

Response of *Impatiens parviflora* functional leaf traits to soil moisture fluctuations in Danube floodplain forests

Malvína Reiffers Čierniková¹, Ivana Vykouková², Andrej Hrabovský³,
Anton Zvala⁴, Jana Šramková⁵

¹ Comenius University, Faculty of Natural Sciences, Department of Soil Science, Bratislava, Slovakia,
e-mail: malvina.ciernikova@uniba.sk (corresponding author), ORCID ID: 0000-0001-7663-6812

² Comenius University, Faculty of Natural Sciences, Department of Soil Science, Bratislava, Slovakia,
ORCID ID: 0000-0002-0954-8713

³ Comenius University, Faculty of Natural Sciences, Department of Soil Science, Bratislava, Slovakia,
ORCID ID: 0000-0001-8960-9944

⁴ Slovak Academy of Sciences, Institute of Hydrology, Bratislava, Slovakia, ORCID ID: 0000-0003-2899-664X

⁵ Comenius University, Faculty of Natural Sciences, Department of Soil Science, Bratislava, Slovakia

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Abstract: The Danube floodplain forests near Bratislava (Slovakia) represent dynamic fluvial systems currently threatened by climate change-induced alterations in hydrological regimes and soil moisture availability. This study investigates the response of the invasive species *Impatiens parviflora* DC. to declining soil moisture, focusing on its role as a biological indicator of environmental shifts in Calcaric Pantofluvic Fluvisol (Ochric). We analyzed soil moisture dynamics and leaf functional traits – specific leaf area (SLA), leaf dry matter content (LDMC), and leaf water content (LWC) – across six sites during a transition from wet (June) to dry (July) periods. Student's *t*-tests confirmed statistically significant differences in soil moisture ($p < 0.01$) and leaf traits between the monitored months. Our results demonstrate a strong negative correlation between SLA and LDMC ($r \approx -0.95$), reflecting a functional shift from an acquisitive to a conservative resource strategy under water deficit. These findings highlight the high phenotypic plasticity of *I. parviflora*, which allows it to thrive in anthropogenically and climatically altered floodplain soils where native vegetation declines, further accelerating biodiversity loss in these protected fluvial habitats.

Keywords: soil moisture dynamics, leaf functional traits, phenotypic plasticity, environmental stress, Fluvisols

INTRODUCTION

Floodplain forests represent complex fluvial ecosystems characterized by a high degree of biological diversity and a tight coupling between hydrological regimes and vegetation dynamics. In Central Europe, these ecosystems are increasingly vulnerable to the synergistic effects of direct anthropogenic modifications such as river regulation and

hydro-engineering projects (Tockner et al. 2008, Havrdová et al. 2023) and the broader impacts of global climate change (Schneider et al. 2011). In the Danube River basin, specifically in the vicinity of Bratislava, these factors have led to a significant alteration of the water table, affecting baseline moisture availability. While global climate shifts and local river engineering dictate long-term hydrological trends, the upper soil horizons

(primarily Calcaric Pantofluvic Fluvisols) experience stark seasonal drawdowns within individual growing seasons. These intense seasonal shifts in moisture availability create a temporary physiological bottleneck for native hygrophilous species, while providing a window of opportunity for highly adaptable, plastic invasive taxa, which can fundamentally alter species composition and ecosystem functions (Baker 1974, Vilà et al. 2011, Bajwa et al. 2016, Kaushik et al. 2022).

The success of invasive species in such fluctuating environments is often a result of their superior phenotypic plasticity (Davidson et al. 2011). This plasticity allows plants to optimize their functional strategies along the “leaf economics spectrum,” which represents a fundamental trade-off between rapid resource acquisition and conservative resource conservation (Wright et al. 2004). Among the most sensitive indicators of this adaptation are leaf functional traits (Violle et al. 2007, Pérez-Harguindeguy et al. 2013, Reich 2014, Griffin-Nolan et al. 2018, Masarovičová et al. 2018). Specific leaf area (SLA), which relates the light-intercepting surface to its dry mass, and leaf dry matter content (LDMC), representing the density of leaf tissues, are crucial for understanding plant–water relations (Cornelissen et al. 2003, Vile et al. 2005, Milla & Reich 2007, Poorter et al. 2009, Wellstein et al. 2017, Kramp et al. 2022). Plants in resource-rich environments typically have a high SLA, promoting rapid growth, whereas a high LDMC is a hallmark of stress-tolerant species that invest in structural integrity to prevent water loss during periods of moisture deficit.

Impatiens parviflora DC. (small balsam), an annual herb native to the mountains of Central Asia, has become one of the most successful forest invaders across temperate Europe (Eliáš 1999, Pyšek & Prach 1995, Chmura & Urbisz 2005, DAISIE 2009, Quinet et al. 2015). In the Danube floodplain forests, it often forms extensive, monospecific stands that suppress the recruitment of native flora (Čuda et al. 2014). While its shade tolerance and high reproductive output are well-documented (Eliáš 1999, Elemans 2004, Godefroid & Koedam 2010, Pyšek et al. 2012, Jarčuška et al. 2016), its physiological resilience to the increasing frequency of summer droughts in floodplain

habitats remains insufficiently understood. As climate projections for the Pannonian region suggest a trend toward more frequent and severe heatwaves, understanding the functional response of *I. parviflora* to soil moisture fluctuations becomes essential for predicting future shifts in forest understory composition.

This study focuses on the adaptive mechanisms of *I. parviflora* across six distinct sites in the Danube floodplain area, characterized by varying micro-topography and soil moisture conditions. Our primary objective was to quantify the shifts in SLA, LDMC, and leaf water content (LWC) during the transition from the moist conditions of early summer (June) to the more arid conditions of mid-summer (July). We hypothesized that *I. parviflora* would exhibit a high degree of trait plasticity, shifting from an acquisitive strategy to a resource-conservative strategy as soil moisture declines. By linking soil physical parameters with plant biological response, this research contributes to a more integrated understanding of how invasive species exploit hydrological instability in protected fluvial ecosystems.

MATERIALS AND METHODS

Study area

The study was conducted in the Danube floodplain forests near Bratislava. The area belongs to a warm and temperate climate zone, characterized by a mean annual temperature of approximately 10.5°C and an annual precipitation of 550–600 mm (Bochníček & Hrušková 2015). Hydrologically, the locality is tightly linked to the dynamic discharge regime of the Danube River, which historically drives groundwater table fluctuations. However, contemporary hydrological conditions in these floodplain habitats are significantly altered and stabilized by the operations of the Gabčíkovo Waterworks, making the ecosystem highly sensitive to atmospheric summer droughts. These long-term alterations have triggered a gradual degradation of native softwood communities, driving a decline in hydrophilic taxa (Petrášová-Šibíková et al. 2017) and facilitating a severe shift toward neophyte invasion and altered successional pathways (Mikulová et al. 2020).

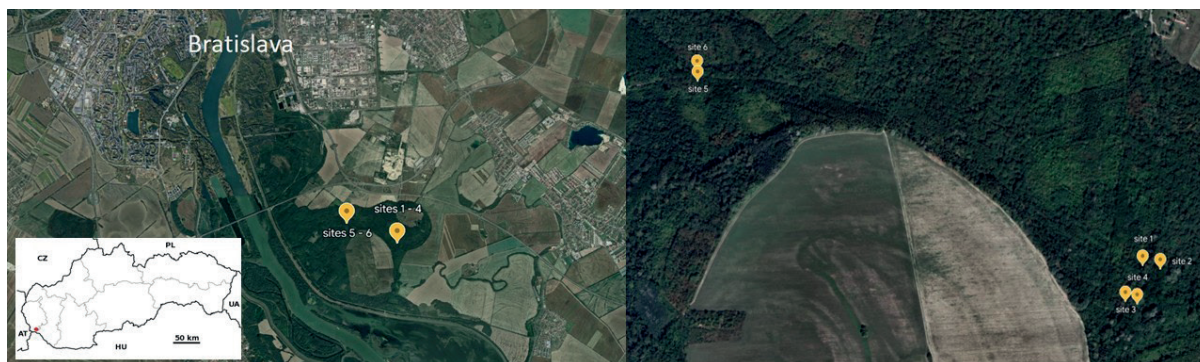


Fig. 1. Floodplain forests in the vicinity of Bratislava (Slovakia) with study sites marked

The study site is in the cadastral territory of the city of Bratislava (the capital city of Slovakia). We identified six sites (Fig. 1) in the invasive species *I. parviflora* was found. Three sites (1 – 48°04'35.3"N 17°12'03.4"E, 3 – 48°04'32.2"N 17°12'01.0"E, 5 – 48°04'51.2"N 17°11'2.5"E) are lower lying, where we assumed higher soil moisture, and the other three (2 – 48°04'35.0"N 17°12'05.8"E, 4 – 48°04'32.0"N 17°12'02.6"E, 6 – 48°04'52.1"N 17°11'02.5"E) are at higher elevations, with assumed lower soil moisture. All six sites are in floodplain forest, with the same vegetation composition. The species composition of all surveyed plots is documented by the phytocoenological relevé performed in June. We classified the forest communities according to the *Fraxino pannonicæ-Ulmetum* Soó in Aszód 1936 corr. Soó 1963, and species cover-abundance was evaluated using the Braun-Blanquet scale (r: rare; +: solitary with small cover; 1: <5% cover; 2: 5–25% cover; 3: 25–50% cover) (Braun-Blanquet 1964):

Union: *Alnion incanae* Pawłowski in Pawłowski et al. 1928

Subunion: *Ulmenion* Oberd. 1953

Association: *Fraxino pannonicæ-Ulmetum* Soó in Aszód 1936 corr. Soó 1963

The names of the syntaxones are given according to Jarolímek and Šibík (2008). The species composition was recorded in the following phytocoenological relevé:

E₃ (tree layer): 90%, E₂ (shrub layer): 25%, E₁ (herb layer): 70%, 20 m × 20 m.

E₃: *Fraxinus excelsior* (incl. *angustifolia*) 3, *Acer campestre* 1, *Populus alba* +, *Quercus robur*

agg. 1, *Robinia pseudoacacia* +, *Ailanthus altissima* +

E₂: *Acer campestre* 2, *Ulmus minor* +, *Crataegus monogyna* +, *Staphylea pinnata* +, *Ulmus laevis* r.

E₁: *Convallaria majalis* 2, *Impatiens parviflora* 2, *Parietaria officinalis* 2, *Polygonatum latifolium* 2, *Hedera helix* 2, *Viola mirabilis* 1, *Galium odoratum* 2, *Alliaria petiolata* +, *Staphylea pinnata* r, *Viburnum opulus* +, *Fraxinus excelsior* (incl. *angustifolia*) r, *Chelidonium majus* +, *Populus alba* +, *Viola reichenbachiana* 1, *Stachys sylvatica* +, *Allium ursinum* 1, *Acer campestre* +, *Polygonatum multiflorum* r, *Melica nutans* +, *Galium mollugo* +, *Lamium maculatum* +, *Crataegus monogyna* +, *Anthriscus sylvestris* r, *Geranium robertianum* +, *Ulmus laevis* r, *Geum urbanum* +, *Ailanthus altissima* +, *Heracleum sphondylium* r, *Robinia pseudoacacia* r, *Arctium lappa* r, *Quercus robur* r, *Ulmus minor* 1.

Floodplain forests were selected as the primary study environments due to their status as critically threatened ecosystems, where anthropogenic pressures and shifting hydrological regimes significantly alter native vegetation structures. These ecological transitions often facilitate the expansion of invasive species at the expense of indigenous flora. The invasive herb *I. parviflora* was chosen as a model organism not only for its high abundance within the Danube floodplain area but also for its specific leaf morphology. Its leaf structure is particularly sensitive to fluctuations in environmental conditions, making it an ideal subject

for quantifying phenotypic plasticity through leaf functional traits such as SLA and LDMC.

Fieldwork and collection of leaves

Fieldwork was conducted during two distinct periods of the 2024 growing season: the first half of June (optimal moisture conditions) and the second half of July (peak summer drought). At each of the six selected sites, representative individuals of *I. parviflora* were randomly selected from the understory. To ensure trait consistency, only healthy, fully expanded leaves without visible herbivory or pathogen damage were collected from the upper canopy of the plants (Cornelissen et al. 2003). Ten samples were taken from each location, representing a total of 120 samples. Immediately after collection, the leaves were placed in airtight plastic bags with moist filter paper and stored in a portable cooler at approximately 5°C to maintain turgor pressure and prevent water loss during transport to the laboratory (Pérez-Harguindeguy et al. 2013). The sample size of 10 fully developed individuals per site was chosen in strict accordance with the standardized international protocols for plant functional trait measurements (Pérez-Harguindeguy et al. 2013), which establish that $n = 10$ is fully representative and statistically robust for capturing intra-specific trait variation within localized populations of herbaceous species.

Functional traits measurements

In the laboratory, the fresh weight of each leaf was measured using a precision analytical balance (accuracy ± 0.001 g). The measurement of the functional traits of the plants was in accordance with the procedure described in Cornelissen et al. (2003). The leaf characteristics of the plants that have been determined include FM – fresh leaf weight [g], DM – dry leaf weight [g], LA – leaf area [cm²] (using WinDIAS 3.2.). Using these values, the functional traits were calculated as: specific leaf area: $SLA = LA/DM$ [cm²·g⁻¹], leaf dry matter content: $LDMC = DM/FM$ [g·g⁻¹], leaf water content: $LWC = 1 - LDMC$ [g·g⁻¹].

Soil measurements and soil moisture

To confirm the occurrence of the same soil type, a soil pit was dug at each site. The field survey and description of the morphological characteristics of the soil profiles were done according to

the *Guidelines for Soil Description* (Food and Agriculture Organization of the United Nations 2006). The soil units were classified according to the World Reference Base for Soil Resources (IUSS Working Group WRB 2022).

Soil moisture measurements were taken from topsoil to a depth of 6 cm using a three-pronged electromagnetic probe (ML2x, Delta-T, Burwell, Cambridge, UK) connected to a handheld readout unit (HH2; Delta-T, Burwell, Cambridge, UK). Soil moisture measurements were collected 10 times at each plot on the same day in June and on the same day in July, and then averaged to determine the representative soil moisture for each plot.

Statistical analysis

Statistical analyses were performed using RStudio (RStudio Team 2022). Prior to parametric testing, the underlying assumptions of normality and homogeneity of variances were formally verified for all datasets using the Shapiro–Wilk test and Levene’s test, respectively. Most of the targeted datasets conformed to a normal distribution ($p > 0.05$). Student’s *t*-test for independent samples was employed to evaluate the differences in leaf functional traits (SLA, LDMC, LWC) and soil moisture between the sampling periods (June and July), with Welch’s correction applied automatically in cases of unequal variances. In three specific cases where the assumption of normality was violated ($p < 0.05$; LDMC at Site 2, SLA at Site 3, and SLA at Site 6), a non-parametric Mann–Whitney *U* test was deployed instead. The relationship between soil moisture and functional traits was quantified using Pearson correlation coefficients (*r*).

RESULTS

Meteorological conditions during the study period

Weather data from the nearest official meteorological station (SHMÚ, Bratislava) for the summer of 2024 were analyzed to provide a climatological context for the observed shifts in plant functional traits. June 2024 was characterized by above-average precipitation totals (approx. 90–100 mm) and moderate temperatures, maintaining high baseline soil moisture. In stark contrast, July 2024 was classified as climatologically exceptionally hot and dry, featuring a prolonged

heatwave with daily maxima frequently exceeding 33°C and a critical deficit in atmospheric precipitation (less than 20 mm total for the month) (Faško et al. 2024, Kotříková et al. 2024). In fact, July 2024 recorded the highest monthly mean temperature at the Bratislava station since at least 1931 (Faško et al. 2024). This intense atmospheric forcing explains the sharp drop in soil moisture content and the subsequent adaptive shifts in leaf functional traits (SLA, LDMC) observed between the two sampling periods.

Soil type and soil moisture

We confirmed the occurrence of the Calcaric Pantofluvic Fluvisol (Ochric) soil type in each of the six investigated areas. Soil moisture was measured at each site at ten different locations in June and July. All measurements were averaged (Fig. 2). We assumed higher soil moisture at lower elevation

sites compared to higher elevation sites. However, we were unable to demonstrate this. It was generally true that higher soil moisture was recorded in June, but the distribution of the plots themselves did not affect the moisture conditions.

Statistical differences in traits and soil moisture

Statistical differences for SLA, LDMC, LWC, and soil moisture between June and July were calculated using Student's *t*-tests and non-parametric Mann–Whitney *U* tests, depending on the data normality (Tab. 1). The specific leaf area difference between June and July was statistically significant at the $\alpha = 0.05$ level. The leaf dry matter content and leaf water content were more significantly different ($\alpha = 0.001$). The difference in soil moisture content in June and July was statistically significant at the $\alpha = 0.01$ level.

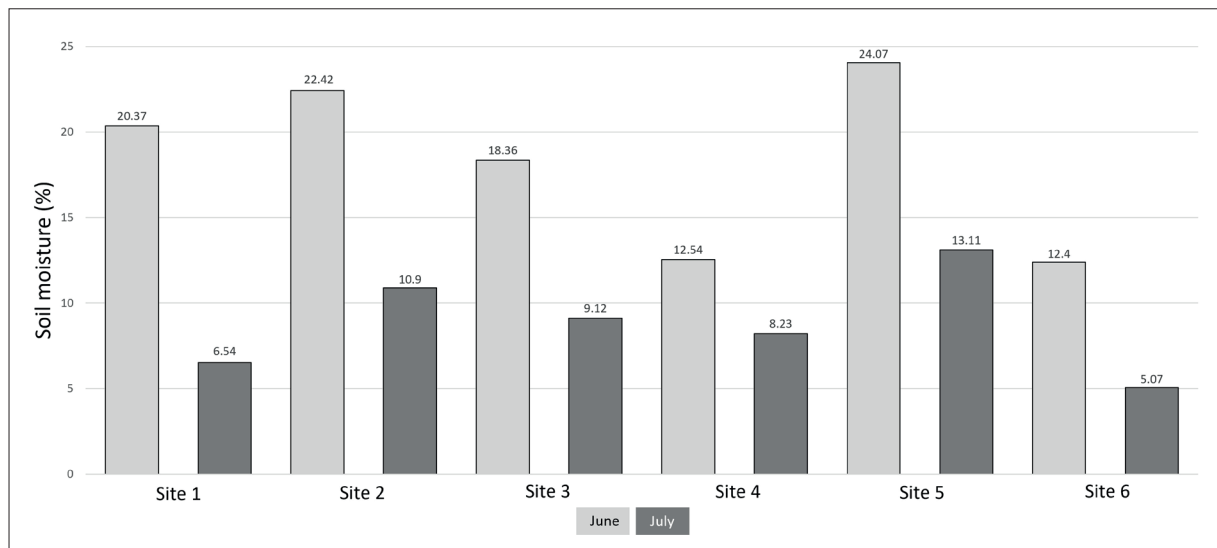


Fig. 2. Average soil moisture contents in June and July at six study sites (1, 3, 5 – located lower, 2, 4, 6 – located higher)

Table 1

Results of statistical differences in leaf functional traits and soil moisture between June and July

Statistical analysis	SLA	LDMC	LWC	Soil moisture
Test statistic	2.9279 ^{t*}	5.2653 ^{t*}	5.2653 ^t	4.0642 ^t
<i>p</i> -value	0.015090	0.000365	0.000365	0.002271
α	<0.05	<0.001	<0.001	<0.01

^t – Student's *t*-test statistic (*t* value); * – Mann–Whitney *U* test was applied for sites with a non-normal data distribution (site 2 for LDMC, sites 3 and 6 for SLA).

Specific leaf area (SLA) and leaf dry matter content (LDMC)

The specific leaf areas measured in June were higher compared to the values in July (Fig. 3), confirming the plants' adaptation to drought, which manifests itself in resource conservation, which is reflected in smaller leaves. At sites 1 to 5, SLA values were above $1,100 \text{ cm}^2 \cdot \text{g}^{-1}$ in June and below $1,100 \text{ cm}^2 \cdot \text{g}^{-1}$ in July. Site 6 differs in both SLA measurements. This area had the lowest SLA value in June ($1,055 \text{ cm}^2 \cdot \text{g}^{-1}$) and the highest SLA value in July ($1,265 \text{ cm}^2 \cdot \text{g}^{-1}$). This contrast with the other sites can be hypothetically attributed to a higher degree of localized shading at site 6. However, as microclimatic radiation data (such as photosynthetically active radiation) were not measured, this explanation remains a hypothesis.

The largest range of SLA values was observed in June (Fig. 3). In general, June was wetter than July, so the plants had suitable ecological conditions

for their growth and invested more in leaf area. In contrast, we can see that the spread of all values was considerably smaller in July. The plants had to cope with the decrease in soil moisture in some way. Their response was a strategy where they invested more energy in dry matter rather than in leaf area to survive.

Adaptation to stress is also evident in the results of the leaf dry matter content, which, in contrast, was lower in June than in July (Fig. 4). The greater variance of LDMC values in June indicates generally good conditions for plant growth. Sufficient water and nutrients were reflected in the size of the leaves and generally good plant condition. The leaves were larger and stiffer. The LDMC values in July were almost twice as large as those in June (Fig. 4). Plants do not need a large leaf area under these conditions, but it is more important that the leaves are thicker and stronger. Such leaves, with a high dry matter content, are able to retain water better and subsequently manage it better during drought conditions.

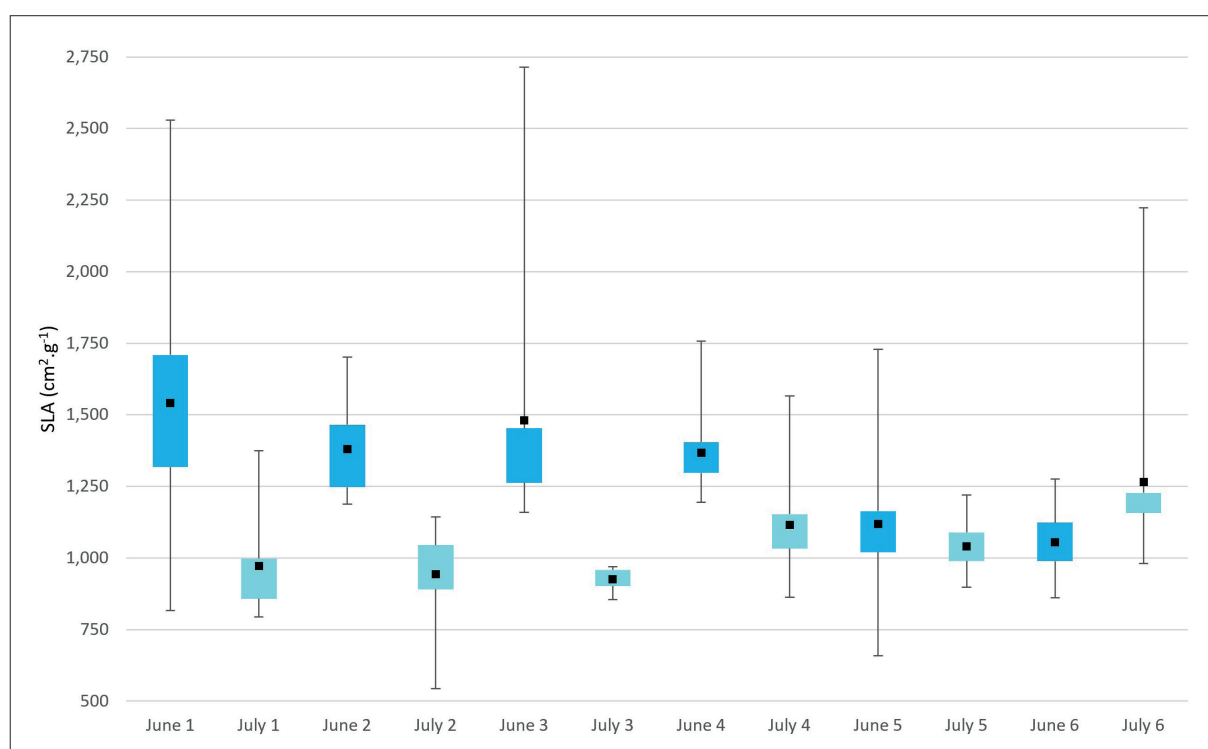


Fig. 3. Specific leaf area in June and July at all six sites

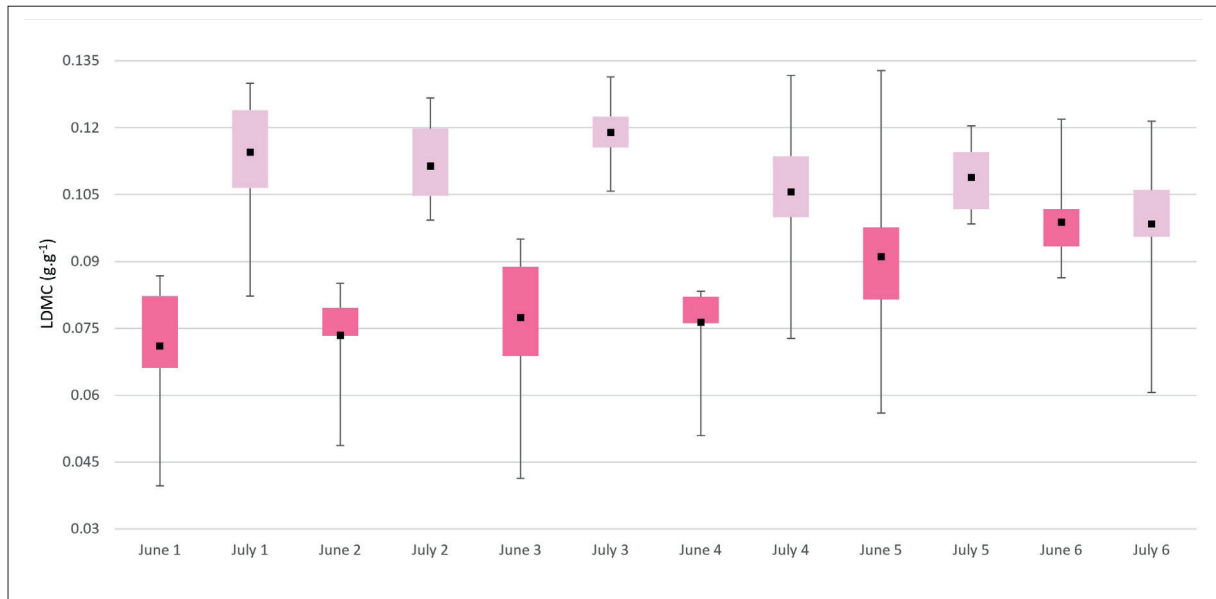


Fig. 4. Leaf dry matter content in June and July at all six sites

Leaf water content (LWC)

The leaf water contents were higher in June (Fig. 5), confirming better soil moisture conditions. Although the LWC values were lower in July, the species was able to adapt, and these values did not drop enough to cause significant stress to the plants, as the forest sampling locations were

relatively shaded. All areas except for site 6 met our assumptions again. As in the case of the SLA values, site 6 showed the lowest value of water content in the leaves in June ($0.9011 \text{ g} \cdot \text{g}^{-1}$) and, conversely, the highest in July ($0.9015 \text{ g} \cdot \text{g}^{-1}$). We hypothesize that this trend is linked to localized shading, although direct microclimatic radiation data to verify this are lacking.

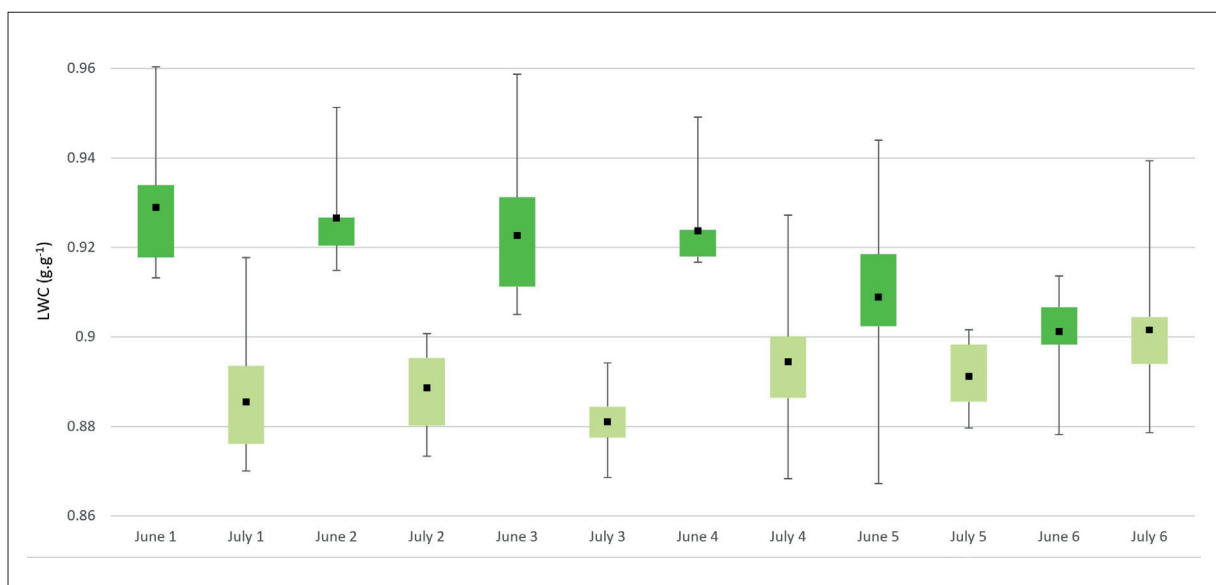


Fig. 5. Leaf water content in June and July at all six sites

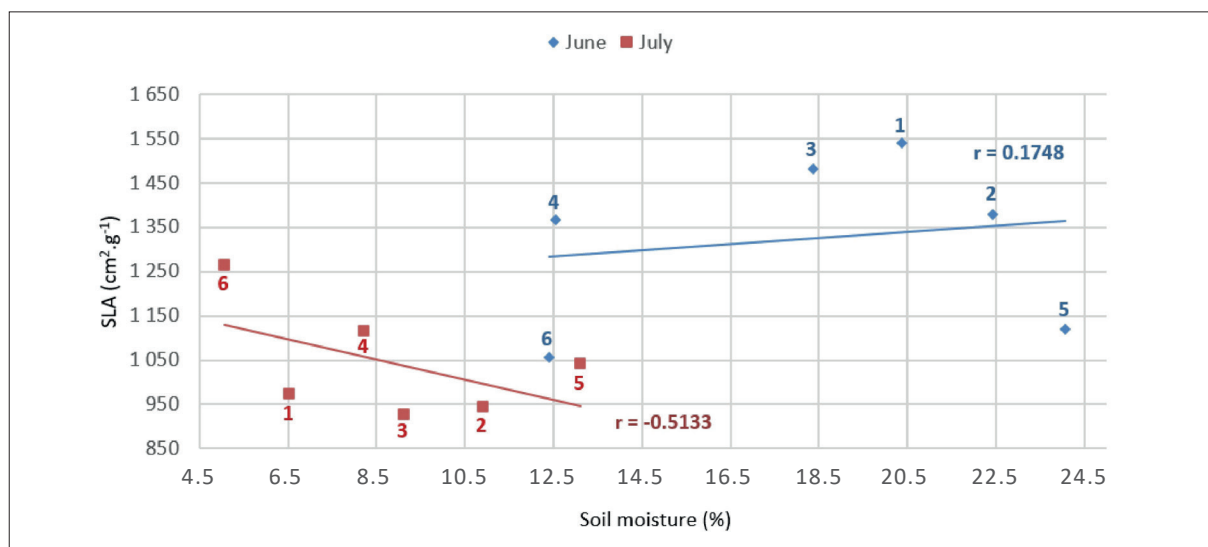


Fig. 6. Correlation between average specific leaf area and soil moisture in June and July

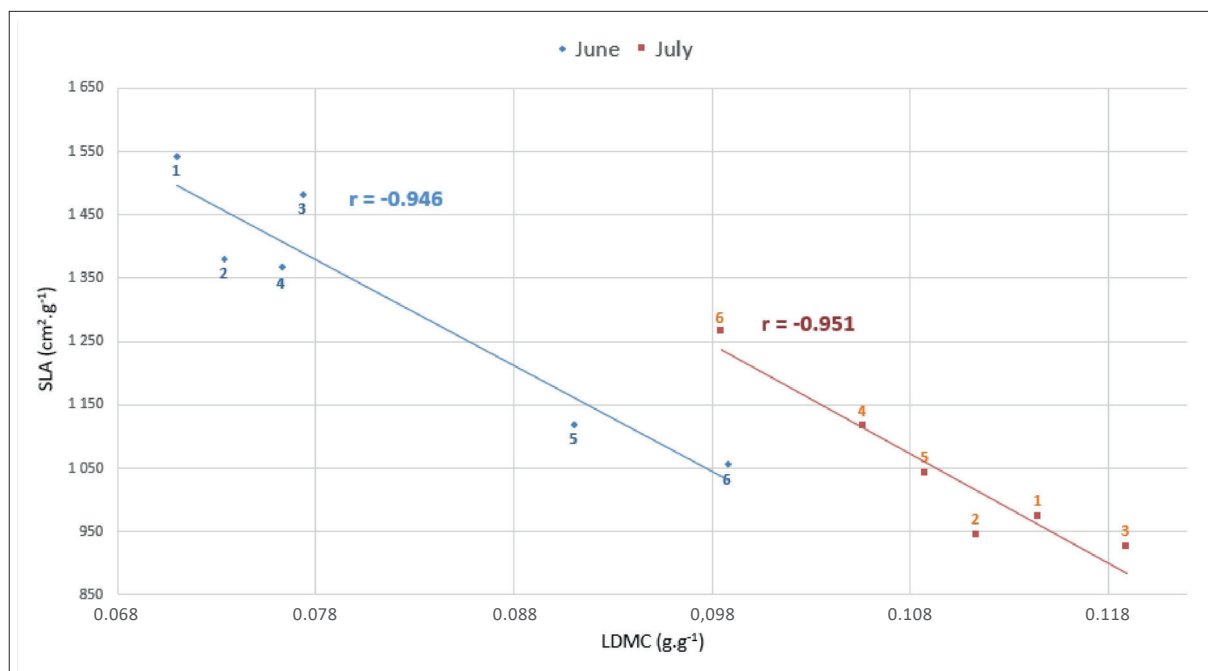


Fig. 7. Correlation between average values of specific leaf area and leaf dry matter content in June and July

Relationship between SLA and soil moisture

The correlation between the SLA and soil moisture was low in June, with a value of 0.1748, which we consider a weak dependence (Fig. 6). This result represents the site condition in June when the moisture was higher, and this parameter has little effect on the leaf area. In July, a moderate negative

correlation ($r = -0.5133$) was observed (Fig. 6), indicating a moderate indirect dependence between SLA and soil moisture.

Relationship between SLA and LDMC

The correlation (Fig. 7) between SLA and LDMC in June and July shows a very strong indirect dependence. The correlation coefficients for the June

and July values were -0.946 and -0.951 , respectively. Both speak about the relationship between these functional traits, where increasing leaf dry matter content is proportional to decreasing values of specific leaf area. Higher SLA values in June were associated with higher soil moisture values, and conversely, July was associated with higher LDMC values when it was dry, and the plant needed more energy for leaf construction and not for leaf area.

DISCUSSION

Soil moisture dynamics and the environmental filter of floodplain forests

The significant reduction in volumetric soil moisture recorded between June and July reflects a pronounced seasonal transition that acts as a temporary environmental filter for forest understory vegetation. Our findings indicate that the topsoil layer (0–6 cm) in the Danube floodplain forests is highly susceptible to rapid desiccation during the summer months. While this immediate drop represents standard intra-annual moisture dynamics, the baseline vulnerability of these soils is historically exacerbated by the synergy of climate change and local hydrological modifications. As noted by Tockner et al. (2008), floodplain ecosystems are among the most threatened globally due to their dependence on fluctuating water regimes. In the Bratislava region, the impact of the Gabčíkovo hydropower structures (Mikulová et al. 2020, Gáspár & Škrinár 2023), combined with a trend of rising average temperatures, has led to a systematic decline in the water table, directly affecting the moisture content of Calcaric Pantofluvic Fluvisols (Frymark-Szymkowiak & Karliński 2020).

This moisture deficit, which we recorded as a drop from optimal levels in June to stress levels in July, creates a physiological bottleneck. Such environmental stressors in the Danube floodplains are the primary drivers of shifts in species dominance (Mikulová et al. 2020, Havrdová et al. 2023). Our data confirm that soil water availability is the distal driver of the phenotypic expressions in *I. parviflora*, where the plants must rapidly transition from a growth-oriented to a survival-oriented state.

Functional trait plasticity: the “acquisitive vs. conservative” trade-off

The core of our results lies in the remarkable plasticity of leaf functional traits. The high specific leaf area measured in June corresponds with the “acquisitive” end of the leaf economics spectrum (Wright et al. 2004). During this period of high soil moisture, *I. parviflora* maximizes its light-capturing surface area per unit of biomass to accelerate photosynthetic gain and rapid expansion. This strategy is typical for invasive annuals that exploit resource-rich “windows of opportunity” (Clements & Ditommaso 2011).

However, the significant shift observed in July, characterized by a decrease in SLA and a substantial increase in leaf dry matter content (LDMC), indicates a transition to a “resource-conservative strategy.” This increase in LDMC reflects a higher investment in structural tissues and secondary metabolites, which increase leaf density and reduce water loss through cuticular transpiration (Garnier et al. 2001, Vile et al. 2005). This trade-off is further supported by the strong negative correlation ($r = -0.95$) between SLA and LDMC found in our study. Such a robust correlation is consistent with the global patterns identified by Diaz et al. (2016) and Pérez-Harguindeguy et al. (2013), who argue that LDMC is a more stable indicator of long-term nutrient and water retention than SLA.

Competitive advantage and invasive success in fluctuating habitats

The success of *I. parviflora* in Slovakia, where it is now a permanently naturalized and dominant invasive species (Eliáš 2023), can be largely attributed to this observed plasticity. Our study supports the hypothesis by Davidson et al. (2011), who posit that invasive species often exhibit higher phenotypic plasticity than native species, allowing them to maintain higher fitness across environmental gradients. In the context of floodplain forests, where native hygrophilous herbs are often physiologically constrained by drought, the observed phenotypic adjustments in *I. parviflora* (such as the sharp increase in LDMC) likely facilitate its survival during periods of seasonal moisture deficit. However, it is important to note that

our study did not quantify the functional traits of co-occurring native species during the dry period. Consequently, attributing a direct trait-based competitive advantage to *I. parviflora* remains hypothetical, as we cannot rule out similar levels of plastic responsiveness in the surrounding native flora.

Furthermore, Hejda (2012) highlights that the impact of *I. parviflora* on native biodiversity is closely linked to its ability to form dense monospecific stands. This invasive success cannot be decoupled from other critical life history dimensions that were not measured in this study, such as its high shade tolerance, high fecundity, and aggressive ballistic seed dispersal, which collectively enhance its establishment capacity even under environmental stress (Eliáš 1999, Pyšek et al. 2012). Therefore, while the plastic shift along the leaf economics spectrum supports the species' physiological resilience, it acts in tandem with these reproductive and microclimatic adaptations rather than as a standalone driver of native species displacement. It is important to note, however, that while localized microclimatic factors such as canopy shading likely influenced the deviant trait patterns observed at site 6, our interpretation remains hypothetical since direct photosynthetically active radiation was not quantified. This multi-trait synergy is consistent with broader frameworks evaluating the role of phenotypic plasticity in successful plant invasions (Richards et al. 2006).

Leaf water content and physiological resilience

The decrease in LWC recorded in July, although statistically significant, did not result in visible wilting or population collapse at the monitored sites. This observation suggests that *I. parviflora* possesses robust physiological mechanisms to cope with transient water deficits. According to Coombe (1956), this species exhibits a high degree of shade tolerance and a flexible water-use strategy, which allows it to survive in the fluctuating light and moisture conditions of forest understories.

Its ability to maintain structural integrity despite a lower LWC is a direct result of the increased LDMC, which provides the necessary mechanical support to prevent cellular collapse under low

turgor pressure (Pérez-Harguindeguy et al. 2013). As highlighted by Florianová and Münzbergová (2018), the widespread successful naturalization of *I. parviflora* in Central Europe is attributed to its ability to complete its life cycle even under sub-optimal environmental conditions. Our results confirm that the toughening of leaves (increased density) is a key resilience trait that ensures the plant survives long enough to produce seeds, even when the topsoil moisture in the Danube floodplains drops to critical levels.

Geological and environmental implications for the Danube region

From an environmental engineering and geological perspective, the transition between strategies utilized by *I. parviflora* is an indicator of terrestrialization processes in floodplain habitats. As soil moisture dynamics shift toward more arid regimes, the invasive-dominated understory may alter litter decomposition rates and soil organic matter cycling. Jarčuška et al. (2016) noted that the environmental requirements of *I. parviflora* are relatively broad, but its peak performance in drying floodplains suggests that it acts as a “sentinel species” for climate-induced degradation of fluvial systems.

In the Bratislava reach of the Danube, where hydrological connectivity has been altered, the functional response of this invader serves as a proxy for evaluating the health of the Fluvisol–water–vegetation continuum. Our data imply that without active hydrological restoration, the continued desiccation of these soils will further consolidate the dominance of highly plastic invaders, leading to a permanent shift in the ecological and functional character of these protected forests.

CONCLUSION

The results of this study confirm that phenotypic plasticity in leaf functional traits is a decisive factor in the invasive success of *I. parviflora* within the Danube floodplain forests. The seasonal transition from optimal moisture in June to a significant deficit in July induced a fundamental strategic shift from rapid resource acquisition to conservation and tissue protection.

Based on our research, the following conclusions can be drawn:

1. **Adaptive mechanism.** The significant increase in LDMC and simultaneous decrease in SLA during July demonstrate the species' ability to structurally reinforce its leaves, preventing permanent damage from drought. This high phenotypic plasticity potentially underpins its resilience during periods of seasonal water stress.
2. **Indicator value.** The strong correlation between volumetric soil moisture and leaf traits confirms that *I. parviflora* is a reliable biological sensor for detecting hydrological stress within Fluvisol ecosystems.
3. **Management implications.** The ability of this species to adapt to sharp seasonal moisture drops suggests that under scenarios of long-term climate degradation and potential terrestrialization, protecting the biodiversity of these areas requires addressing the underlying causes of drying (hydrology) rather than focusing solely on the mechanical removal of invasive populations.

Future research should investigate how these functional shifts impact decomposition processes and nutrient cycling, as changes in leaf litter quality (due to increased LDMC) may have long-term consequences for soil biochemistry in protected floodplain areas.

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