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A Case Study: The Implementation of a Nature-Based Engineering Solution to Restore a *Fallopia japonica*-Dominated Brook Embankment

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Abstract

Considering the high abundance of knotweeds along river courses, the expected increase of invasion and the consequent negative impacts on riparian ecosystems, there is a high demand for innovative approaches and management strategies. While a primary aim of weed management is to reduce the population of an invasive plant species, the goal of the presented nature-based engineering solution (NABES) is to reinstall native riparian forests and to restore ecosystem functioning. The concept of NABES is to support the implemented species by frequent removal of the knotweed shoots until the native vegetation represses the knotweeds by root competition and shadow pressure. In order to be able to develop adaptive knotweed management strategies, knowledge concerning seasonal biomass development and the most effective maintenance intervals must be improved. Additionally, greater understanding of the interaction between invasive and native species is essential. In the present study, the effectiveness of a willow brush mattress (a frequent technique for controlling riverbank erosion) in combination with adapted management strategies was tested on a *Fallopia japonica*-dominated brook embankment. Due to its high ecological amplitude and excellent soil bioengineering properties the species *S. purpurea* was used. In the upper part of the embankment, *F. japonica* shoot production was by far the strongest, while it was low in the sections next to the water. The strongest biomass production was observed in the months April and May. Even though the temporal interval between shoot removal was increased, shoot production decreased strongly and nearly ceased in August. Branches of *S. purpurea* with contact to the water of the brook showed good development. In contrast to *F. japonica*, which suffered a rapid decrease in biomass production after the third survey, the coverage ratio of *S. purpurea* decreased gradually over the vegetation period.

Keywords

Fallopia japonica, Soil Bioengineering, Ecosystem Restoration, Riparian Vegetation

1. Introduction

According to the European Commission, the invasion of alien biota is the second-largest threat to biodiversity after habitat loss. The spread of invasive alien plants (IAPs) has significant implications for agriculture, forestry, aquaculture, ecosystem services, and human health (Commission of the European Communities, 2013). Compared to other pressures on protected areas (e.g. land-use change), the impacts of IAPs are frequently less well understood (Hulme et al., 2014). Riparian habitats are among the most prone to invasion, as these habitats are strongly affected by both natural and human-driven disturbances. Further spread of IAPs into riparian habitats is facilitated by hydrological alterations (Stromberg et al., 2007), climate change (e.g. Dudgeon et al., 2006; Settele et al., 2014), or human interventions within the riparian zone (Haag & Krüsi, 2014). These disturbances tend to alter environmental conditions in a manner that increases the potential for invasion by IAPs (Santoro et al., 2011) and, therefore, losses of natural riparian habitats have to be expected alongside running waters (IUCN, 2000). Out of all the potential plant invaders, the complex of species *Fallopia spp.* (Asian knotweeds) is of particular concern for conservationists and land managers. The species is currently listed in Europe's top 100 most invasive plant species by DAISIE (2008) and is highly invasive within riparian zones. In the literature, there is inconsistent information about the applicability and efficacy of non-chemical control measures. Various methods have been tested for Asian knotweeds but they are often largely inefficient and expensive. One of the most efficient methods is early uprooting and disposal, combined with constant monitoring of areas at risk (Dommanget et al., 2016). Additionally, repeatedly mowing is a solution, which is commonly used for eradicating or at least reducing Asian knotweeds in conservation areas. However, these procedures are labor-intensive and require repeated treatment, and thus become quickly expensive (Delbart et al., 2012; UBA, 2015). The presented case study pursues a different approach, by developing nature-based engineering solutions (NABES). These are built on the principles of soil bioengineering, with specific adaptations to effectively support the natural riparian plants against dominating IAPs. Soil bioengineering is a construction technique that uses biological components for hydraulic and civil engineering solutions. Nowadays, soil bioengineering is of increasing importance as there is a high demand for engineering solutions which take into consideration not only technical issues but also ecological and socio-economic values (e.g. Durlo & Sutili, 2005; Lammeranner, Rauch, & Laaha, 2005; Rauch, Sutili, & Hoerbinger, 2014). In order to achieve these ambitions, soil bioengineering makes use of different materials. First and foremost, living materials, such as seeds, plants, plant parts and so forth, are applied. This means that soil bioengineering structures are dependent on the properties and development of plants. In revitalization projects, the techniques of soil bioengineering can provide an effective means of treating sites where steep slopes and soil instability result in revegetation problems. Recently revitalized areas are often scarcely covered by vegetation. Since the majority of IAPs have a high light requirement and grow on nutrient-rich soils, the promotion of competitive native vegetation in combination with the creation of nutrient-poor locations is a promising approach. Open niches, e.g. on eroded river banks, are particularly vulnerable to recolonization by IAPs. Soil bioengineering is an appropriate technique for the stabilization of erosion-prone areas as it helps to eliminate flood damage, and consequently to prevent the spread of unwanted species in the locality. In areas already colonized by IAPs, the invaders are effectively pushed back through shading and rooting competition by the installed native vegetation. In experimental tests, Dommanget et al. (2015) planted the cuttings of fast-growing *Salix viminalis* on previously mowed knotweed patches in order to stimulate the regeneration of a competitive canopy. After two or three years of repeated cuts, the Asian knotweeds present were dominated by willows, and their biomass had significantly decreased. Similarly, Delbart et al. (2012) showed that mowing associated with transplanting of native trees was the most efficient mechanical control method. However, little is known about the effectiveness of different native riparian species when competing with IAPs. Dommanget et al. (2013) found that the allelopathic effect of *Fallopia japonica* influenced the growth of Salicaceae species to a different degree and that the choice of resistant species could prove crucial for restoration success. In the present study, the effectiveness of a willow brush mattress (a frequent technique for controlling riverbank erosion) in combination with adapted management strategies was tested. The concept of NABES is to support the implemented species by frequent removal of the knotweed shoots until the native vegetation represses the knotweeds by root competition and shadow pressure. Through immediate erosion control by the auxiliaries, further downstream colonization should be prevented by uprooting of knotweed rhizomes. Over the course of the present study the development of both the installed vegetation and the invasive knotweeds was examined during the first vegetation period.

2. Materials and Methods

2.1. Location and Site Conditions

This case study involves a nature-based engineering solution on a *F. Japonica*-dominated embankment at the Steinbach Brook, located in the west of Vienna, Austria (see **Figure 1**) (48˚14'11.4"N 16˚11'34.7"E). The experiment started with the implementation of the intervention in March 2018 and extended over the whole vegetation period until September 2018. The site of intervention is within the Wienerwald Biosphere Reservoir. Due to the dominance and rapid spread of invasive alien plants within the Biosphere Reservoir, the diversity of plant species and thus the resilience of the native ecosystems is reduced (UNESCO, 2013). The numerous rivers and small brooks are particularly affected by knotweed invasion. The broad range of climatic and geological conditions in the Wienerwald is the reason for its great diversity in vegetation types. During the term of the experiment the mean temperature was high compared to the normal long-term value (see **Figure 2**). Dry conditions in the beginning of the vegetation period affected the initial growth of vegetation. In July, the sum of precipitation clearly exceeded the long-term value. However, this higher value resulted mainly from heavy rainfall events, which reached a high of 49 mm of total precipitation in one day (ZAMG, 2019). The soil in the Wienerwald is underlain by sandstone. As a result, during heavy rain the soil quickly saturates, resulting in substantial runoff. Thus, the flow of the Steinbach Brook can quickly increase, and affect the dispersal dynamics along the brook. As flooding favors the spread of invasive alien knotweeds along rivers (Truscott et al., 2006), an increased frequency of high flows has the potential to intensify this effect. For instance, a riverine patch of *F. japonica* could gradually colonize downstream banks with every flooding event (Duquette et al., 2015). In the lower reach of the Steinbach Brook the surrounding land is characterized by both the Wienerwald and housing structures. In a field survey it was observed that, downstream of the experiment, where the brook flows into the Mauerbach Brook, frequent *F. Japonica* populations were present and formed monospecific stands. Against this

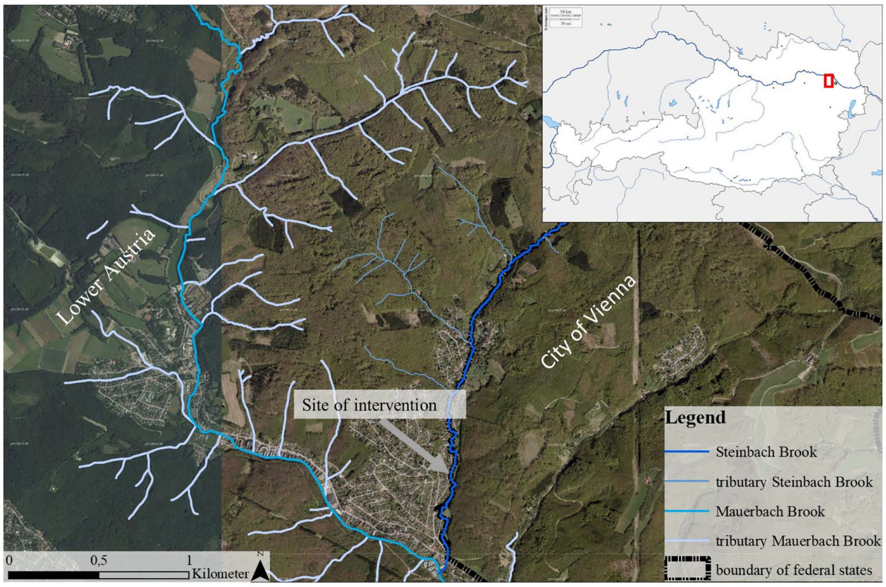

Figure 1. Map of Austria showing the site of intervention, marked in the northeast (d-maps, 2018), and the location of the site of intervention at local level (basemap.at).

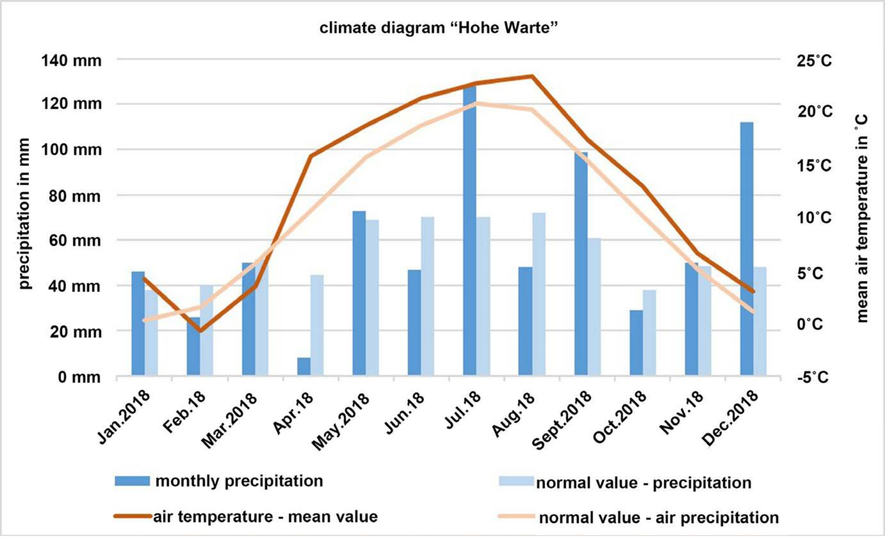

Figure 2. Climate diagram illustrating the monthly sum of precipitation and the monthly mean air temperature for the year 2018. Additionally, the normal values, calculated from the long-term monthly mean of the years 1981-2010 are shown. Data was recorded nearby the site of intervention by the meteorological measuring station "Hohe Warte" (ZAMG, 2019).

background, a nature-based engineering solution was designed with the aims of the immediate prevention of further spread originating from this *F. japonica* patch, the reinstallation of site-specific riparian vegetation, and the re-establishment of ecosystem service provision. At the same time the intervention has to serve to secure bank stability and resist high hydrological pressure.

2.2. Intervention-Application of a Willow Brush Mattress

The site of the intervention is located on a very steep embankment of difficult accessibility. Hence, it was decided to execute the structure by hand without the aid of any machines. The intervention was executed in the following sequence: firstly, the embankment was raked and cleaned of above-ground plant material and stones. Only large rhizome parts of *F. japonica*, which could easily be pulled out, were removed. At the toe of the embankment a trench was dredged into the bed of the brook. Subsequently, branches of *Salix purpurea* were placed densely on the embankment in a way that the thicker ends of the branches were positioned within the trench (see **Figure 3**). Due to the height of the embankment, a second layer of willow branches was installed. The upper branches did not have access to the water. In the next step, a willow fascine was installed in the trench and fixed with wooden poles. The willow branches were fastened to the embankment by the use of wire and wooden laths. The whole structure was covered by a thin layer of soil. It was decided to use *S. purpurea* due to its high ecological amplitude. It is a deciduous medium-sized to large-sized shrub that adapts equally well to wet or dry sites and exhibits great vegetative reproducibility (Hörandl et al., 2002). A small segment (3 m^2) of the willow brush mattress was

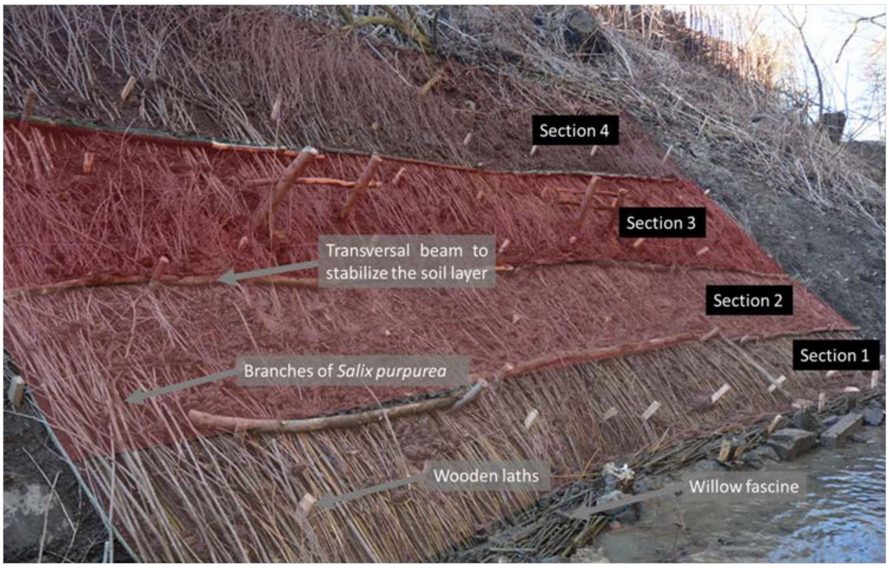

Figure 3. Illustration of the intervention after its construction, including descriptions of the constructive elements and allocations of the sections.

built by using *Salix fragilis*. This segment was not considered in the analysis below but will be addressed in the discussion.

2.3. Maintenance and Monitoring

Intensive maintenance work was carried out in order to support the implemented *S. purpurea* in competing with Asian knotweeds. Shoots of *F. japonica* were removed in very high frequency (three-week cycle). Over the course of the vegetation period, the shoot production of *F. japonica* decreased significantly and almost ceased. Therefore, the frequency of shoot removal was reduced. In order to evaluate the above-ground biomass production of *F. japonica*, the harvested shoots were dried and the dry biomass was measured in the laboratory. The ground coverage ratio of the vegetation was determined by image analysis. In order to determine the total coverage ratio, photographs were taken before shoot removal. A second image, taken after shoot removal, shows the ground coverage ratio of the implemented willows (see **Figure 4**). The data gained from this non-destructive analysis is used to monitor the development of the willows and their above-ground competitiveness. The analyses were performed by using the script "HORST" (Obriejetan, 2015) which is based on ImageJ, a Java-based image-processing program. "HORST" is an automated method for effective and accurate evaluation of the ground-coverage ratio from images. It analyzes the green tones of an image and calculates their relative area percentage. The color space used for the image analysis is the L* a* b* color system, which reflects the human perception of colors in a three-dimensional coordinate system. The green component or red component is expressed via the a* axis, while the b* axis defines the blue or yellow component of a picture. The luminance or brightness of the color values is displayed on the L* axis. After selection of the green values,

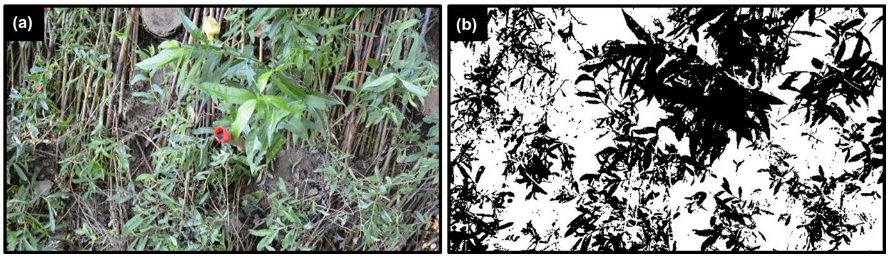

Figure 4. Coverage ratio analysis of the 4th survey (21. June 2018). (a) Image taken after the removal of knotweed shoots and (b) The analyzed image with the extracted vegetation in black.

the marked portions are converted to a binary image characterized by the presence of black and white pixels. In order to reduce any image noise, the median filter is used, which recalculates all pixel values based on their own value and the neighboring pixels. Finally, the proportion of black pixels is calculated relative to the number of total pixels and the result is output in percent.

3. Results

Plant Development

The development of *S. purpurea* differed significantly between the four sections of the intervention (see Figure 5). Within the section at the toe of the embankment, *S. purpurea* showed the strongest shoot production. In other sections, the development decreased with distance to the brook. Especially in the third and fourth sections, where branches of *S. purpurea* were implemented without water contact, the production of leaf mass decreased more strongly across the vegetation period than in the lower sections. At the first survey, on the 12th of April, the first leaves of *S. purpurea* had already developed, while *F. japonica* had not produced any above-ground biomass yet (see Figure 6). The pattern of spatial distribution of *F. japonica* shoot production was inverted compared to that of *S. purpurea*. Within the upper section, *F. japonica* shoot production was by far the strongest, while it was relatively low in the sections next to the water. Over the vegetation period the biomass production decreased significantly. The strongest biomass production was observed in the months April and May. Even though the temporal interval between shoot removal was increased, shoot production decreased strongly and nearly ceased in August. The photographs in Figure 7, taken at different surveys, illustrate the development of the intervention over the vegetation period.

4. Discussion

Invasive knotweeds impact multiple ecosystem functions provided by riparian vegetation and jeopardize river systems. They are pressure on the riparian system by themselves and often have a major impact if they act in combination with other pressures. Considering the high abundance of knotweeds along river courses, the expected increase of invasion and the consequent negative impacts

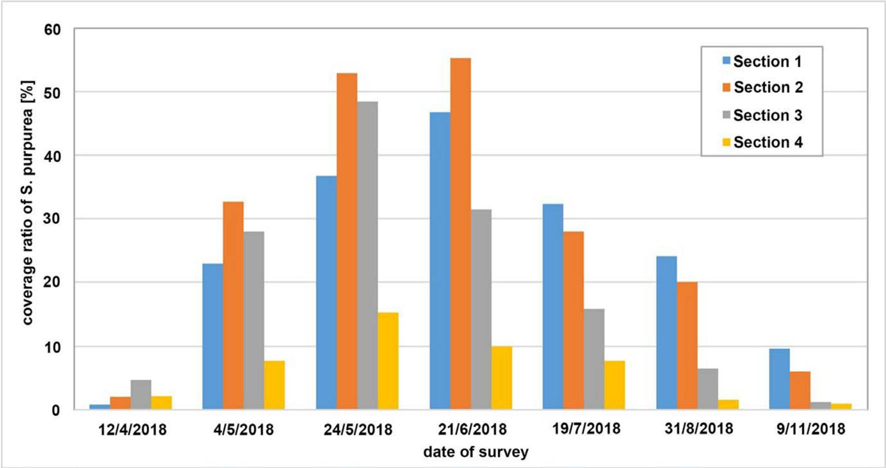

Figure 5. Development of the coverage ratio of *Salix purpurea* in the four sections over the vegetation period.

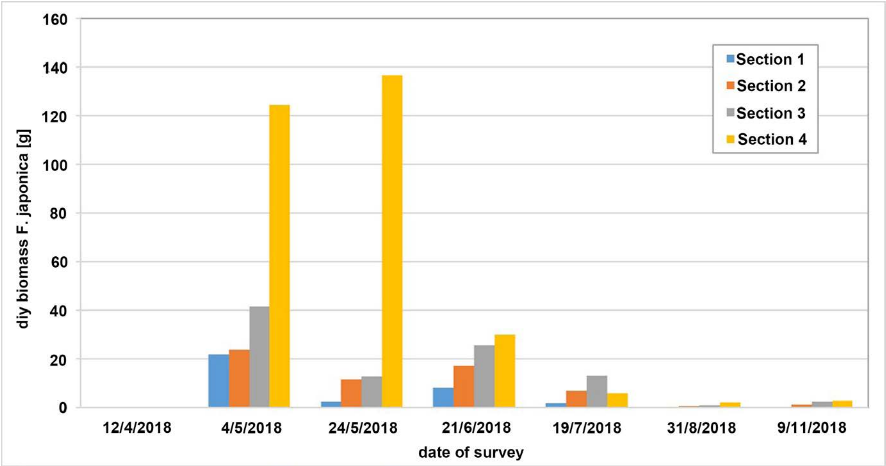

Figure 6. Development of the dry biomass production of *Fallopia japonica* in the four sections over the vegetation period.

on riparian ecosystems, there is a high demand for innovative approaches and management strategies. Conventional management efforts are ongoing and long-term, and will hardly reach a state of "eradication". In order to be able to develop adaptive knotweed management strategies, knowledge concerning seasonal biomass development and the most effective maintenance intervals must be improved. Additionally, greater understanding of the interaction between invasive and native species is essential.

4.1. Analyses of *F. japonica's* Biomass Production Reveals Its Response to Competition and Frequent Shoot Removal

F. japonica developed distinctly in the four defined sections on the brook embankment. In particular, within the two sections next to the brook it developed hardly any shoots. By far the strongest biomass development was observed in the uppermost section. At each of the seven surveys, all present shoots of *F. japonica*

Figure 7. Photographs from selected surveys to illustrate the development of the intervention along the course of the first vegetation period after construction.

were removed. Although the interval of shoot removal was shortest in the months of May and April, the amount of removed biomass was by far the greatest. Due to weak shoot production in the subsequent months, the intervals between surveys were gradually extended. With each session of shoot removal the natural development of *F. japonica* was set back and it seems that it could not recover efficiently after the second cutback. The hot and partly dry climate conditions might have additionally restrained regeneration. *F. japonica* developed significantly less above-ground biomass where the competitive vegetation could establish itself. This indicates a negative impact of the installed *S. purpurea* on the knotweed population. This could be observed particularly within the lower sections, where *S. purpurea* formed a high ground coverage.

4.2. Analyses of *S. purpurea's* Cover Ratio Reveals Its Development on *F. japonica*-Dominated Embankments

Branches of *S. purpurea* with contact to the water of the brook showed good development and could withstand the hot and dry climate conditions during the term of the experiment. Additionally, *S. purpurea* could successfully compete with *F. japonica*. The second layer of willow branches, without contact to the brook, showed significantly less shoot production and shoots partially died back throughout the summer months. In contrast to *F. japonica*, which suffered a rapid decrease in biomass production after the third survey, the coverage ratio of *S. purpurea* decreased gradually over the vegetation period. Noticeable was the good performance of the small implemented patch of *S. fragilis*. Although the branches had no water contact, very strong shoot development was observed. *S. fragilis* is a willow tree, which is characterized by very strong growth and competitive strength. The stronger performance of *S. fragilis* compared to *S. purpurea* was unexpected. The botanical habitat of *S. fragilis* is on moist locations while *S. purpurea* has the greatest ecological amplitude of native willow species in Austria and naturally occurs also in dry locations (Hörandl et al., 2002). The strong growth of *S. fragilis* could be an indicator of competitive strength against *F. japonica*. However, the use of *S. fragilis* for water engineering purposes is limited due to its fast growth and low resistance against fraction. It is only applicable if waterways are sufficiently dimensioned.

4.3. Nature-Based Engineering Solutions (NABES) and Management Perspectives

While a primary aim of weed management is to reduce the population of an invasive plant species, the goal of the developed NABES is to reinstall native riparian forests and to restore ecosystem functioning. The presented study demonstrates that comprehensive monitoring is crucial in the initial phase of NABES. Through monitoring, the timing when maintenance activities are most efficient can be determined. By the removal of knotweed shoots, development of the desired natural vegetation can be effectively supported. It must be taken into account that both monitoring as well as maintenance activities involve considerable expenditures. Besides adapted maintenance practices, the selection of implemented species is also decisive in the success of the intervention. There is still little known about the interaction between riparian species and Asian knotweeds. Accordingly, further investigation into the competitiveness of soil bioengineering species against Asian knotweeds is needed. The concept of NABES encompasses the removal of knotweed shoots in order to support the implemented species until they effectively push the knotweeds back through shading and rooting competition. As soon as the natural vegetation is successfully established, monitoring and maintenance activities can be reduced. Especially in sensitive areas and small initial patches of *F. Japonica* NABES seems to be an appropriate technique for sustainable knotweed control.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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