



Invasive non-native plants indirectly destabilise riverbanks

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Abstract Invasive Non-Native Plant species (INNP) establishment along rivers continues to accelerate globally, with potential consequences for riverbank stability, ecosystem functions and services. Riverbank stability is dependent on the balance between destabilising forces (e.g., shear stress) and stabilising influences (e.g., sediment cohesion and native vegetation reinforcement). However, disturbance driven INNP invasions are attributed to decreasing riverbank stability through outcompeting and replacing native vegetation. One such INNP, *Impatiens glandulifera* (Himalayan Balsam), has been linked to increased riverbank erosion over winter owing to an annual post summer phenological dieback. Yet the impact of *I. glandulifera* on riverbank stability remains unknown. Here we show that *I. glandulifera* invasion indirectly amplifies seasonal

reductions in riverbank shear strength. We found, using piecewise Structural Equation Modelling, that previous summer *I. glandulifera* cover indirectly influences riverbank shear strength via suppression of overwinter native vegetation cover, promoting the formation of bare ground. Riverbank shear strength was ~30% lower over winter in invaded compared to uninvaded sites. Our results demonstrate how an annual INNP can amplify expected seasonal decreases in riverbank stability because of a seasonal phenological feedback. INNP influence on riverbank stability has key implications for ecosystem function and services. As invaded riverbanks may be more vulnerable to erosion leading to morphological changes and downstream habitat degradation from increased sediment loading. Furthermore, these findings have management implications with potentially additional intervention measures required to mitigate reduced riverbank stability during INNP removal activities.

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Introduction

Riparian corridors are the transitional zones between freshwater and terrestrial habitats, associated with high species richness, diversity and dynamism, providing numerous ecosystem services (Nilsson and Svedmark 2002; Riis et al. 2020). Riverbank stability,

the ability to resist structural failure, is a product of the balance between fluvially and gravitationally exerted shear stresses and the opposing resistance forces acting on the bank toe and face (Thorne and Tovey 1981; Davis and Harden 2014). Whilst sediment cohesion and riverbank geometry are key controls on riverbank stability, riparian vegetation plays a central role (Rowntree and Dollar 1999; Pollen and Simon 2005; Pollen-Bankhead and Simon 2010; Krzeminska et al. 2019). However, increasing anthropogenic disturbances (e.g., water extraction, habitat modification, etc.) along riparian corridors promotes the establishment of Invasive Non-Native Plant species (INNPs), threatening native riparian vegetation and in-turn their role in sustaining riverbank stability (Maracahipes-Santos et al. 2020; Wohlgemuth et al. 2022).

Riparian vegetation stabilises riverbanks through mechanical and hydrological reinforcement (Pollen-Bankhead and Simon 2010; Krzeminska et al. 2019). Roots increase sediment cohesion by redistributing shear stress across the riverbank (Pollen and Simon 2005; Bischetti et al. 2009), while evapotranspiration enhances infiltration and mediates pore-water pressure (Boldrin et al. 2017; Ni et al. 2018). Above ground plant traits such as high biomass and stem flexibility deflect near-bank flows, reducing shear stress (Griffin et al. 2005; Caroppi et al. 2022; Barmann and Kumar 2024). These stabilising effects are dynamic, varying with phenology (e.g., peak summer plant biomass) and life history (perennial versus annual plant species) (Krzeminska et al. 2019). By stabilising riverbanks, riparian vegetation supports ecosystem services including erosion control, reduced fine sediment loading, improved water quality and flood mitigation (Riis et al. 2020). Therefore, additional pressures on native riparian vegetation, such as invasion by INNPs can impact these ecosystem services.

Globally, INNPs are spreading rapidly in riparian corridors driven by climate change, hydrological connectivity, disturbance and other anthropogenic pressures (Pattison et al. 2017; Chapman et al. 2020). INNPs can significantly alter river processes, for example *Reynoutria japonica* (Japanese Knotweed) reduced summer discharge by 8% (Galster and Vanderklein 2023) and *Arundo donax* (Giant Reed) decreased riverbank stability by up to 44% compared to native vegetation (Stover et al. 2018). By

forming dense stands that can suppress native vegetation, INNPs can reduce sediment cohesion through changes to root length and density, and/or stem flexibility (Stover et al. 2018; Sodhi et al. 2019; Livingstone et al. 2020). Such changes can impact riparian ecosystem services and restructure river geomorphology (Robertson and Coll 2019). For instance, *Tamarix* spp. (Salt Cedar) invasion increased total river corridor area by 13% to 30% following a 1 in 40-year flood (González et al. 2019), while *R. japonica* cover was linked to a reduction in water quality due to increased turbidity during storm events (Arnold and Toran 2018). Despite these impacts, the effects of INNPs on riverbank stability remain understudied (Hardwick et al. 2025).

Most existing research is focussed on semi-arid systems of south-western United States, studying woody perennials such as *Tamarix* spp. and *Elaeagnus angustifolia* (Russian Olive) (Pollen-Bankhead and Simon 2010; Jaeger and Wohl 2011; Cadol et al. 2011), or grasses such as *A. donax* (Stover et al. 2018). Extrapolating from these systems to temperate rivers is problematic, as most INNPs are either annual or perennial herbs with marked seasonal variation in biomass. With the frequency of non-native plant introductions predicted to increase by 2050 (Seebens et al. 2017; Seebens et al. 2021), there is an urgent need to understand their geomorphic impacts to inform management and safeguard ecosystem services.

Impatiens glandulifera (Himalayan Balsam) has rapidly spread across the UK, and throughout Europe, since its introduction in the 1830s (Helsen et al. 2021). *Impatiens glandulifera* is an annual herb, that forms dense stands, exploiting fluvial processes that also sustain diverse native vegetation (Tanner and Gange 2020). Reported impacts include suppression of native vegetation (Hulme and Bremner 2006; Pattison et al. 2017), altered invertebrate biodiversity (Chittka and Schürkens 2001; Seeney et al. 2019), and potential links to increased riverbank erosion (Greenwood and Kuhn 2014). Increased riverbank erosion risk is thought to arise from overwinter dieback of *I. glandulifera*, which leaves riverbanks bare during winter flooding (Greenwood and Kuhn 2014), coupled with the displacement of stabilising clonal and/or rhizomatous native species, such as *Urtica dioica* (Common Nettle) and *Phalaris arundinacea* (Reed Canary Grass)

(Hulme and Bremner 2006). However, evidence remains limited (e.g. Greenwood and Kuhn 2014; Greenwood et al. 2018), and the extent to which *I. glandulifera* destabilises riverbanks has not been quantified, limiting predictions of long-term geomorphic and ecosystem services impacts.

Disentangling these effects is challenging, as invasion interacts with native plant competition and geomorphological feedbacks. Here, we assess the role of *I. glandulifera* invasion on riverbank stability by comparing paired invaded and uninvaded lowland riparian sites. Specifically, we (i) quantify vegetation community composition and cover, (ii) compare seasonal variation in riverbank shear strength and (iii) using piecewise structural equation modelling (pSEM) we test direct and indirect effects of invasion on riverbank stability.

Methods

Site selection

Eight paired invaded and uninvaded sites were established along two UK lowland rivers; the River Tees (North Yorkshire, England) and River Forth (Stirlingshire, Scotland) (Fig. 1). Each site was 100 m in length and selected based on the following criteria: similar planform sinuosity, pronounced riverbank profile, tree cover and level of invasion. Sites with low tree cover (<10%) were selected as this negates the effects of tree-induced bank stabilisation (Abernethy and Rutherford 2000), isolating the effect of herbaceous vegetation. *Impatiens glandulifera* communities are well established along the River Forth (>15 years) and River Tees

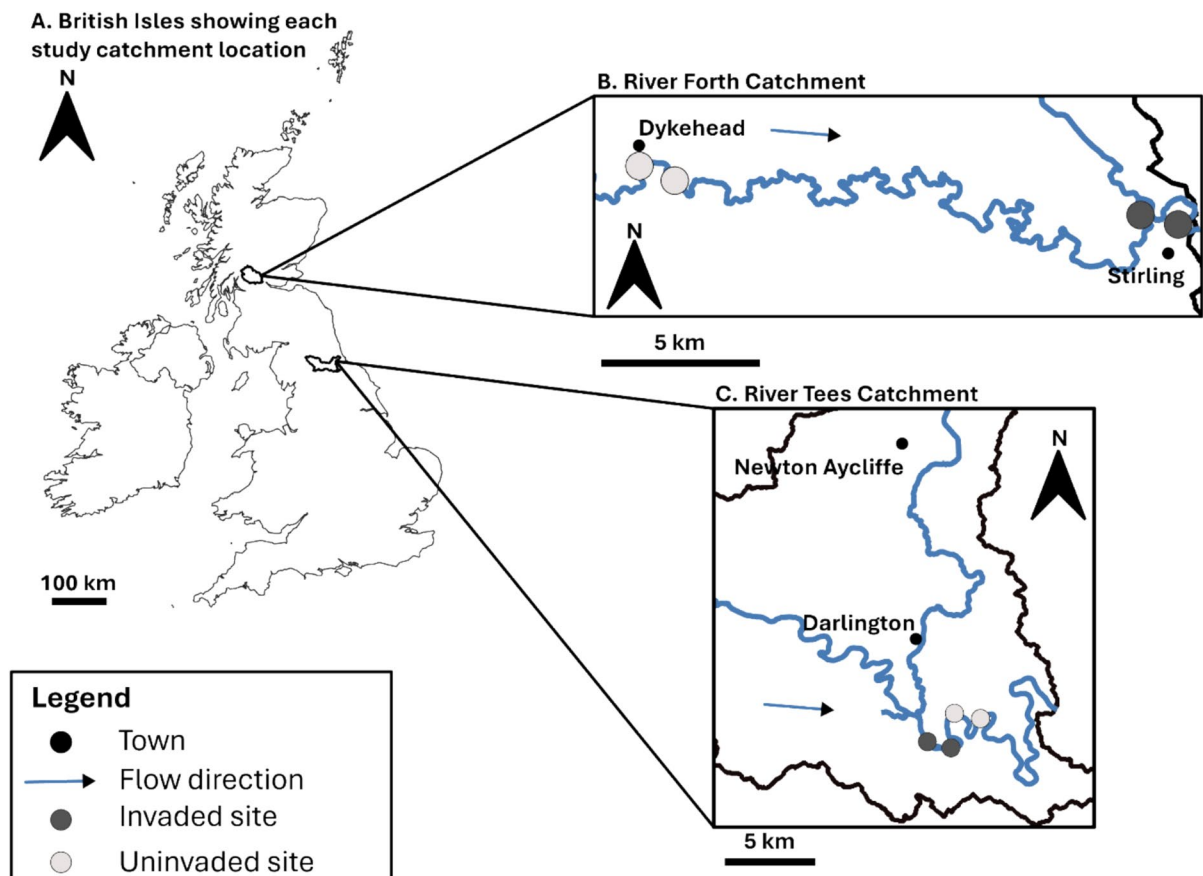


Fig. 1 Map showing the (A) location of the two study catchments in Britain, (B) position of paired invaded and uninvaded sites in the River Forth Catchment, and (C) position of paired

invaded and uninvaded sites in the River Tees Catchment. Individual site coordinates are listed within Supplementary Information 1

(> 10 years). Uninvaded sites were characterised where total *I. glandulifera* cover was < 5%, with the assumption that below this threshold there was minimal impact on native vegetation (Hulme and Bremner 2006). Across most of the uninvaded sites *I. glandulifera* was absent however, at one site on River Forth *I. glandulifera* had < 1% cover ($n=4$ individuals).

Collection of vegetation data

Repeated vegetation surveys were conducted in winter and summer from 2022 to 2024 to quantify seasonal changes in riparian vegetation community composition and cover. At each site, a 100 m length of riverbank was surveyed using 10 six metre permanent transects (marked by flags) placed at 10 m intervals perpendicular to the river channel. Two one-meter squared quadrats were established per transect: one at the bank face (water's edge) and one at the bank top (where the bank profile plateaus, 5–6 m from the bank face). In each quadrat ($n=160$ per sampling period), all plant species were identified and cover of each species quantified using the five-point Braun-Blanquet scale (Wikum and Shanholtzer, 1978). *I. glandulifera* density was quantified as the number of individual stems per quadrat; we additionally recorded total *I. glandulifera* cover using the Braun-Blanquet scale.

Environmental data

Environmental covariates were measured at the quadrat scale: volumetric soil moisture, tree density and ground cover classes. Volumetric soil moisture was measured using a handheld soil moisture meter ($\pm 3\%$ accuracy; SM150, Delta-T devices LTD, Cambridgeshire, UK) at 5 points in each quadrat up to 15 cm depth to account for the active root zone (Walker et al. 2004), thereafter averaged for each quadrat. Distance to tree was measured from each quadrat to the nearest tree, as a proxy for shading and capturing tree-riverbank reinforcement. The percentage cover of three ground cover classes per quadrat were visually estimated: bare ground, dead *I. glandulifera* stems and native vegetation cover (Zobell et al. 2020).

Collection of geotechnical data

For each sampling period, riverbank stability was assessed by measuring the unconfined compressive and shear strength within each quadrat. A handheld penetrometer (Pocket Penetrometer; AMS Inc.) and torvane (Torvane; Controls Group S.p.A) were used to undertake rapid, non-destructive measurements without disturbing overlying riparian vegetation. We acknowledge that these rapid methods may underestimate the degree of root reinforcement owing to a small cross-sectional area of force being applied to the bank ($< 3 \text{ cm}^2$). However, using these rapid methods enables multiple non-destructive measurements to be taken. Within each quadrat, five replicate measurements were taken and averaged for unconfined compressive and shear strength. Sediment cores (15 cm deep) were also collected from each quadrat using an Eijkelkamp soil auger and the dominant grain size for each sediment core was classified visually using a Wentworth chart (Wentworth 1922), to account for grain size effects on shear strength. Additional contextual riverbank geomorphology features such as tension cracks, large woody debris, and anthropogenic structures were also recorded per site.

Data analysis

Analyses were conducted using R version 4.4.4 (R Core Team 2024) using the packages 'lme4' (Bates et al. 2015), 'DHARMA' (Hartig 2024) and 'performance' (Lüdtke et al. 2021).

Impact of *Impatiens glandulifera* on native vegetation

To assess the effect of *I. glandulifera* cover on native plant species richness across invaded and uninvaded plots during the summer (*I. glandulifera* growing season) survey period, we used a generalised linear mixed effects model (GLMM) with Poisson distribution and log-link function to account for count data. *I. glandulifera* cover was square root transformed and scaled prior to modelling to improve model performance. Model performance was assessed using changes in Akaike Information Criterion (AIC). An interaction between *I. glandulifera* cover and survey period was used to test if *I. glandulifera*'s effect on native plant species richness varied across survey periods, both summer and winter. A nested random

effect of transect within site was included to account for both the hierarchical sampling design and spatial distribution of quadrats. GLMM fit was evaluated for overdispersion and assessed using simulated residuals plotted against each explanatory variable.

Variation in riverbank shear strength

Univariate visualisation and descriptive statistics were initially undertaken to assess seasonal variability in riverbank shear and compressive strength. Due to low variation between sites, compressive strength was excluded as a response variable (Supplementary Information 2). Riverbank shear strength was then modelled using a linear mixed effect model (LMM), with invasion status (invaded vs. uninvaded) and survey period as fixed effects, including their interaction to test for variation in seasonal effects. Riverbank shear strength was log transformed to improve model fit, and a gaussian distribution with a log link function was applied. Transect nested within site was included as a random effect to account spatial variation and pseudoreplication. Model fit was visually assessed using simulated residuals plotted against each explanatory variable for normality.

The role of *Impatiens glandulifera* in overwinter riverbank stability

To disentangle the direct and indirect effects of explanatory variables on riverbank shear strength, piecewise Structural Equation Modelling was implemented (pSEM; Lefcheck 2016); focusing on the overwinter period due to marked differences in riverbank shear strength in relation to previous summer *I. glandulifera* cover. First, a conceptual model was developed to represent hypothesised causal relationships between variables (Fig. 2). We hypothesised that high previous summer *I. glandulifera* cover (predictor) suppresses overwinter native vegetation cover, which mediates an increase in bare ground, thereby reducing riverbank shear strength. Sediment grain size was also expected to negatively affect shear strength, as coarser sediments are less cohesive (Thorne and Tovey 1981).

The use of pSEM allows quantification of both direct and indirect effects through multiple constituent LMMs. Prior to analysis, response variables were examined for normality and square root transformed

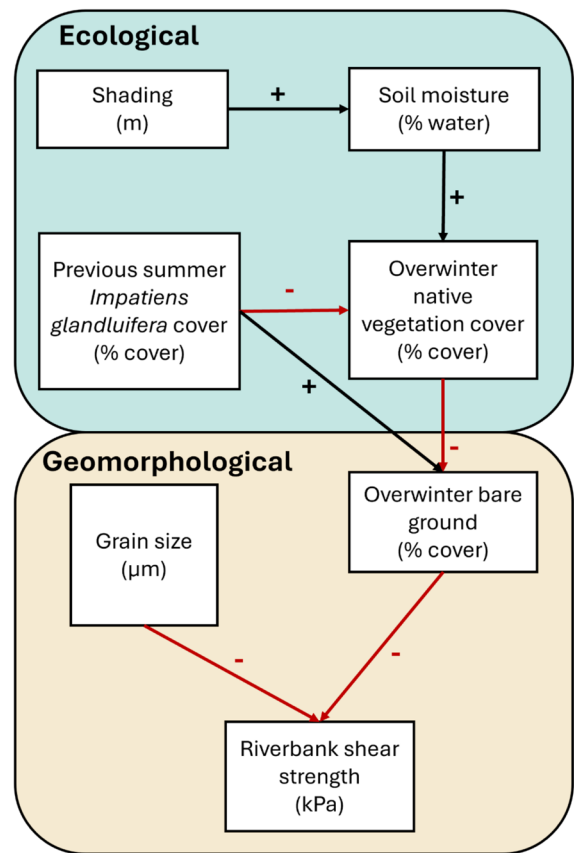


Fig. 2 Conceptual model representing the hypothesised direct and indirect relationships between ecological and geomorphological variables and riverbank stability over winter. Red arrows indicate negative effects; black arrows indicate positive effects

where necessary. Continuous explanatory variables were mean centred and scaled to one standard deviation, to enable comparison of variable coefficients. To reduce model collinearity, highly correlated ($r > 0.6$) explanatory variables were removed based on ecological and geomorphological reasoning. Each constituent LMM was fitted using 'lme4' (Bates et al. 2015), with survey period and transect as random effects to account for spatial autocorrelation and inter survey period variation, respectively. Each model was assessed for violation of linearity, normality, homoscedasticity and multicollinearity ($VIF < 5$; *car* package, Fox & Weisberg 2019) (Supplementary Information 3).

Constituent LMMs were integrated into a single pSEM. Potentially missing pathways between

variables were evaluated using d-separation testing (Shipley 2009) and included only when supported by ecological or geomorphological reasoning. Non-significant pathways were removed when justifiable (e.g. soil moisture and tree density: $p > 0.05$; Supplementary Information 3). Overall pSEM fit was assessed using Fisher's C, where $p > 0.05$ indicates the model is supported by the data. Standardised path coefficients from the winter pSEM were reported as a causal pathway diagram.

Results

3.1 Effect of *Impatiens glandulifera* cover on native species richness

Overall, increasing *I. glandulifera* cover had a significant negative effect on native plant species richness ($\beta = -0.118$, $p < 0.001$; Fig. 3). Seasonal variation also influenced species richness, with a reduction in summer 2023 compared to summer 2022 ($\beta = -0.526$, $SE = 0.047$, $p < 0.001$); but without a significant difference between summer 2023 and summer 2024 ($p = 0.85$). There was no significant interaction between *I. glandulifera* cover and survey

period (summer 2023 interaction: $p = 0.36$; summer 3 interaction: $p = 0.85$ compared to summer 2022). Overall, fixed effects explained 30.7% (marginal R^2) of the variation with the nested random effect (transect within site) increasing total variance explained to 49.3% (conditional R^2).

Seasonal change in riverbank stability

Riverbank shear strength varied between seasons ranging from 3.8 to 68.0 kPa across all sites. Shear strength was greatest in summer (mean $\pm$ SE: 32.9 ± 0.51 kPa, SD: 10.78, range: 8.5–68 kPa) and lowest in winter (mean $\pm$ SE: 14.3 ± 0.36 kPa, SD: 6.50, range: 3.8 to 35.2 kPa; Fig. 4). In summer, during peak *I. glandulifera* growth, shear strength was 27.9% higher in uninvaded (37.1 kPa, SD: 10.93) compared to invaded (29.0 kPa, SD: 9.07) sites. Similarly, in winter, shear strength was 66.4% greater in uninvaded (17.8 kPa, SD: 6.32) compared to invaded (10.7 kPa, SD: 4.36) sites.

LMM results showed a significant effect of invasion status on riverbank stability, with uninvaded sites having greater shear strength overall ($\beta = 0.192$, $p < 0.05$). Shear strength was significantly lower in winter compared to the summer (winter 2022:

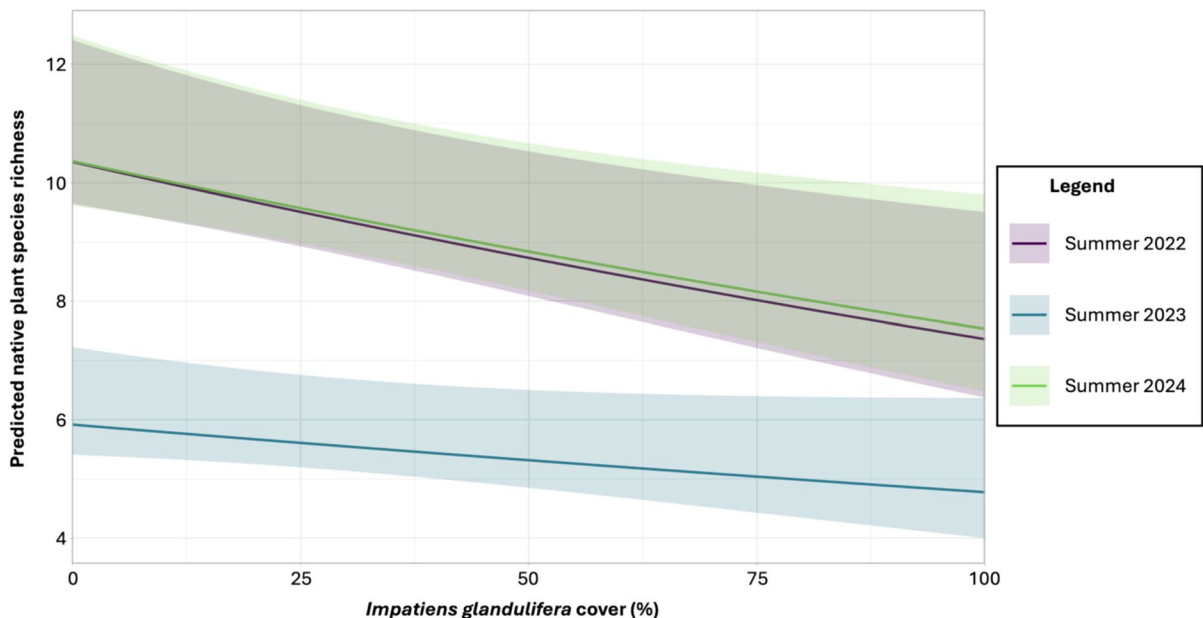


Fig. 3 Generalised linear mixed model predictions for native vegetation species richness in response to increasing *Impatiens glandulifera* cover and summer survey period

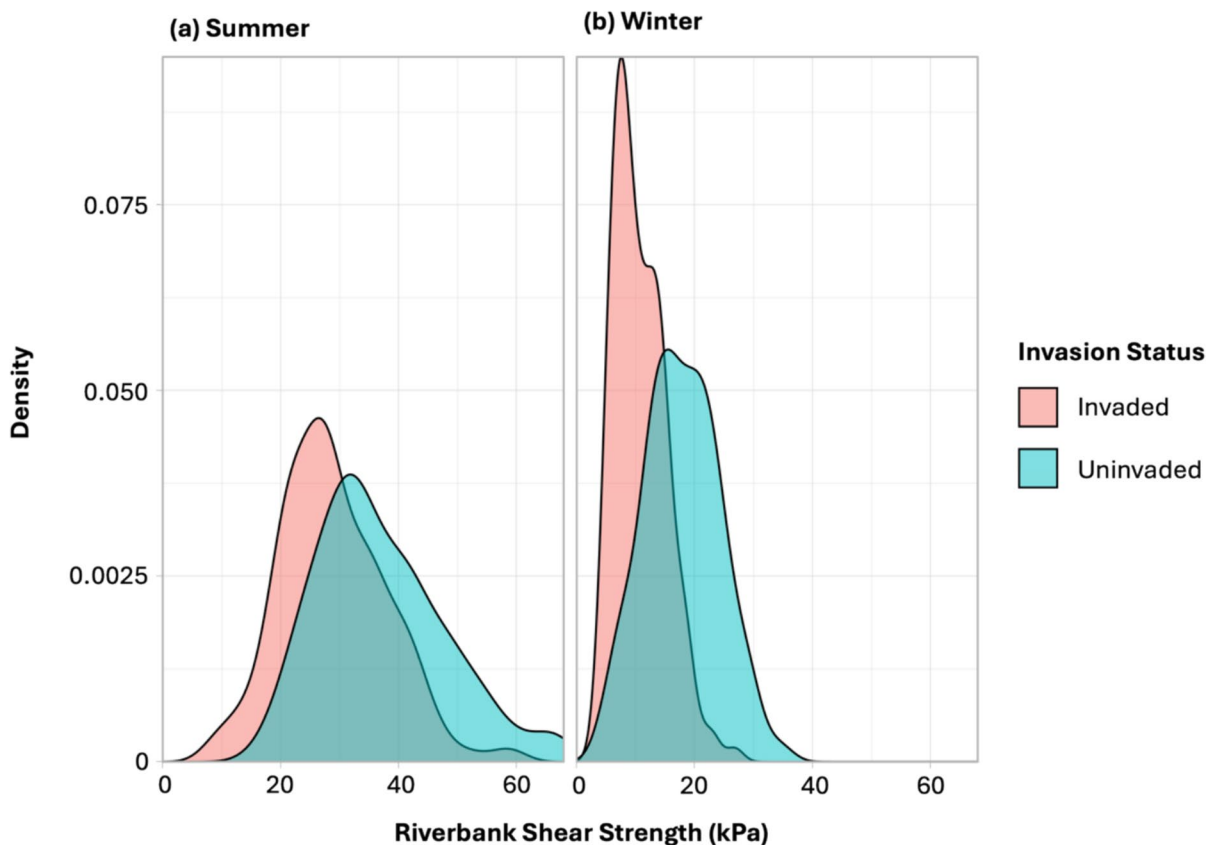


Fig. 4 Density plots showing variation in riverbank shear strength with invasion status by season in (a) summer and (b) winter

$\ell = -1.091$, $p < 0.001$; winter 2023: $\ell = -0.728$, $p < 0.05$). There was also a significant interaction between invasion status and season on riverbank stability, with a positive interaction in summer 2023 ($\ell = 0.178$, $p < 0.05$), winter 2022 ($\ell = 0.396$, $p < 0.05$), and winter 2023 ($\ell = 0.177$, $p = 0.05$), reflecting the consistency lower riverbank shear strength at invaded sites. Overall, fixed effects explained 67.0% (marginal R^2) of the variation, with the nested random effect (transect within site) increasing total variance explained 73.0% (conditional R^2).

Direct and indirect effects of *Impatiens glandulifera* on riverbank stability in winter

The pSEM was well supported by the data (Fisher's $C = 9.051$, $p = 0.171$) and revealed direct and indirect pathways by which previous summer *I. glandulifera* cover affects riverbank stability (Fig. 5). Previous summer *I. glandulifera* cover indirectly reduced

riverbank shear strength by reducing native vegetation cover ($\beta = -0.2581$, $SE = 0.0578$, $p < 0.05$), which in turn mediated the extent of overwinter bare ground ($\beta = -0.8052$, $SE = 0.0408$, $p < 0.05$). Previous, summer *I. glandulifera* cover indirectly increased bare ground cover in the subsequent winter by suppressing native vegetation cover. Bare ground then significantly reduced riverbank shear strength ($\beta = -0.4977$, $SE = 0.0475$, $p < 0.05$), highlighting the influence of vegetation on geomorphological stability. Sediment grain size also had a significant positive direct effect on shear strength ($\beta = 0.1345$, $SE = 0.0426$, $p = 0.05$), reflecting its geotechnical role in stabilizing riverbanks irrespective of vegetation cover. D-separation testing identified a missing pathway: a direct negative effect of previous summer *I. glandulifera* cover on riverbank shear strength ($\beta = -0.1697$, $SE = 0.0500$, $p < 0.05$). Overall, the final pSEM explained substantial variance in the key response variables, particularly bare ground (R^2

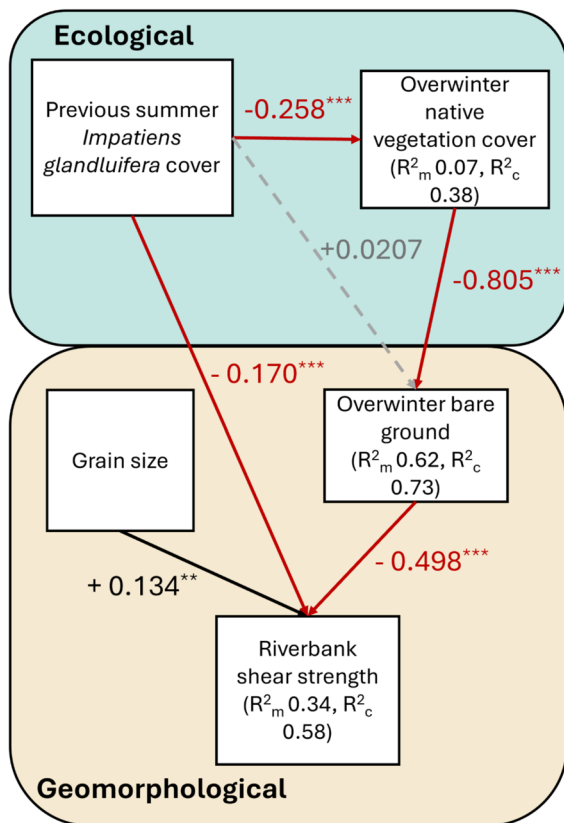


Fig. 5 Piecewise Structural Equation Model showing effects of previous summer *Impatiens glandulifera* cover on over-winter riverbank shear strength. Boxes represent variables; arrows indicate direct relationships (black=positive effects, red=negative). Significant paths are denoted by *** $p < 0.001$, ** $p < 0.01$, and $p < 0.05$, while non-significant paths ($p > 0.05$) are shown as dashed grey lines. Marginal (R^2_m) and conditional (R^2_c) R^2 values show the variance explained by fixed and random effects, respectively

marginal=0.62, R^2 conditional=0.73), shear strength (R^2 marginal=0.34, R^2 conditional=0.58) and, to a lesser extent, native vegetation cover (R^2 marginal=0.07, R^2 conditional=0.38).

Discussion

The influence of riparian INNPs on riverbank stability is understudied, with often conflicting results (Hardwick et al. 2025). Previous research has linked INNP-driven native vegetation replacement to changes in riverbank stability (Jaeger and Wohl 2011; Stover et al. 2018). However, the evidence base for

this is biased as existing studies focussed on arid river systems, leaving other systems, including temperate rivers, underexplored. By using *I. glandulifera* as a model INNP, we show how invasion amplified riverbank destabilisation over winter in temperate river systems, leading to a significant decline (39.9%) in riverbank shear strength.

Effect of seasonal variation and invasion status on riverbank stability

Seasonality strongly influenced riverbank stability, with winter shear strength up to 56.8% lower than summer. This pattern reflects peak summer vegetation cover enhancing sediment cohesion (Polvi et al. 2014; Ali et al. 2017; Lann et al. 2024), followed by senescence (dependent on a plants life history traits) weakening below- and above-ground riverbank reinforcement (Simon and Collison 2002; Pollen-Bankhead and Simon 2010; Krzeminska et al. 2019; Capobianco et al. 2021). Invasion by *I. glandulifera* significantly reduced riverbank stability seasonally, with shear strength ~30% lower at invaded sites over winter, when vegetation cover was low and riverbanks more vulnerable to erosion. While this may partly reflect *I. glandulifera* invasion of already-disturbed habitats (Bieberich et al. 2021), amplification (i.e. the interaction between invasion status and survey period) of an expected seasonal reduction in shear strength indicates a destabilising effect of non-native plant invasions on riverbanks.

The effect of *impatiens glandulifera* on riverbank stability

Our results showed that *I. glandulifera* leads to a reduction in riverbank shear strength both directly and indirectly. Native vegetation cover had a direct effect on the proportion of bare ground over winter, which mediates the relationship between summer *I. glandulifera* cover and shear strength over winter. Bare ground cover had a direct effect on riverbank shear strength, as above and belowground vegetation structures that provide riverbank stability are lost. Because previous summer *I. glandulifera* cover reduces native plant species richness in summer during peak growing season and suppresses native vegetation cover over winter, it indirectly leads to a reduction in riverbank shear strength, increasing

the risk of erosion. The impact of *I. glandulifera* on native plant communities can vary and is often context specific. Our results are consistent with Hulme and Bremner (2006) who reported a ~25% reduction in native plant species richness along northeast UK rivers. However, others including Hejda and Pyšek (2006) reported negligible effects of *I. glandulifera* on native plant diversity along six rivers in the Czech Republic. Hejda et al. (2009) also found that *I. glandulifera* had a minor impact on native plant species richness, attributed to the formation of discrete clusters of *I. glandulifera* individuals, rather than monospecific stands.

I. glandulifera cover exceeded 80% along invaded sites in summer. Thus, the direct effect of previous summer *I. glandulifera* cover on overwinter native vegetation is consistent with Vilà et al. (2011), who suggest that riparian vegetation is more affected by invasions during the summer when there is intense competition for space and light. Species composition between invaded and uninvaded sites varied from diverse perennial reed or grass (e.g. *Lolium perenne*, *Holcus lanatus* and *P. arundinacea*) communities in the uninvaded sites to low species diversity in the *I. glandulifera* dominated invaded sites (other species included: *U. dioica*, *Galium aparine* (cleavers) and *P. arundinacea*). Suppression of native vegetation by *I. glandulifera* significantly increased bare ground cover over winter, mediating a reduction in riverbank shear strength. Bare ground is well established as a driver of riverbank instability, with lower shear strength linked to loss of above- and below-ground plant structures that enhance sediment cohesion (Simon and Collison 2002; Yu et al. 2020). *Impatiens glandulifera* likely exacerbates this effect by suppressing growth of native vegetation and through its own limited rooting structures. Preliminary pilot study evidence using in-situ minirhizotron imagery indicates that root length density is lower in the invaded (mean 0.49 cm cm⁻³) compared to uninvaded (mean: 1.16 cm cm⁻³) sites (J. Hardwick, pers. obs.). Differences in root architecture and phenology may also explain the direct negative effect of previous summer *I. glandulifera* cover on riverbank stability. Unexpectedly, grain size had a positive effect on shear strength, contrasting with prior studies that link larger grains to reduced cohesion (Julian and Torres 2006; Douglas et al. 2024). This likely reflects high sediment heterogeneity across sites.

Limitations

Our results may underestimate INNPs impacts on riverbank stability. Although *I. glandulifera* dieback is typically linked to bare ground (Usher et al. 1986; Greenwood and Kuhn 2014; Greenwood et al. 2018), the direct pathway to bare ground cover was non-significant, probably due to stable, long-established *I. glandulifera* populations (>10–15 years). Instead, invasion indirectly increased bare ground via reduced native plant richness and cover. Similarly, soil moisture had no effect, likely because it was measured on single survey days rather than capturing antecedent dynamics (Heerdt et al. 2017). Finally, we did not quantify hydraulic reinforcement, which may be important given the evidence that other INNPs, such as *R. japonica*, can greatly increase soil water loss of up to up to 8.5 L day⁻¹ m⁻² which likely alters pore pressure of riverbanks (Pollen-Bankhead and Simon 2010; Ni et al. 2018; Galster and Vanderklein 2023).

Conclusions

Our study provides the first direct evidence that an annual herbaceous INNP, *I. glandulifera*, reduces riverbank stability in temperate rivers, exceeding expected seasonal declines. By suppressing native vegetation, promoting bare ground, and contributing little to below ground riverbank reinforcement, *I. glandulifera* amplified winter shear strength reductions by ~30%. Understanding how INNPs alter riverbank stability is critical for predicting geomorphological change and informing riparian management, including INNPs control and riverbank restoration. Future work should quantify invasion impacts along a gradient of INNPs cover to investigate hydrological reinforcement.

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Author contributions JH, ZP and CH conceived the ideas and designed the methodology; JH collected the data; JH, ZP, CH and AL analysed the data; JH led the writing of the manuscript. ZP secured funding; All authors contributed critically to the drafts and gave final approval for publication.

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Data availability The data and code that supports the findings of this study are openly available in the following Zenodo repository: <https://doi.org/10.5281/zenodo.15310800>.

Declarations

Competing interests Authors declare no competing interests.

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