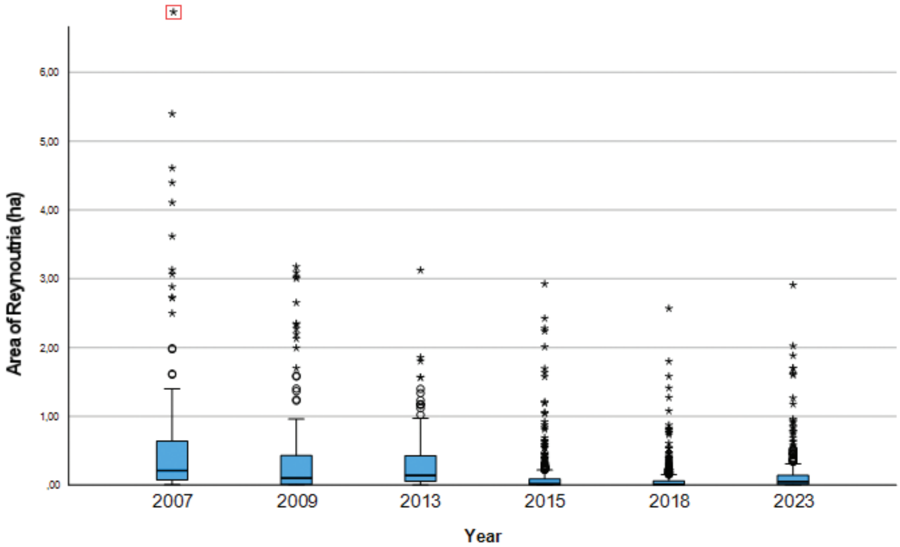

Figure 5. Development of the size of mapped stands invaded by *Reynoutria*. Outliers are represented by a circle and extreme outliers by an asterisk. The asterisk in the red square shows one area from 2007 of 8.1 ha which is outside the scale range.

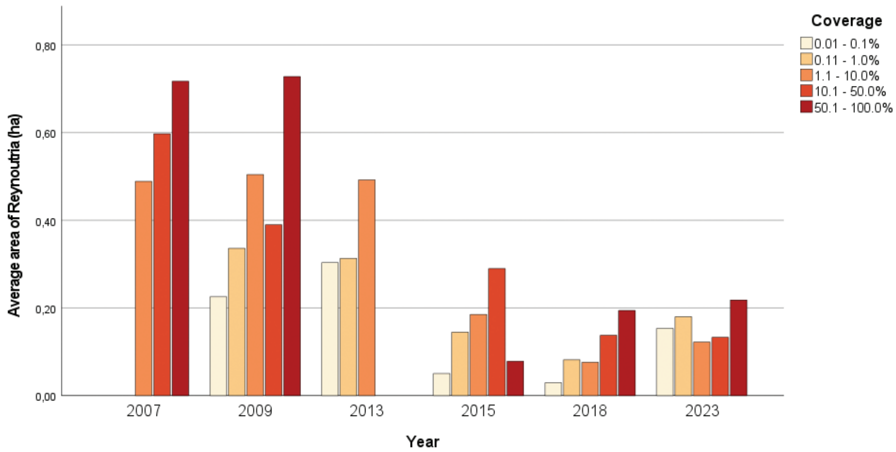

Figure 6. Average sizes of mapped stands invaded by *Reynoutria* by coverage intervals.

During the mapping, the structure of vegetation type where *Reynoutria* occurred was also monitored in selected years (Table 1, Fig. 7). Fig. 7 shows that the habitats where *Reynoutria* occurred have changed as a result of ongoing management. In 2007, 73.1% of the area invaded by *Reynoutria* was forest, 25.4% was grassland and 1.4% was gravel bars (no vegetation). In 2015, there is an overall decrease in the occurrence of *Reynoutria* in the study area, but there is a change in the structure; forest stands represent 77.4%, grassland 22.5% and gravel bars 0.4%. In 2023, *Reynoutria* was already present in 82.7% in forest stands, 13.5% in grassland and 0.8% on gravel bars. According to the 2018 CLC, deciduous forest stands accounted for 83.7% of the area invaded by *Reynoutria*, grassland (mainly meadows) for 16.1% and other areas for 0.3%. The structure of these areas thus corresponds to the structure of *Reynoutria* vegetation in 2023 (Fig. 7). This indicates that the chemical control was more successful when used on grassland than in the forest.

However, testing of the effects of time, habitat and biotope did not reveal significant differences of changes of extent and abundance over different environments.

Table 3. Number of areas invaded by *Reynoutria* in each coverage interval.

Coverage (%)	2007	2009	2013	2015	2018	2023
0.01–0.10	–	36 (21.1%)	83 (55.7%)	93 (26.4%)	180 (34.0%)	66 (19.1%)
0.11–1.0	–	54 (31.5%)	48 (32.2%)	125 (35.5%)	109 (20.6%)	102 (29.6%)
1.1–10.0	48 (30.0%)	61 (35.7%)	18 (12.1%)	106 (30.1%)	117 (22.1%)	104 (30.1%)
10.1–50.0	40 (25.0%)	17 (9.9%)	–	21 (6.0%)	96 (18.1%)	53 (15.4%)
50.1–100.0	72 (45.0%)	3 (1.8%)	–	7 (2.0%)	28 (5.3%)	20 (5.8%)
Total	**160** (100%)	**171** (100%)	**149** (100%)	**352** (100%)	**530** (100%)	**345** (100%)

Note: The value in parentheses represents the percentage of occurrences of *Reynoutria* in a specific category.

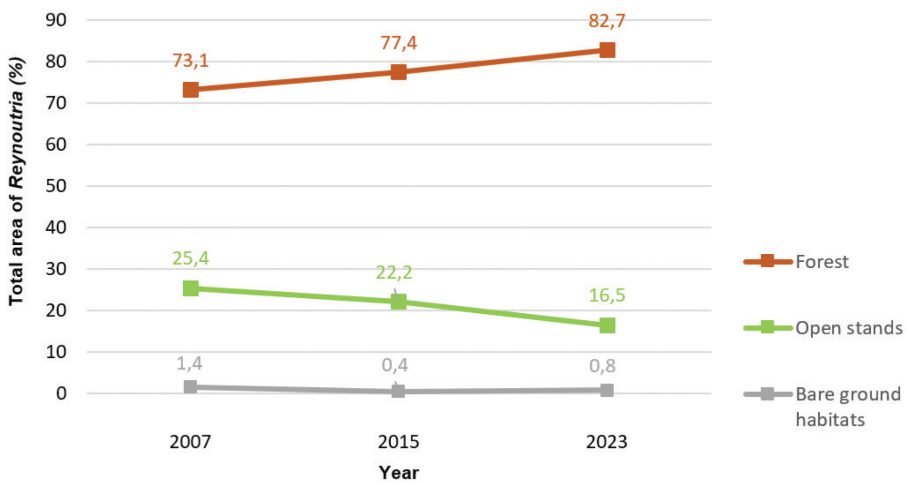

Figure 7. Extent of *Reynoutria* based on Vegetation cover type.

There were no significant interactions between year, abundance, moisture type (F = 1.86, DF = 2,1536, n.s.), and vegetation cover type (F = 0.71, DF = 2,846, n.s.), which indicates that there are no differences in reaction to management in the studied habitat and vegetation types. Significant effect of year (F= 24.2, DF = 1,1537, p < 0.001) shows that the extent of *Reynoutria* sites changes. Additional comparisons are shown in Table 4.

The results of GNSS mapping of *Reynoutria* stands from 2007–2015 were published using the web-based map application http://gisak.vsb.cz/knotweed/. This application allows comparison of the changes in the distribution/spread of *Reynoutria* stands with the recorded attributes (stand coverage, moisture, vitality, ID number) in each year using OpenStreetMap (Fig. 8).

Analysis of the attributes of invaded habitats

In the mapped years 2009, 2013, 2015, 2018 and 2023, the dependence between pairs of attributes was tested using Pearson's Chi-square test of independence in a contingency table. The tests intended to statistically demonstrate the dependence between the categorical attributes were mapped (Table 1), and we were specifically interested in the dependence on Moisture type. The test P-values are shown in Table 4. We aggregated the attribute Area into the categories of small *Reynoutria* stand area (0.01–0.07 ha) and large *Reynoutria* stand area (0.08–8.1 ha).

For the Coverage – Vitality attribute pair, we demonstrated statistically significant dependence or relationship in all years under study. This dependence is logical.

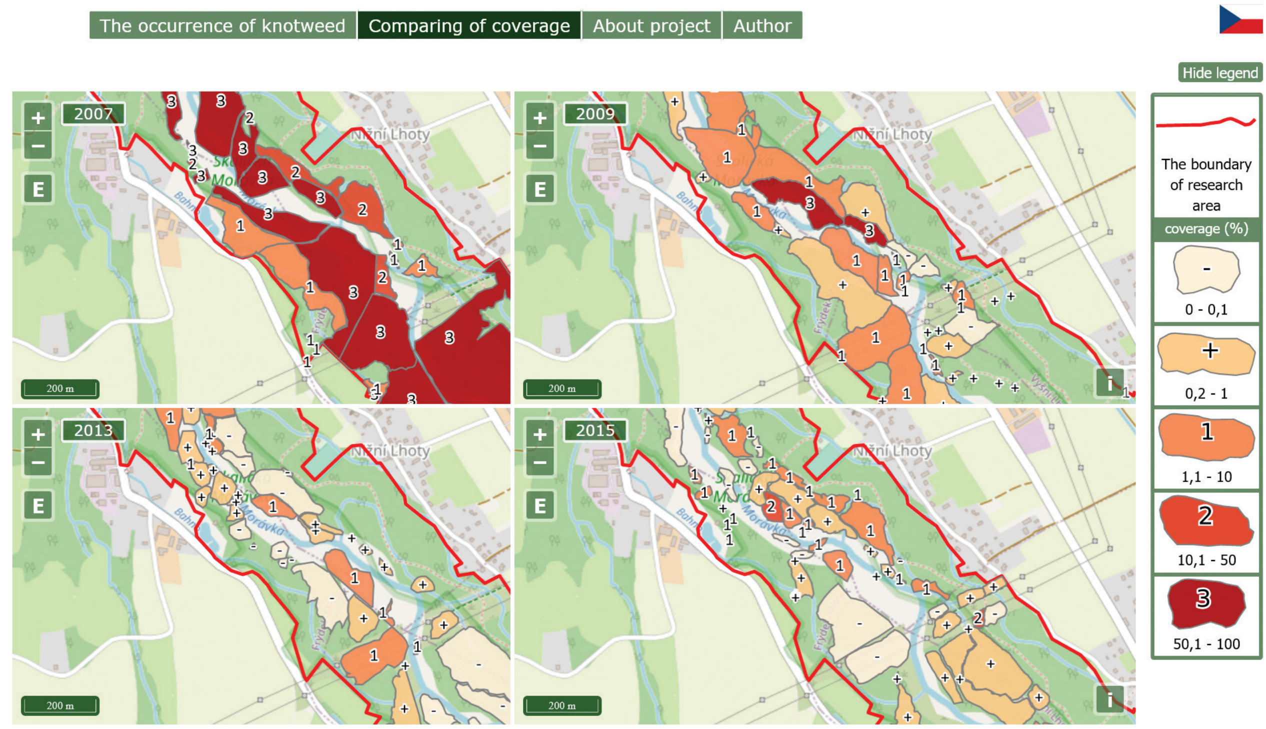

Figure 8. Example of the web-based map application "*Reynoutria* occurrence". The section shows a comparison of *Reynoutria*-invaded habitats, including their coverage in the vicinity of the 8th river kilometre near the village of Nižní Lhoty.

Table 4. P-values of Chi-square test of independence of pairs of attributes.

P-value	2009	2013	2015	2018	2023
Area – Coverage	0.289	0.229	0.960	**0.003**	**0.002**
Area – Moisture type	**< 0.001**	**0.011**	0.437	0.066	0.156
Area – Vitality	0.698	0.708	0.696	**0.046**	0.556
Coverage – Moisture type	**< 0.001**	0.279	**0.015**	**< 0.001**	**< 0.001**
Coverage – Vitality	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Vitality – Moisture type	**0.002**	0.098	0.070	**< 0.001**	**0.026**

Note: For p-values in bold, dependence was demonstrated with 95% confidence (2009, N = 171; 2013, N = 149; 2015, N = 352; 2018, N = 530; 2023, N = 345).

Areas with *Reynoutria* stands with high coverage also had high vitality and vice versa. For the Area – Moisture type pair we showed a dependence in 2009 and 2013. Dry habitats have only a local occurrence in the river floodplain and were therefore not frequently represented or occurred less frequently among large areas (0.08–8.10 ha). Normal habitats were more common among small areas (0.01–0.07 ha) in 2009 and 2013. Aggregate area size therefore depended on Moisture type in these years.

For the Coverage – Moisture type attribute pair, dependence was demonstrated in all years examined except for 2013. In these years, the aggregated Coverage depended on Moisture type. Areas with higher coverage of 1.1–100.0% were more likely to occur in the moist habitat type in these years. Conversely, areas with lower coverage of 0.01–1.00% occurred less frequently in the wet habitat type.

In the Vitality – Moisture type attributes we demonstrated a relationship in 2009, 2018 and 2023. The Vitality attribute was therefore dependent on the Moisture type habitat in which the *Reynoutria* was situated in those years. The wet habitat type had stands with high vitality. On the other hand, in the dry habitat type there were stands with lower vitality. The Area – Coverage attributes were only able to show a relationship between the two most recent years of measurement, i.e., in 2018 and 2023. This suggests that the more extensive the stands were, the higher the *Reynoutria* coverage was and vice versa. For the Area – Vitality attribute pair, a relationship was only demonstrated in 2018.

Using spatial analysis, we evaluated the distribution and size of *Reynoutria* stands as a function of distance from the river. For this purpose, we successively created buffer zones around the river with increments of 20 metres, i.e., 19 zones in total (Table 5). The results of the analysis showed that the *Reynoutria* stands extended the furthest from the watercourse (up to 360 m) in 2007, before the start of the plant chemical treatment. During the management, the extent of *Reynoutria* stands was reduced, so that in 2013 they extended to no more than 280 m from the watercourse. Since 2015, *Reynoutria* has been pushed back further from the watercourse to a distance of up to 320 m. However, the growth of *Reynoutria* areas within 220 m from the watercourse is minimal in all years.

Table 5 shows that at least 25% of the *Reynoutria* stands are located within 40 m from the Morávka River. More than half of all stands were located within 80 m from the stream, except for in 2013, when this distance was even lower (60 m). In total, 75% of *Reynoutria* stands were located within 120 m, except for in 2013 when this distance was 100 m. Thus, the cumulative area sizes show that *Reynoutria* is concentrated in relatively close proximity to the river and the river is the main factor in the occurrence of *Reynoutria*.

Table 5. Cumulative area size of *Reynoutria* at regular distances from the Morávka River. The values below are in hectares (ha).

Year		2007	2009	2013	2015	2018	2023
Extent of zones from the river	0–20	16.47	11.71	7.78	6.25	6.61	10.36
	0–40	30.87	22.34	16.20	13.07	13.78	18.86
	0–60	45.15	32.21	25.06	20.83	20.57	26.23
	0–80	58.24	40.91	32.49	28.34	26.23	32.21
	0–100	69.01	47.99	38.00	34.47	30.67	37.15
	0–120	77.27	53.83	42.00	39.22	33.83	40.59
	0–140	83.64	58.33	44.74	42.84	36.26	43.87
	0–160	87.94	61.44	46.18	45.30	37.42	46.20
	0–180	90.80	63.41	47.05	47.03	38.24	47.92
	0–200	92.66	64.48	47.59	48.01	38.90	49.17
	0–220	93.82	65.00	47.86	48.65	39.57	50.11
	0–240	94.42	65.22	48.08	48.84	40.24	50.90
	0–260	94.83	65.26	48.22	48.93	40.85	51.52
	0–280	95.51	65.26	48.24	49.04	41.38	52.08
	0–300	96.11	65.26	48.24	49.08	41.58	52.40
	0–320	96.49	65.28	48.24	49.08	41.73	52.60
	0–340	96.76	65.28	48.24	49.08	41.82	52.62
	0–360	96.85	65.28	48.24	49.08	41.82	52.62
	0–380	96.85	65.28	48.24	49.08	41.82	52.62
Quartile (%)	25	24.21	16.32	12.06	12.27	10.46	13.16
	50	48.43	32.64	24.12	24.54	20.91	26.31
	75	72.64	48.96	36.18	36.80	31.37	39.47

Note: The size of the *Reynoutria* areas smaller than half of the total size of the *Reynoutria* areas are shown in red. Areas larger than half of the total size of the *Reynoutria* areas are shown in white. Green cells show the areas where their size is no longer increasing and *Reynoutria* was no longer present there.

Conclusion and discussion

The goal of this paper was to describe and analyse the patterns of invasion of *Reynoutria* and, more importantly, the effectiveness of its management. The data covers 17 years of continuous management which provides a robust and unique overview of the invasion, reinvasion, and suppression dynamics. Given the large area and long timespan, our results can be appreciated by many stakeholders working on the control or suppression of *Reynoutria*. We hope that this paper will stimulate publishing more studies based on long-term efficiency of management of this important invasive species. *Reynoutria* is a problematic and persisting invasive species in most of Europe, North America, and Asia and therefore the species has been widely studied. Because of its negative impact on biodiversity as well as other effects, there are numerous studies focused on its regeneration, spread, and management (Kabat et al. 2006; Chmura et al. 2013; Kadlecová et al. 2022) as well as studies focused on its ecology, genetics and taxonomy (Bímová et al. 2003; Mandák et al. 2005; Parepa et al. 2014; Lavoie 2017). Even in Europe, where there is a reluctant attitude toward biocontrol, the species has been subject to various attempts to establish successful biocontrol for many years (Shaw et al. 2011). Individual countries, municipalities, and stakeholders spent enormous resources for its control, and *Reynoutria* is classified as one of the costliest species in Europe (Haubrock et al. 2021). While the initial aim of many nature conservation organisations, NGOs and municipalities was to eradicate knotweeds completely, it is now becoming more and more evident that full large-scale control is almost impossible and the aim is therefore to mitigate its negative impact and prevent further spread.

Many studies focus on the methods of management of *Reynoutria* (see overview in Kadlecová et al. 2022). The studies offer a range of methods from purely mechanical methods (mowing, grazing, covering soil with plastic, heat treatments, disposing the material to compost), to chemical treatment (various chemical substances and timing), to biocontrol (Shaw et al. 2011). Unfortunately, economic evaluation of the methods is only rarely available (Hocking et al. 2023). The results from long-term sustainable control are missing, as the studies cover only a limited time span or are based on small study sites, or even use only experimental data from laboratory or experimental gardens (Kettenring and Adams 2011; Jones and Eastwood 2019). Nevertheless, the practical nature protection and land managers need the long-term studies that can be applied on a large scale (Pergl et al. 2020b). It has been repeatedly shown that the patterns can differ significantly between short and long-term studies even if they are based in the same area, and sometimes provide the opposite results (Lepš 2014; Čuda et al. 2017).

As knotweeds are widely recognized as problematic species and thus are widely managed, they become a suitable model system for various schemes of planning and prioritizing management. Apart from this, the three closely related *Reynoutria* species are also often studied due to their differences in their invasion potential and regeneration ability (Pyšek et al. 2003; Schmiedel et al. 2016; Kadlecová et al. 2022). However, we are not aware of any data on management valid for more than five years published for any of the species. Our study focuses on the use of herbicides, which presents only one type of management from the large list of available methods (Bzdega et al. 2022). In addition to the data presented in our study, it would be highly beneficial to evaluate a large-scale and long-term study, including the effectiveness of various methods of *Reynoutria* management.

Our data shows that within a few years after the management of the area started, the extent of the *Reynoutria* stands sharply decreased and the large polycormons were split to small and less dense ones. Within the first five years of the management, the extent of *Reynoutria* decreased to 49.7% of initial values (96.9 ha) in 2013, and the size of the average stands (polycormons) decreased to 0.32 ha. Since *Reynoutria* is a species with a high negative impact on vegetation when growing in large stands (Hejda et al. 2009, 2021), reducing its size at invaded sites has been important for nature protection. Nevertheless, *Reynoutria* exhibits high regeneration potential, which required a repeated chemical treatment, applied locally since 2013. Despite a slight increase in 2015, there has been a significant reduction in the *Reynoutria* area to 41.8 ha in 2018, i.e., 43.1% of initially invaded area. However, despite ongoing local management in subsequent years where some sites were locally treated the total area of *Reynoutria* spp. increased to 52.6 ha in 2023. We attribute this increase to the time lag of 5 years since the last coordinated herbicide application.

Another factor in the increase in the total species area may also be the increased flood flows (cca 70 m^3/s) reached during the 2020 floods. These flows cause overlaying of the river channel and its course, and the disappearance and creation of new gravel bars and islands. As a consequence, *Reynoutria* stands are disturbed and their rhizomes fragmented and further spread. These fragments serve *Reynoutria* to regenerate, as described above (e.g., Bímová et al. 2003).

Not only the size of the stands (polycormons) significantly changed, but also the coverage of *Reynoutria* rapidly decreased. At the time of the start of the chemical spraying, the study area was mainly *Reynoutria* stands with high coverage and the two categories of areas with the lowest coverage were not at all represented. This changed dramatically as a result of three years of systematic whole area chemical management. There was a significant reduction in areas in the case of higher coverage sites as shown in Fig. 4, and in 2013 even no more high coverage sites were recorded (coverage categories 10.1–50.0% and 50.1–100.0%). However, since 2015 the trend has been reversed and in 2018, despite ongoing chemical interventions in parts of the area, the largest area was already in the 10.1–50.0% coverage category. In the last year of monitoring (2023), the largest area was occupied by *Reynoutria* with coverage between 0.11–1.00%, which is probably the result of mixed effect of local chemical treatment and floods in 2020, as mentioned above.

The area size of most *Reynoutria* stands (except for in 2007) prior to the start of eradication was less than 1 ha throughout the management period. Nevertheless, we identified areas of several hectares in each of the years studied (Fig. 5). The smallest average area size of *Reynoutria* (0.08 ha) was recorded in 2018, which was also the year with the largest number of mapped areas (530). At the same time, *Reynoutria* occurred in more than half of them with a coverage of less than 1% (Table 3). This is indicative of the increased fragmentation of areas with *Reynoutria* stands that has been occurring since 2015 (Fig. 5, Table 3). In 2018, fragmentation increased further due to chemical treatment with herbicide. As more time passed since chemical treatment, the number of areas decreased again to 345 in 2023, which made it comparable to 2015 (352).

The mapping results indicated that there was a change in the total area of habitat covered with *Reynoutria*, which was a result of chemical treatment (Fig. 7). However, the non-significant interactions show that the change for each occurrence is similar across all types, i.e., *Reynoutria* responds to chemical control in the same way in all habitats.

Such changes of invaded population structure are important for neighbouring species. In a study by Hejda et al. (2021) it was found that stands with low to moderate cover of knotweed have approximately more than twice as many species as dense *Reynoutria* stands. In our study area, reduction of the *Reynoutria* cover induced regeneration of the species diversity, as documented in the study by Halas et al. (2018). On phytocoenological plots where the herbicide was applied more frequently, the ruderal plant species, e.g., *Crepis biennis*, *Impatiens parviflora*, *Lactuca serriola* and *Solidago canadensis*, prevailed. On the contrary, in places where the herbicide was not applied so often, a frequent occurrence of autochthonous plant species of a submontane floodplain forest, e.g., *Carex remota*, *Dentaria glandulosa* and *Veronica montana* could be observed apart from some ruderal plant species. However, with the time passing since the last herbicide application, the abundance of both native and non-native plant species has increased, and so the coverage of the native plant species. Nevertheless, as a side negative effect, growth deformations of many native herbaceous species were detected even one year after the last application of herbicide (Halas et al. 2018).

In spatial analysis we found (Table 5) that at least 25% of *Reynoutria* stands occur within 40 m from the Morávka river. More than 50% of the stands occurred within 80 metres, except for in 2013, when this distance was only 60 metres. Similar to the study by Shen et al. (2015), we found that the closest vicinity of the riparian zone has the greatest impact on the observed phenomenon, in our case the spread of invasive neophytes. From 2007 to 2013, the distance from the watercourse where *Reynoutria* stands were still recorded decreased from an initial 380 m in 2007 to 280 m in 2013. In the following years, *Reynoutria* stands expanded again to 320 m. However, from a distance of 220 m from the Morávka watercourse, the cumulative growth of *Reynoutria* areas was low.

All field measurements of the spatial extent of *Reynoutria* were made using autonomous GNSS measurements based on ZTM 10 and Orthophoto digital mapping, which were chosen due to the complexity of the field and forest cover where phase measurements would be difficult to implement. Similar GNSS mapping was also carried out by Moore et al. (2006), whose mapping concept was similar. However, their results do not include a statistical evaluation of the *Reynoutria* areas and so our results cannot be compared with their study in this respect. The accuracy of autonomous GNSS measurements is in the order of units of metres (up to tens of metres in adverse conditions) and is influenced by several factors such as observational conditions and the state of the atmosphere, the presence of vegetation, buildings, the relief shape, etc. (Blažek and Švec 2010; Tomaštík et al. 2017; Teunissen and Montenbruck 2017). Currently, some low-cost apparatuses for GNSS measurements on Android platforms are being tested (Dabove et al. 2019; Halaj and Kačmařík 2022). This includes the possibility of using differential GNSS (DGNSS) or real-time kinematic (RTK) correction measurements (Netthonglang et al. 2019; Tomaštík et al. 2021). Mapped areas of *Reynoutria* stands are published for selected years in the *Reynoutria* occurrence web-based application (http://gisak.vsb.cz/knotweed/). An alternative to ground-based mapping of invasive neophytes is the currently increasingly used Remote Sensing. Both satellite and aerial data is used to study invasive neophytes. Currently, UAV data, as noted by Martin et al. (2018), Michez et al. (2016), Dorigo et al. (2012), Negrea et al. (2022), are increasingly used. The advantage of this approach is the speed of data acquisition, without the need for direct mapping in the field, and the possibility to map even difficult or inaccessible locations. Another advantage is the possibility of automated processing of invasive neophyte occurrence data using different classification methods or machine learning (Müllerová et al. 2013; Jones et al. 2020b; Dyrmann et al. 2021). Therefore, we would like to continue and expand the study of the issue in the study area by comparing the results of GNSS mapping (using satellite data) and UAV imagery.

Implications for practical management

The most important point in the whole *Reynoutria* management is to work in long-term scale. It is important to note that any management action must be followed by reasonable land use. It is useless and is only a waste of resources to make any random and single control actions (cutting, herbicide application) without a concept of future land use that will restrict *Reynoutria* reinvasion. Based on the results from other studies (e.g., Jones et al. 2020a; Kadlecová et al. 2022) we have come to conclusion that the only effective control management is application of herbicide. Therefore, in areas where regional restrictions allow its use, this is the preferred type of management. However, chemical treatment must be quite long-term. Even three years of intensive herbicide application was not sufficient for the complete control of *Reynoutria*. Following field mapping in 2013 (i.e., 3 years after the end of the chemical treatments) it was clear that *Reynoutria* would start to expand again without further management of the area. In several locations, particularly in hydrically normal habitats in the floodplain forest, *Reynoutria* was forming vigorous stands without necroses. Without further intervention, we anticipated its successful regeneration and expansion in the study area. These assumptions were confirmed, because despite further local treatment carried out gradually in all parts of the site, the areas with *Reynoutria* increased by 4.4 ha over the next ten years (2013–2023). However, these interventions have reduced *Reynoutria* coverage in invaded areas and *Reynoutria* remains under control due to management.

Therefore, the key message resulting from our study concerns the structure of long-term management by herbicides. Based on the presented data and gained field experience, we propose the following procedure:

1. In largely infested sites, the first step is to reduce the distribution of *Reynoutria* stands to isolated polycormons (ca 1×1 m^2) . This phase can last 3–5 years.
2. After reaching the state of sparse distribution of *Reynoutria* (although several large clones may remain at a site), apply the herbicide only in period of every 3–5 years depending on the local context and rate of regrowth. More frequent applications increase economic costs and increase the risk of negatively affecting the surrounding flora and fauna. Longer breaks between individual applications allow significant regeneration of stands. It is recommended to maintain the reduced *Reynoutria* sites by long-term land-use such as mowing or grazing. However, the risk of potential spread of *Reynoutria* biomass must be considered in such cases.
3. At sites exposed to soil disturbances (e.g., after floods, road constructions), where the soil is contaminated by fragments of *Reynoutria* rhizomes, there is a need to apply herbicide immediately to target newly resprouting individuals. New and young resprouts are highly susceptible to herbicide (due to low nutrient stock) and such application has higher efficiency leading to full eradication.

The proper application of herbicide is also crucial. Glyphosate dosage/application rates are discussed by Delbart et al. (2012), Jones and Eastwood (2019), or Kadlecová et al. (2022). Also, several literature sources recommend to reduce above-ground biomass prior to herbicide application (Jones and Eastwood 2019; Hocking et al. 2023).

We are aware that herbicide application can be a conflicting issue for the public and also for some parts of nature protection. However, it is clear that the use of herbicides is needed for some highly resprouting species (Csiszár and Korda 2017; Pergl et al. 2020a). In some cases (e.g., *Reynoutria*), it was shown that herbicide application is the most effective approach in the context of costs and side effects on the environment (Hocking et al. 2023). Properly used chemicals also limit the risks of accidental spread of the rhizomes and contaminated soil by mechanical methods (e.g., digging or excavating) and importantly for the managers, they are also cheaper. Similarly, improperly applied herbicides may negatively affect the neighbouring biota as well as decrease the efficiency of the management. In addition, correct herbicide application becomes more important in the era of changing climate conditions with increased CO_2 levels and rising drought and heat, when herbicides may become less effective (Varanasi et al. 2016; Bzdega et al. 2022). The local conditions and possible restrictions on the use of chemicals are always to be considered, as well as interaction with the public.

To compare the patterns of management effectivity, more long-term studies on management of the species and from other regions/types of habitats are needed. To fulfil such needs, detailed monitoring of the management actions and their results is recommended with specification of the management methods used, costs of treatment, etc. In this study, we were unable to properly cover the issue of costs and effort of management, as management was done by several bodies. Despite this, we believe that the presented study offers a valuable contribution to the proper management of *Reynoutria* species.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Example of mapped *Reynoutria* coverage by each mapped category

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Data type: PNG

Explanation note: 1 – Coverage of less than 0.1%. 2, 3 – Coverage of 0.11–1.0%. 4 – Coverage of 1.1–10.0%. 5 – Coverage of 10.1–50.0%. 6 – Coverage of 50.1–100.0% – In this category of coverage, the area is almost impassable.

Link: https://doi.org/10.3897/neobiota.94.122337.suppl1

Supplementary material 2

Example of the impact of chemical control on *Reynoutria*

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Data type: PNG

Explanation note: 1, 2 – Chemically treated area one year after herbicide application (July 2008). The success rate of chemical control is high, *Reynoutria* regenerates sporadically after spraying. Overall coverage increases and new species with ruderal tendency appear. The photo foreground shows the invasive species *Impatiens parviflora* and *Impatiens glandulifera*. 3, 4, 5 – Example of various forms of malformation and necroses after chemical eradication of *Reynoutria*. The height of *Reynoutria*, including the leaf forms, is greatly altered, with the formation of various "deformed" forms.

Link: https://doi.org/10.3897/neobiota.94.122337.suppl2

Supplementary material 3

Example of the mapped Moisture types

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Data type: PNG

Explanation note: Habitat moisture was categorised by relief, soil cover, and vascular plant species representation. 1 – Areas with lowlands, oxbow lakes, pools, clay soils were mapped and classified as wet habitats or stands. 2 – Normal habitats were located on flat relief without frequent floodwater influence, away from river channels and pools. Normal habitats were characterized by loose, humic soils, lacking wetland and arid-loving plant species, with mesophilous herbs being common. 3 – Dry habitats were mapped on elevated sites, primarily on gravel bars, accompanied by dry coarse-grained substrate.

Link: https://doi.org/10.3897/neobiota.94.122337.suppl3

Supplementary material 4

The Morávka River and its surroundings in the study area

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Data type: PNG

Explanation note: 1 – The Morávka River represents a uniquely preserved Carpathian-type stream in the Czech Republic. Especially in the preserved locality Profil Morávky, there are unique pools with clear water. 2 – There are also rock thresholds and rapids. 3 – After the flood, the riverbed is "cleaned" of the vegetation and the position of the riverbed changes. The photo taken after the flood in 2010. 4 – Due to deep erosion, the riverbed is deepened about 10 m below the river floodplain in the lower part of the stream. This process is still ongoing. 5 – The middle part of the stream in the Vyšní Lhoty area differs from the lower part of the stream.

Link: https://doi.org/10.3897/neobiota.94.122337.suppl4