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### Please cite this article as:

Gach M.B., Lukačević M., Słowiński K., Grygierzec B., Štefanić E., Synowiec A., Tabor S., Gładyś O. Rhizome diameter as a driver of sprout vigor in Japanese knotweed (*Reynoutria japonica* Houtt.): implications for management. Journal of Plant Protection Research. DOI: 10.24425/jppr.2026.3430

Original article

**Rhizome diameter as a driver of sprout vigor in Japanese knotweed (*Reynoutria japonica* Houtt.): implications for management**

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Received: Jun 26, 2026

Accepted: July 29, 2026

Pre-proof Publication: October 23, 2026

Responsible Editor: Irena Suwara

DOI: 10.24425/jppr.2026.3430

## Abstract

Understanding the regenerative capacity of Japanese knotweed (*Reynoutria japonica* Houtt.) is essential for developing effective management strategies. This study investigated how rhizome fragment diameter—classified as thin ( $\leq 1.0$  cm), medium (1.1–2.0 cm), and thick ( $\geq 2.0$  cm)—affects early sprouting. The one-way ANOVA and Tukey's HSD post-hoc test revealed that sprout length increased significantly with rhizome diameter ( $p < 0.001$ ), accounting for 62.40% of the variation in sprout growth. Specifically, thick fragments produced the longest sprouts ( $38.29 \pm 1.70$  cm), significantly outperforming medium ( $27.38 \pm 1.43$  cm) and thin ( $17.67 \pm 1.76$  cm) fragments. Despite these differences in vigor, resprouting frequency did not differ significantly between rhizome classes ( $p > 0.05$ ), indicating that even the thinnest fragments retain regenerative potential. The hierarchical cluster analysis (HCA) further identified two functional clusters, separating thin fragments into a “survivalist” cluster characterized by reduced growth compared to medium and thick fragments, which formed a “vigor-driven” cluster with a far superior regenerative potential. Moreover, these findings highlighted a critical management loophole; that is, mechanical control alone may have contributed to rhizome fragmentation, creating the impression of reduced infestations while viable fragments persisted and regenerated following disturbance, a phenomenon termed the “latency period.” Thus, effective management must shift from strategies that merely fragment rhizomes to those that ensure the complete suppression of rhizome viability.

**Keywords:** invasive weeds, mechanical control, rhizomes, resprouting frequency, vegetative propagation

## Introduction

Globally ranked among the most destructive invasive species, Japanese knotweed (*Reynoutria japonica* Houtt., Polygonaceae) poses a serious threat to ecosystem stability worldwide (Weber and Gut 2004; Lavoie 2017). Native to eastern Asia, the species was introduced to Europe during the 19<sup>th</sup> century as an ornamental plant and has since spread extensively throughout much of the continent (Beerling *et al.* 1994; Child and Wade 2000). Supported by an extraordinarily broad ecological plasticity (Landolt 1977; Beerling *et al.* 1994), the species rapidly colonizes and

dominates diverse habitats (Conolly 1977; Seiger 1997). Following establishment, *R. japonica* typically forms dense, monospecific stands that suppress native flora, reduce biodiversity, and alter ecosystem processes through shading, allelopathy, and changes in nutrient cycling (Seiger 1996; Urgenson 2006; Dommagnet *et al.* 2014). In riparian areas, infestations obstruct water flow and, by extension, amplify flood risk (Seiger 1997; Child and Wade 2000). Following the autumn senescence of these riparian stands, riverbanks and steep slopes are left bare during winter, leaving the soil highly prone to erosion (Evans *et al.* 2006; Urgenson 2006).

The management of *R. japonica* remains a formidable challenge, primarily because current control methods have proven to be of a limited effect for this difficult-to-manage species (Child and Wade 2000; Evans *et al.* 2006). Chemical control, while often effective, is increasingly restricted due to herbicide-associated ecotoxicological risks, the development of resistance, and restrictions imposed by EU legislation (Jones *et al.* 2018; Taylor and Glaister 2018; Jones and Eastwood 2019). Biological control remains experimental and has yet to demonstrate large-scale effectiveness. The Japanese knotweed psyllid (*Aphalaria itadori* Shinji) currently represents a promising control agent (Child and Wade 2000; Djeddour and Shaw 2010). By contrast, mechanical control is time-consuming, labor-intensive, and often ineffective, as it regularly triggers vigorous resprouting, necessitating repeated follow-ups (Child and Wade 2000; Taylor and Glaister 2018).

A key factor underpinning the global invasiveness of *R. japonica* is its exceptional capacity for vegetative regeneration via an extensive subterranean rhizome network (Seiger 1997; Child and Wade 2000; Lawson *et al.* 2021). Even very small rhizome fragments can resprout successfully, notwithstanding that larger fragments with greater carbohydrate reserves and higher densities of viable dormant buds exhibit particularly high regenerative potential (Seiger and Merchant 1997; Price *et al.* 2002; Bímová *et al.* 2003; Gowton *et al.* 2016). This biological resilience undermines conventional control efforts; rather than eliminating established populations, such efforts often fragment rhizomes, thereby exacerbating existing infestations and promoting secondary spread (Child and Wade 2000; Taylor and Glaister 2018; Jones and Eastwood 2019).

Admittedly, the role of rhizomes in the regeneration of *R. japonica* is well established; however, the specific influence of rhizome diameter on sprout development and resprouting capacity remains

insufficiently quantified. Clarifying this relationship is essential for addressing the risks of inadvertent spread associated with rhizome fragmentation during management operations, and for improving management outcomes. Accordingly, this study investigated how rhizome fragment diameter affects (i) sprout length, (ii) resprouting frequency, and (iii) overall regenerative capacity under controlled conditions.

## **Materials and methods**

### **Collection site and plant material**

A population of *R. japonica* was identified on August 5, 2025 near a tributary of the Pilica River, in the vicinity of Kały village, southern Poland (50°54'42.5"N; 19°49'16.2"E) (Fig. 1). The on-site taxonomic identification was based on the taxonomic key of Jávorka and Csapody (1979). Following identification, rhizome excavation was conducted in strict accordance with guidelines of the International Union for Conservation of Nature (1989), after which a representative voucher specimen (KAiPR2025/8) was prepared and deposited in the herbarium collection of the Department of Agroecology and Crop Production, University of Agriculture in Krakow.



**Fig. 1.** Location of *R. japonica* specimens near Kąty village, Poland (map prepared using the QGIS software, v. 3.34.5.)

### Rhizome excavation and preparation

Dormant rhizomes were excavated on November 10, 2025, from the upper 10 cm of the soil profile. The rhizomes were then thoroughly washed under running tap water and cut into uniform 4-cm-long fragments. To simulate winter conditions, fragments were stored for three months at 3°C in the dark. Subsequently, they were planted in 0.5 L plastic pots (11 cm × 8.5 cm) filled with commercial garden substrate (BIOVITA sp. z o.o., PL) and kept at 20°C under a 12 h/12 h photoperiod with regular irrigation.

## Experimental design

The experiment followed a completely randomized design (CRD) and was conducted in two stages. Initially, the resprouting frequency was monitored for 130 rhizome fragments, classified into three diameter classes: (i) thin ( $\leq 1.0$  cm;  $n = 25$ ), (ii) medium (1.1–2.0 cm;  $n = 49$ ), and (iii) thick ( $\geq 2.0$  cm;  $n = 56$ ). Thereafter, a morphometric analysis was performed on 2-week-old sprouts following their emergence to evaluate the effect of rhizome diameter on sprout development. The sprout length (cm) was measured from the point of attachment on the rhizome to the apical meristem as a measure of sprout vigor. Throughout the experiment, sprout emergence was monitored daily to assess regenerative capacity.

## Statistical analysis

Preliminary data processing was carried out in MS Office Excel 2024 (Microsoft Corporation, Redmond, WA, USA, v. 2603). The normality of data distribution and the homogeneity of variances were evaluated using the Shapiro–Wilk ( $W_{\text{Length}} = 0.971$ ,  $p = 0.575$ ) and Levene’s test ( $F_{\text{Length}} = 0.745$ ,  $p = 0.484$ ), respectively. Sprout length was analyzed using the one-way ANOVA, followed by Tukey’s HSD post-hoc test. Differences in sprouting frequency between diameter classes were determined using Pearson’s chi-square test and Fisher’s exact test (Fisher–Freeman–Halton extension). Additionally, the Cochran–Armitage trend test was employed to assess the linear relationship between increasing rhizome diameter and resprouting capacity. Finally, rhizome fragment diameter, sprout length, and resprouting frequency were integrated into a unified model using a hierarchical cluster analysis (HCA). The HCA was performed on Z-score standardized data to account for different units of measurement. The clustering was based on the Euclidean distances and Ward’s  $D^2$  linkage method to minimize within-cluster variance. The HCA was conducted in R environment (Vienna, Austria, v. 4.5.0) via RStudio (Boston, MA, USA, v. 2026.1.2.418) using the *dendextend* package (v. 1.19.1). Statistical significance was set at an  $\alpha = 0.05$ . All other analyses were conducted using the PQStat software (PQStat, Poznań, Poland, v. 1.8.6.126).

## Results

### Influence of rhizome diameter on sprout length

Sprout length differed significantly between rhizome classes ( $p < 0.001$ ), with diameter accounting for 62.40% of the variation in sprout growth (Table 1). Likewise, Tukey's HSD post-hoc test confirmed significant differences between diameter classes ( $p < 0.05$ ). In particular, a clear upward trend was observed; that is, mean sprout length increased with fragment diameter. The length ranged from  $17.67 \pm 1.76$  cm for thin fragments to  $27.38 \pm 1.43$  cm for medium ones, while thick fragments reached a maximum of  $38.29 \pm 1.70$  cm (Fig. 2).

**Table 1.** One-way ANOVA results for sprout length of *R. japonica* rhizome fragments

| Source of variation | SS      | df | MS     | F     | $p$             | $\eta^2$ |
|---------------------|---------|----|--------|-------|-----------------|----------|
| Rhizome diameter    | 1438.90 | 2  | 719.45 | 22.42 | $< 0.001^{***}$ | 0.624    |
| Error               | 866.60  | 27 | 32.10  |       |                 |          |
| Total               | 2305.50 | 29 |        |       |                 |          |

Significance thresholds: n.s. – not significant, \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

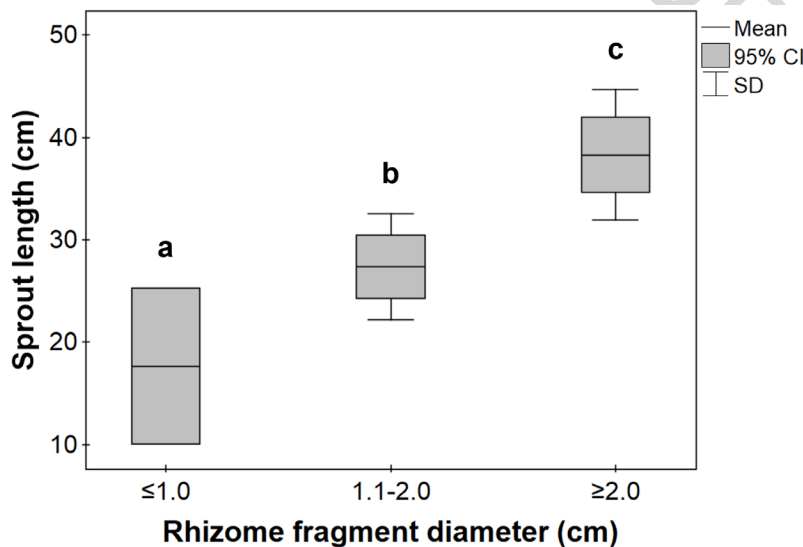


**Fig. 2.** Sprout length of *R. japonica* in relation to rhizome fragment diameter. Different letters indicate statistically significant differences according to Tukey's HSD post-hoc test ( $p < 0.05$ ).

## Influence of rhizome diameter on resprouting frequency

Rhizome fragments varied in their resprouting capacity by diameter (Fig. 3A–B). Of the 130 fragments examined in total, the thick class ( $\geq 2.0$  cm) was most represented, followed by the medium (1.1–2.0 cm) and thin classes ( $\leq 1.0$  cm) (Fig. 3A). Sprout emergence was observed across all classes; nevertheless, larger fragments generally had higher resprouting capacity. Specifically, only three fragments from the thin class resprouted (12.00%), whereas the medium and thick classes showed higher rates of 27.00% and 25.00%, respectively (Fig. 3B).

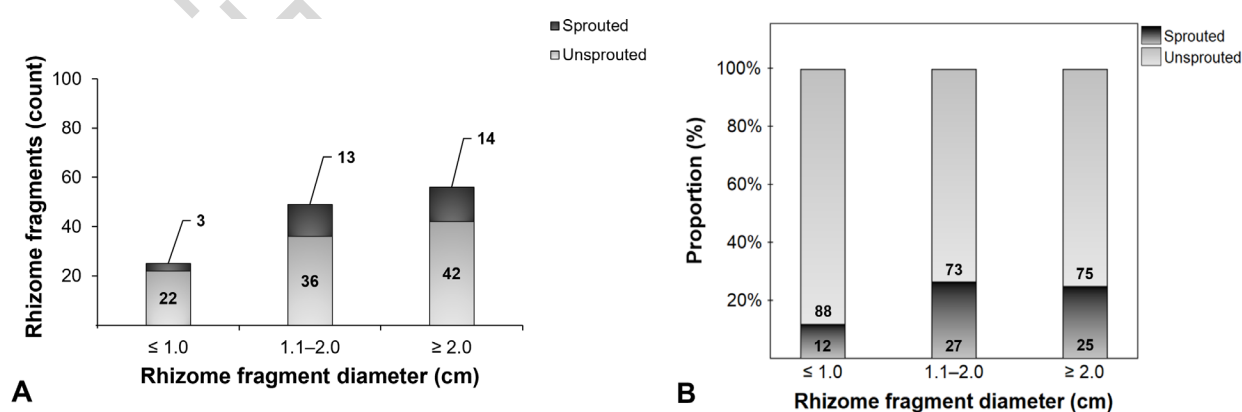


**Fig. 3.** Effect of rhizome fragment diameter on the resprouting frequency of *R. japonica*: A – total number of sprouted and unsprouted fragments; B – relative proportion of sprouted fragments across different diameter classes.

Despite these observations, Pearson's chi-square test ( $\chi^2_{(2)} = 2.174$ ,  $p = 0.337$ ) and Fisher's exact test ( $p = 0.354$ ) revealed that the effect of rhizome diameter on resprouting frequency was not statistically significant. Moreover, the Cochran–Armitage trend test did not detect a significant linear relationship between increasing rhizome diameter and resprouting frequency ( $\chi^2_{(1)} = 1.132$ ,  $p = 0.287$ ).

## Multivariate assessment of regenerative capacity

The HCA was conducted to explore relationships between rhizome fragment diameter, sprouting frequency, and sprout length (Fig. 4). The resulting dendrogram grouped the rhizome fragment classes into two distinct functional clusters. The first cluster was comprised of thin rhizome

fragments ( $\leq 1.0$  cm), characterized by lower overall resprouting frequency and minimal sprout elongation. Conversely, the second cluster grouped medium (1.1–2.0 cm) and thick ( $\geq 2.0$  cm) rhizome fragments, which were marked by far superior regenerative potential. This grouping demonstrated that rhizome fragments exceeding 1.0 cm in diameter had notably greater regenerative capacity.

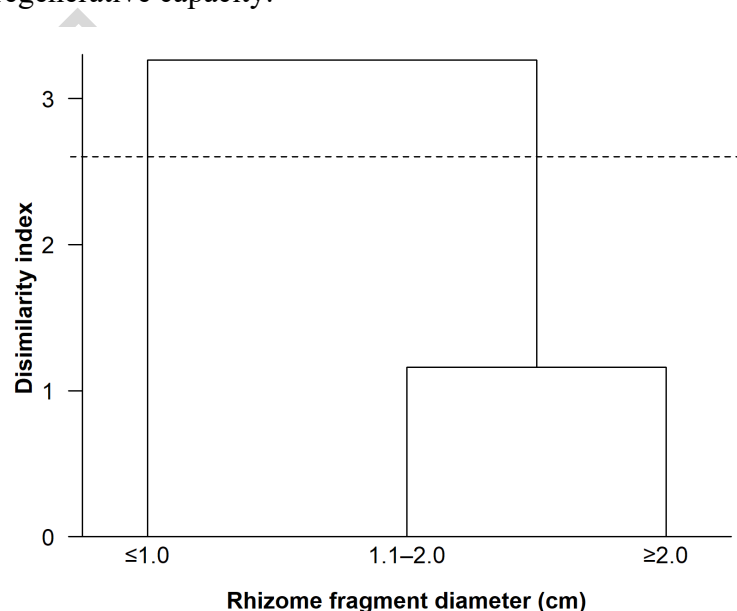


**Fig. 4.** Hierarchical cluster analysis (HCA) of *R. japonica* based on rhizome diameter, sprout length, and resprouting frequency. The dashed line indicates the dissimilarity threshold used to distinguish functional clusters.

## Discussion

### Rhizome fragment diameter as a driver of sprout vigor

This study showed that rhizome fragment diameter was a key determinant of early sprout growth. Medium-sized and thick fragments produced significantly longer sprouts; however, their resprouting frequencies did not differ significantly from those of thin fragments. These results indicated that, profound though the impact of fragment size on sprout growth may be, even the thinnest fragments ( $\leq 1.0$  cm) retained the resprouting capacity. The observed pattern was consistent with previous studies reporting that larger rhizome fragments with greater carbohydrate reserves supported more vigorous early sprout development (Price *et al.* 2002; Gowton *et al.* 2016;

Jousson *et al.* 2026). Nonetheless, the lack of a statistically significant difference in resprouting frequency suggested that successful sprout emergence may depend more on the presence of at least one viable dormant bud rather than rhizome diameter itself. This conclusion was further supported by Lawson *et al.* (2021) and Jousson *et al.* (2026), who noted that although larger rhizomes generally contain more buds, the regeneration of individual fragments ultimately depends on the viability of those buds, which was not directly assessed in the present study.

### **Regenerative strategies of rhizome fragments**

The HCA provided additional insights into the regenerative behavior of rhizome fragments by grouping them into two distinct functional clusters. The clusters provided compelling evidence for the bud-dependent regenerative variation reported by Lawson *et al.* (2021) and the diameter-dependent resprouting capacity described by Jousson *et al.* (2026), presenting distinct management challenges. The first cluster, comprised of exclusively thin fragments ( $\leq 1.0$  cm), was designated a “survivalist” cluster due to low resprouting frequency and reduced sprout length. These fragments pose a high risk because their regenerative capacity remains intact despite their small size, allowing them to persist undetected in the soil. On the other hand, the second, “vigor-driven” cluster groups medium (1.1–2.0 cm) and thick ( $\geq 2.0$  cm) fragments reflect a shared capacity for rapid sprout emergence and vigorous growth. Taken together, the two clusters highlight a dual regenerative strategy of *R. japonica* characterized by (i) persistence through regeneration from small fragments and (ii) rapid establishment and vigorous growth from larger fragments following disturbances.

### **Cross-regional management applicability**

The environmental conditions at the Polish collection site, characterized by a temperate climate and moist alluvial soils, provided a representative model for other regions where *R. japonica* is highly invasive. This ecological setting mirrors infested riparian corridors across temperate North America and Western Europe, where the species consistently exhibits severe invasiveness (Conolly 1977; Seiger 1997; Child and Wade 2000). Consequently, the observed relationship between rhizome diameter and sprout vigor represented a universal regenerative strategy applicable to management efforts in similar riparian ecosystems worldwide. Although resprouting occurred

across all diameter classes, the significantly shorter sprouts in thin fragments suggested a lower threshold of stored reserves. This relationship directly reflected clonal plant physiology, as larger rhizomes typically store more carbohydrates, which serve as the primary energy source for initial sprout elongation (Seiger and Merchant 1997; Klimešová and Klimeš 2007). Because *R. japonica* relies heavily on vegetative propagation (Beerling *et al.* 1994; Child and Wade 2000), these energy reserves determine long-term survival in competitive field conditions. A similar dependence is well documented for *Fallopia × bohemica*, where fragment size strongly predicts establishment and invasion success following disturbance (Bímová *et al.* 2003).

### **Mechanical control-associated risks and the “latency period”**

From a management perspective, these findings underscore the inherent risk of soil disturbance (Child and Wade 2000; Evans *et al.* 2006; Taylor and Glaister 2018). Despite the fact that the larger fragments produced the most vigorous sprouts, the ability of even the smallest fragments to resprout stresses the fundamental limitation of mechanical control. Although mechanical excavation and removal may reduce above-ground biomass and yield immediate results, they are often costly and can inadvertently facilitate further spread (Child and Wade 2000; Taylor and Glaister 2018; Jones and Eastwood 2019). By fragmenting rhizomes and redistributing them through the soil profile, such interventions can increase the number of viable fragments despite an apparent reduction in infestation size. This, in turn, creates the appearance of suppressed infestations, but at the same time leaves numerous viable rhizome fragments concealed and scattered in the soil. The resulting hidden regenerative potential creates a deceptive period of apparent control, a phenomenon referred to here as the “latency period.”

### **Implications for the integrated management framework**

Bearing in mind the demonstrated regenerative capacity of even the smallest rhizome fragments, management frameworks must move beyond simple biomass reduction and focus on complete suppression of rhizome viability. Integrating mechanical control with innovative disposal techniques, such as microwave-induced soil sterilization (Słowiński *et al.* 2024), could offer a more sustainable alternative to chemical treatments, which are increasingly restricted due to

ecotoxicological risks (Child and Wade 2000; Taylor and Glaister 2018). Such a transition is essential to eliminate the risk of regrowth from even the smallest, overlooked fragments that current on-site burial or soil-screening practices may miss. By combining mechanical removal with these advanced disposal methods, it is possible to mitigate the long-term persistence associated with the “latency period” and improve management outcomes in invaded riparian ecosystems.

## Conclusions

In conclusion, this study demonstrated that while larger rhizome fragments drive the most vigorous regrowth of *R. japonica*, even small fragments retain regenerative capacity. These findings underscored that conventional mechanical control alone is unlikely to achieve long-term suppression. Rather than fully eliminating infestations, mechanical control may lead to rhizome fragmentation, hence multiplying and redistributing them throughout the soil profile. As a result, infestations may appear reduced even as viable rhizome fragments remain concealed in the soil, a phenomenon referred to here as the “latency period.” Therefore, management frameworks must move beyond mere rhizome fragmentation and focus on alternative strategies. This can be achieved, for example, by combining mechanical control methods with innovative disposal techniques such as microwave radiation to eliminate any remaining rhizome fragments in the soil, regardless of their size. Ultimately, an integrated management strategy is essential not only for safeguarding riparian ecosystems and supporting native vegetation recovery, but also for enhancing their long-term sustainability in the face of escalating threats posed by *R. japonica*.

## Funding

This research was funded by a subsidy of the Ministry of Education and Science for the Hugo Kołłątaj University of Agriculture in Krakow for 2026.

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