Freshwater Biology

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ORIGINAL ARTICLE OPEN ACCESS

Garden Ponds: Hidden Sources for Plant Invasions?

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Received: 29 April 2025 | **Revised:** 3 October 2025 | **Accepted:** 10 November 2025

Keywords: citizen science | invasive species | macrophyte | species distribution | urban ecology

ABSTRACT

1. Private garden ponds are increasingly popular among homeowners and can, to some extent, compensate for the loss of natural habitats, but they may be sources of invasive species as pond owners often introduce alien ornamental species.
2. We assessed the popularity, distribution and sources of six invasive macrophyte taxa (*Elodea* spp., *Eichhornia crassipes*, *Ludwigia* spp., *Myriophyllum aquaticum*, *Pistia stratiotes* and *Vallisneria* spp.) in garden ponds across Hungary using a citizen science approach.
3. Using Species Distribution Modelling (SDM), we predicted the potential spread of these taxa into natural waters, comparing the results to confirmed occurrences in the wild.
4. Based on 560 responses, we found that even banned invasive macrophytes remain highly popular and widespread. Pond owners purchase them from various sources, including garden centres, web stores and online communities, with the latter being especially difficult to monitor and regulate.
5. In the European Union, regulations already prohibit the import, possession, and trade of listed invasive species, and customs authorities are responsible for checks at the point of entry. Nevertheless, our findings indicate that invasive species remain widely available, highlighting the complementary need for extensive educational campaigns and outreach activities.

1 | Introduction

Freshwaters are among the most endangered ecosystems on the global scale, threatened by land-use changes, hydrological alterations, pollution, climate change and invasive species (Sayer et al. 2025; Tickner et al. 2020). Ponds are the most numerous aquatic habitats (Downing et al. 2006) and are unique due to their high biodiversity (Biggs et al. 2005; Oertli et al. 2005). Importantly though, these small habitats function best under sufficient connectivity within habitat networks that allow the dispersal of organisms (Barta et al. 2024; Szabó et al. 2024). Connectivity, however, may also have negative consequences by aiding the spread of invasive species (Aronson et al. 2017). This effect can be even more significant in urban environments that are hotspots for invasive species (Polce et al. 2023). While urban ponds are vital in supporting native biodiversity by counterbalancing the loss of natural habitats and providing ecosystem services for people (Oertli et al. 2023; Cuenca-Cambronero et al. 2023; Krivtsov et al. 2022), their potential adverse impacts (disservices) need to be considered, as well (Horváth et al. 2025; Hassall 2014).

Globally, the aquarium and ornamental trade is responsible for a large share of invasive species introductions (Rahel 2007; Padilla and Williams 2004). In urban ponds, alien macrophytes tend to

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thrive due to frequent introduction resulting in high propagule pressure, coupled with favourable environmental conditions (Hassall 2014). In Europe, a comprehensive assessment of invasive macrophytes is currently missing (IPBES 2023); however, the majority of invasive plants were introduced accidentally or as ornamental plants, predominantly from tropical areas Lukács et al. (2016). Although many of these species are banned under European Union regulation (Council Regulation (EU) 2019), they may still be commercially available (Brunel 2009). For example, water hyacinth (*Eichhornia crassipes*) is one of the world's most prevalent invasive species (IPBES 2023). It originates from South America and invaded wetlands in North America, Africa, South-East Asia and Oceania, where, due to its extensive growth and ability to form dense mats covering entire water bodies, it is causing serious environmental and economic damage (IPBES 2023; Ayanda et al. 2020; Villamagna and Murphy 2010). Its trade is currently banned in the European Union (Council Regulation (EU) 2019); yet, it is readily available for purchase in online stores in Hungary, indicating gaps in enforcement.

In addition to propagule pressure, urban aquatic habitats may provide favourable biotic and abiotic conditions for invasive species. Their establishment and spread can be facilitated by empty niches and the frequent disturbances in urban environments (Davis et al. 2000). Pollution (e.g., salt, nutrient, heavy metal) from run-off has detrimental effects on a range of aquatic organisms (Hassall 2014) but invasive species can be more tolerant and possess dispersal and reproductive traits that further aid their invasion (Sinclair, Adams, et al. 2020). Additionally, invasive species often lack natural enemies and diseases, enabling them to thrive in new environments (Mitchell and Power 2003; Keane and Crawley 2002). The generally higher temperature of cities can also provide suitable conditions for tropical species, which would otherwise be limited by temperate winter conditions (Brans et al. 2018; Oertli and Parris 2019).

Garden ponds are a special type of urban pond as they are mostly located in private gardens, which, in practice, limits access for researchers and monitoring programmes without the cooperation of the pond owners. Hence, citizen science provides an additional tool to study these cryptic habitats (Hamer et al. 2024; Peeters et al. 2023). While garden ponds can be very abundant in some regions and there is an increasing scientific interest in them (Hill et al. 2021; Márton et al. 2025; Peeters et al. 2023), our knowledge of their potential positive and negative roles for biodiversity is still limited compared to other types of urban ponds (Horváth et al. 2025). For example, their role as habitats and potential sources for invasive species is still unexplored. Even though the imported plants may primarily be intended for aquaria (Brunel 2009), they are often placed in lakes and ponds without considering the ecological consequences (Löki et al. 2021; Prins et al. 2024). This is likely more common on private properties, as there may be no restrictions preventing owners from placing these plants in their ponds. Furthermore, even environmentally conscious pond owners may struggle to identify these species and distinguish them from native species that are morphologically very similar. Finally, artificial heating systems may be employed in small garden ponds to ensure the survival of ornamental fish during winter in cold climate regions. This can further increase the chances of tropical and subtropical plants surviving winter and later acting as potential sources of invasions.

Consequently, the rapid proliferation of garden ponds poses a significant potential for the introduction and spread of invasive plants. These ponds may not only serve as reservoirs for non-native species (Oertli et al. 2018) but also facilitate their dispersal into natural ecosystems (Sinclair, Reisinger, et al. 2020; Hassall 2014), particularly under changing climatic conditions that may enhance their survival and establishment (Piria et al. 2022; Liu et al. 2017; Strayer 2010). Once established, the consequences can have a devastating impact on aquatic ecosystems (Vilà et al. 2024; Hussner 2012; Vilà et al. 2011) and local economies (Haubrock et al. 2021; IPBES 2023). Nevertheless, there is a substantial knowledge gap regarding the extent to which garden ponds contribute to this issue.

Hence, our study aimed to (1) conduct a country-level citizen science survey in Hungary to assess the occurrence of invasive aquatic plants in garden ponds, focusing on six easily identifiable taxa via questionnaires; (2) identify the key environmental and management-related factors influencing the presence of invasive aquatic plants; (3) assess the potential risk of their establishment in natural waters across Hungary based on species distribution models (SDMs) using current climatic conditions; (4) compare the predicted habitat suitability of these species with their recorded occurrences in natural habitats to identify discrepancies and potential introduction hotspots.

2 | Materials and Methods

2.1 | Selection of Taxa

Eleven species belonging to eight genera were selected a priori for the study based on their invasive potential, ease of identification and availability on the market in Hungary as assessed by the authors. All species are on the EASIN list of Invasive Alien Species of Union Concern (Council Regulation (EU) 2019; European Union 2022). Following our interaction with pond owners, two species (*Cabomba caroliniana* A. Grey, *Salvinia molesta* D.S. Mitch) were excluded as we deemed these species difficult for laypeople to differentiate from natives with similar growth forms. Thus, we focused on nine species for our risk assessment: *Eichhornia crassipes* (Mart.) Solms, *Elodea canadensis* Michx, *Elodea nuttallii* (Planch.) H. St. John, *Ludwigia grandiflora* (Michx.) Greuter and Burdet, *Ludwigia peploides* (Kunth) Raven, *Myriophyllum aquaticum* (Vell.) Verdc., *Pistia stratiotes* L., *Vallisneria spiralis L.* and *Vallisneria australis* S.W.L. Jacobs and Les.

The rest of the analyses were carried out on datasets where some of the species-level information was aggregated into genus level because we expected the pond owners to be able to recognise the genus but not the species of some macrophytes. Thus, the final list of taxa included *Eichhornia crassipes, Ludwigia* spp., *Elodea* spp., *Myriophyllum aquaticum, Pistia stratiotes and Vallisneria* spp.

2.2 | Risk Assessment

We reviewed the available literature and compiled the relevant information for the risk assessment in Table 1 using information

TABLE 1 | Characteristics of the nine species belonging to the six investigated taxa. The environmental requirements are based on species occurrences in Hungary.

	Common name	Native range	T range (°C)	Other conditions	Main introduction pathway in Hungary	Reproduction and dispersal pathway in Hungary	First recorded in Hungary	Invasion risk[a]	Impact
Eichhornia crassipes[b]	Water hyacinth	South America	10–**25–30**–40 Fruiting: **22.5–35** Germination **5–40**	Eutrophic, high nutrient level 4.5–**6–8**–10 pH Low salinity Calcium > 5 mg/L	Ornamental trade	Vegetative, Hydrochory	1950	High	Mosquito breeding, clogged waterways, low water quality, biodiversity loss
Elodea canadensis	Waterweed, pondweed	North America	1–**10–25**–28	High water quality pH 6–**7–8.5**–10 Salt tolerance Slow water m	Ornamental trade	Vegetative, Hydrochory	1885	Low	Clogged waterways, biodiversity loss
Elodea nuttallii[b]				Slow water movement Oligo- to eutrophic conditions pH: 7–9			1991	Moderate	
Ludwigia grandiflora[b]	Water primrose	South and Central America, Parts of the USA	< 0–**0–10** <	Slow water movement	Ornamental trade	Vegetative, Hydrochory	2004	High	Allelopathy, clogged waterways, low water quality, biodiversity loss
Ludwigia peploides[b]							2010	High	
Myriophyllum aquaticum[b]	Parrots feather, Brazilian water-milfoil	South America	2–**5–20**–30	Eutrophic, high nutrient level Salt tolerance pH: 6.8–**7–8**-9	Ornamental trade	Vegetative, Hydrochory	1968	High	Allelopathy, clogged waterways, low water quality, biodiversity loss
Pistia stratoites[b]	Water lettuce	South and Central America, Africa, South-East Asia	15–**22–30**–35 Seed survival –5 < Germination 20 <	Stagnant water pH: 6.5–7.2	Ornamental trade	Vegetative, Hydrochory	1966	High	Allelopathy, mosquito breeding, clogged waterways, low water quality, biodiversity loss

(Continues)

TABLE 1 | (Continued)

	Common name	Native range	T range (°C)	Other conditions	Main introduction pathway in Hungary	Reproduction and dispersal pathway in Hungary	First recorded in Hungary	Invasion risk[a]	Impact
Vallisneria australis	Eelweed, eelgrass	South Europe, North Africa, Middle East, South-West Asia	22–36	Meso-eutrophic	Ornamental trade	Vegetative, Hydrochory	1900	High	Clogged waterways, biodiversity loss, substrate binding
Vallisneria spiralis			**15–30**				1808	High	

Note: Optimal values are in bold.
[a]Based on risk assessment (Oertli et al. 2018; Table S6).
[b]Invasive alien species of union concern.
Source: CABI Compendium (CABI 2024), GISD database (Invasive Species Specialist Group ISSG 2015), the European Union's list of invasive species (European Union 2022 and Lukács et al. 2016).

from various sources (Table S6) of the nine species using the CABI Compendium (CABI 2024), the GISD database (Invasive Species Specialist Group ISSG 2015), the European Union's list of invasive species (European Union 2022) and Lukács et al. (2016). To evaluate the threat these species pose, we used the trait-based risk assessment method developed by Keller and Drake (2009) and adapted to the European context as the Geneva–Aquatic Weed Risk Assessment by Oertli et al. (2018). We assigned the biological and ecological trait, damage and management scores to each species. Then we expressed the overall score for each category ('trait', 'damage', 'management') as the percentage of the total potential score (Table S5). To obtain the level of risk (low, moderate, high), we plotted these percentage scores following Oertli et al. (2018) in Figure 1.

2.3 | Citizen Science Datasets

Data were collected in three consecutive steps: an online, a paper-based and a follow-up online questionnaire. First, participants filled out an online questionnaire containing 31 questions about their garden pond between 09 July 2021 and 07 September 2022. (for details on the questionnaire, see Hamer et al. 2024; Márton et al. 2025). This provided data on the general features (surface area, depth, age), introduced animals, management practices, the location of the garden ponds and the presence of wild animals visiting them, including wading birds and waterfowl.

Secondly, a subset of participants who had completed the initial questionnaire (number of ponds = 391) volunteered for a sampling campaign where the material received by mail included a 1-page, paper-based questionnaire about invasive plants (Figure S2). In the instructions, the plants were called 'exotic', given the negative connotation of 'invasive', which might discourage participants

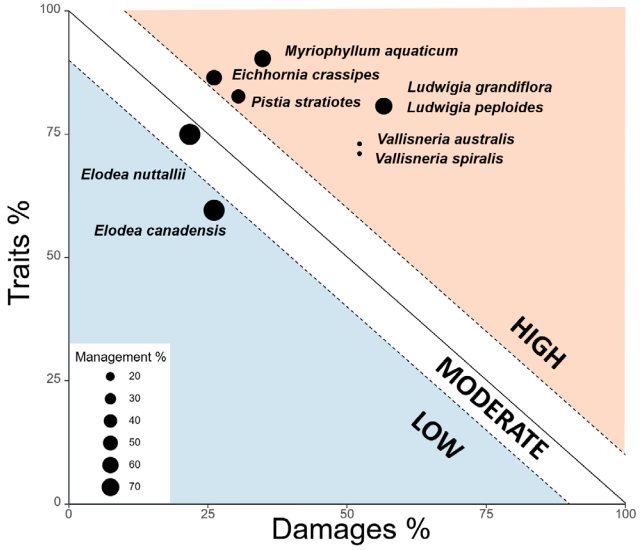


FIGURE 1 | Risk assessment of the nine species based on their ecological and biological traits, damage potential and management difficulty (increasing circle size indicates increasing difficulty of controlling the species). The figure is based on data listed in Table S5 of the Supporting Information following the risk assessment procedure suggested by Oertli et al. (2018).

from answering honestly. They could select which plants they had in their pond based on two images (Table S8) and the common name used in Hungarian. Upon reviewing the returned forms, we noticed that in some cases, all boxes were marked with an 'X'. We interpreted this as a possible mistake, assuming that the pond owners intended to indicate they had none of the listed plants, and treated these forms accordingly. We received 265 valid questionnaires via mail. In addition, the project team sampled 40 garden ponds and filled out the forms together with the pond owners. The resulting dataset contained 305 garden ponds for which information was available on the six invasive taxa and pond characteristics.

Finally, an updated version of the paper-based questionnaire was circulated on social media between August and September 2024 (Figure S3). In this version, participants had the option to select 'I don't know' in case they could not recognise a plant; these responses were treated as missing data (NA). Additionally, we asked participants where the pond is located (municipality level) and where they usually purchased their plants from. The list included garden centres and nurseries, online vendors, online forums such as Facebook groups, acquaintances, garden pond building companies, natural appearance of plants, collection from natural waterbodies and 'I don't know/Prefer not to say'. Solely Facebook was used as it is the most popular social media platform in Hungary (Kemp 2024), and it was used successfully in other ecology-oriented citizen science studies (Neményi et al. 2024; Vitál et al. 2024). To find potentially relevant Facebook groups, we performed a search using the keyword 'kerti tó' ('garden pond') and screened for active groups with at least 1000 members, resulting in a total of 16 groups. The questionnaire was posted by the MyPond project page in 11 of the groups, as only these allowed a 'Page' to share a post and in one group focusing on gardening in general (Table S1). In addition, the post was advertised using a paid Facebook service for 2 weeks to increase its reach. This online questionnaire resulted in 268 responses, of which 255 were new ponds (i.e., not included in the paper-based version). This was confirmed by answering the question on previous involvement in the MyPond project. In one case, the location of the pond could not be determined based on the provided information, thus, this one occurrence was excluded from the map figure but included in other analyses. Combined with the previous datasets, the final dataset contained data on 560 ponds.

The handling and analyses of questionnaire data were in accordance with the GDPR regulations of the HUN-REN Centre for Ecological Research, where the study was conducted following a Legitimate Interest Assessment. Participation in the project was voluntary and conditional upon acceptance of the GDPR guidelines, thus participants gave informed consent.

2.4 | Analyses of the Citizen Science Data

We analysed the data separately for the paper-based questionnaire ($n = 305$) to examine potential drivers and the dispersal role of waterbirds, the online questionnaire ($n = 268$) to link the presence of invasive plants to vendors and the merged dataset ($n = 560$) to assess distribution patterns. In addition, we analysed the six taxa individually and together (i.e., presence of any invasive plant). When the six taxa were analysed together, if one or more were present in a pond, it counted as 'presence', while if all six taxa were absent, it was counted as 'absence'. If a pond had missing data for any species, but at the same time, at least one of the six taxa was present, it counted as 'presence'. If data were missing for one or more taxa from a pond while all other taxa were reported as absent, the pond was treated as missing data, as we could not confirm the absence of all taxa.

We used the merged dataset ($n = 560$) to create a map displaying the number of ponds with invasive plants in Hungary. The administrative boundary layer was extracted from OpenStreetMap (OpenStreetMap contributors 2024) using the QuickOSM (Trimaille 2023) plugin, and it was manually corrected where it was necessary.

We used the online questionnaire data to identify the most common vendors and acquisition routes. We counted the number of invasive plants per pond (0–6) and compared these values across the different vendors using the Kruskal–Wallis test, as the data were not normally distributed (based on a Shapiro–Wilk test). Here, if a pond owner selected multiple vendors, the number of invasive plants in their pond was assigned to each vendor.

To reveal which pond features are associated with the presence of invasive plants, we compared ponds with and without invasive plants using the chi-square and Fisher's test, depending on the number of observations per group. The direction of the association was assessed based on the correlation plots using the Pearson residuals in the corrplot function from the corrplot package (Wei and Simko 2024). The pond features analysed included the presence of animals introduced by the owner (fish, turtle, crayfish, snail, mussel), pond age (young: < 10 years, old: ≥ 10), animals observed by the owner (odonates, adult amphibians, tadpoles), the reason for creating the pond and new function observed by the owner after its construction (aesthetic, nature conservation, education) and pond management practices (use of insecticide and fertiliser in the garden, use of algaecide in the pond, circulation, draining, cleaning the pond bottom, removing leaves in autumn, pruning vegetation). Algaecide treatment included both direct responses (i.e., selecting 'Algaecide' from the list of management practices in the questionnaire) and indirect responses (i.e., free text answers indicating treatments aimed at reducing algal growth, e.g., UV light, lime, addition of bacterial mixture for sludge treatment). Depth and surface area were compared using the Mann–Whitney test, as the data did not follow a normal distribution (based on a Shapiro–Wilk normality test).

As waterfowl and wading birds are potential macrophyte dispersal vectors, we calculated the percentage of ponds that had invasive plants and were also visited by birds to assess the potential role of waterbirds in spreading these plants.

2.5 | Habitat Suitability

In order to assess the habitat suitability of invasive macrophytes across Hungary, we used species distribution modelling (SDM) on the six taxa. Global occurrence data were extracted from the Global Biodiversity Information Facility (GBIF) for all six taxa aggregated from the nine species (Table S7, GBIF.org 2024). Only

presence data points based on human observation with available coordinates were included. Locations with an uncertainty of more than 4000 m were excluded to match the 2.5 min resolution of the raster data of the bioclim database. Duplicates per raster cell were removed to keep only single records for each species in each raster cell, using the 'occ.desegregation.RASTER' function (Di Febbraro 2019). Records from Hungary were excluded because our aim was to predict the potential distribution of these taxa within Hungary. These records were later used to analyse the relative role of habitat suitability in explaining the current distributions. We created the pseudo-absences (10,000 random background points) using the randomPoints function (Hijmans, Phillips, et al. 2024).

As most of the studied plants originate from tropical and subtropical regions (except for *Elodea*), they are more or less frost-sensitive species. Consequently, we selected climatic variables from the available dataset that are most relevant for indicating frost sensitivity. Two variables of the bioclim dataset (2.5 min resolution) were used (Fick and Hijmans 2017): the minimum temperature of the coldest month (BIO6), which represents the lower thermal limit for survival and population establishment, and the annual temperature range (BIO7), which represents variability in temperature conditions (Luukkonen et al. 2024).

The SDM was carried out using the 'Maxent' function from the dismo package (Hijmans, Phillips, et al. 2024) on 75% of the data (training data) with the default 500 iterations. The models were evaluated using the 'evaluate' function (Hijmans, Phillips, et al. 2024) on the remaining 25% of the taxon data (test data). Further packages used for handling data and creating figures are rJava (Urbanek 2024), ggplot2 (Wickham 2016), tidyr (Wickham et al. 2024), stargazer (Hlavac 2022), export (Wenseleers and Vanderaa 2022), R2HTML (Lecoutre et al. 2024) and raster (Hijmans, van, et al. 2024).

To evaluate the habitat suitability model outputs for Hungary, we used generalized linear models (GLM) with a binomial family (logit link). In addition, we tested the total amount of urban land cover as a proxy for human presence and its subset, urban green space as a proxy for the suburban area where garden ponds might be more abundant. As the response variable, we used the occurrence of four invasive taxa extracted from GBIF (GBIF.org 2024) and the Hungarian Flora Mapping Database (Bartha et al. 2024). Data were insufficient for *E. crassipes* and *M. aquaticum*; thus, these were excluded from the analysis. As the Hungarian Flora Mapping Database uses the grid system established for the Central European flora-mapping (Niklfeld 1994) explanatory variables were converted to this grid. The median values of the habitat suitability output values were calculated for each quadrat using the zonal statistics tool in QGIS. The land cover values were extracted from the Ecosystem Map of Hungary (Ministry of Agriculture 2019). Total urban land cover was calculated as the proportion of all urban pixels (1110, 1120, 1210, 1220, 1230, 1310, 1410, 1420) and the urban green space pixels (1410, 1420) relative to the total number of pixels in a quadrat using the zonal histogram tool. Model selection was based on AIC scores.

All analyses and visualisations were carried out in R (R Core Team 2024 v.4.4.1) and in QGIS v.3.28.1. (QGIS.org 2024).

3 | Results

Based on the review of relevant characteristics linked to invasion risk, all species except *Elodea nuttallii* and *E. canadensis* pose a high risk in Hungary (Figure 1). All the investigated species prefer slow-moving or stagnant water with high nutrient content and were introduced to Hungary as ornamental plants via the aquarium or aquatic garden trade between 1808 and 2010. They primarily reproduce via the dispersal of vegetative fragments carried by water movement. In invaded systems, they can clog waterways, reduce water quality, and contribute to biodiversity loss (Tables 1, S5).

3.1 | Presence in Garden Ponds

Based on citizen-contributed records from 560 ponds, *Elodea* was the most common invasive plant, occurring in 25% of the garden ponds. It was followed by *Pistia* (20%), *Eichhornia* (14%), *Myriophyllum* (13%) and *Ludwigia* (11%), while *Vallisneria* was the least common, found only in 5% of the ponds. Approximately half of the surveyed garden ponds across Hungary (288 ponds, 51%) contained at least one of the six invasive plants. A higher number of records were reported from the capital city, its neighbouring municipalities and larger towns (Figure 2). This pattern was also observed when analysing the presence of the six taxa individually (Figure S1).

The most popular vendors for garden pond macrophytes are professional sources, such as garden centres, online shops and garden pond building companies. Acquiring plants from acquaintances or online forums and communities, such as Facebook groups is also common. In a small portion of cases, plants are collected in nature by the owners or they appear without the knowledge or active aid of the owner. There were 4% of answers where the owner either did not know or preferred not to disclose the source of their plants (Figure 3A). The number of invasive taxa in a pond did not show a significant relationship with the primary source from which pond owners acquired their plants ($\chi^2_7 = 9.02$, $p = 0.25$; Figure 3B).

The number of cases when participants were unable to identify a plant (i.e., they answered 'I don't know') was relatively low, ranging from 0% to 4%. It was 0% for *Pistia* and *Eichhornia*, 1% for *Vallisneria*, 2% for *Ludwigia* and *Elodea* and 4% for *Myriophyllum*.

Ponds containing at least one of the six invasive plant taxa were more likely to be young and stocked with ornamental fish and other animals (Tables 2, S2). Pond owners who introduced invasive plants were also more likely to use circulation systems and apply treatments to control algae. Additionally, those who created their ponds for aesthetic purposes tended to introduce invasive plants. No other relationships were detected between the reason for creating a pond and the presence of invasive plants, and there was no correlation between the presence of invasive plants and odonates or amphibians.

When testing for individual associations, we found that, except for *Vallisneria* and *Eichhornia*, all species correlated

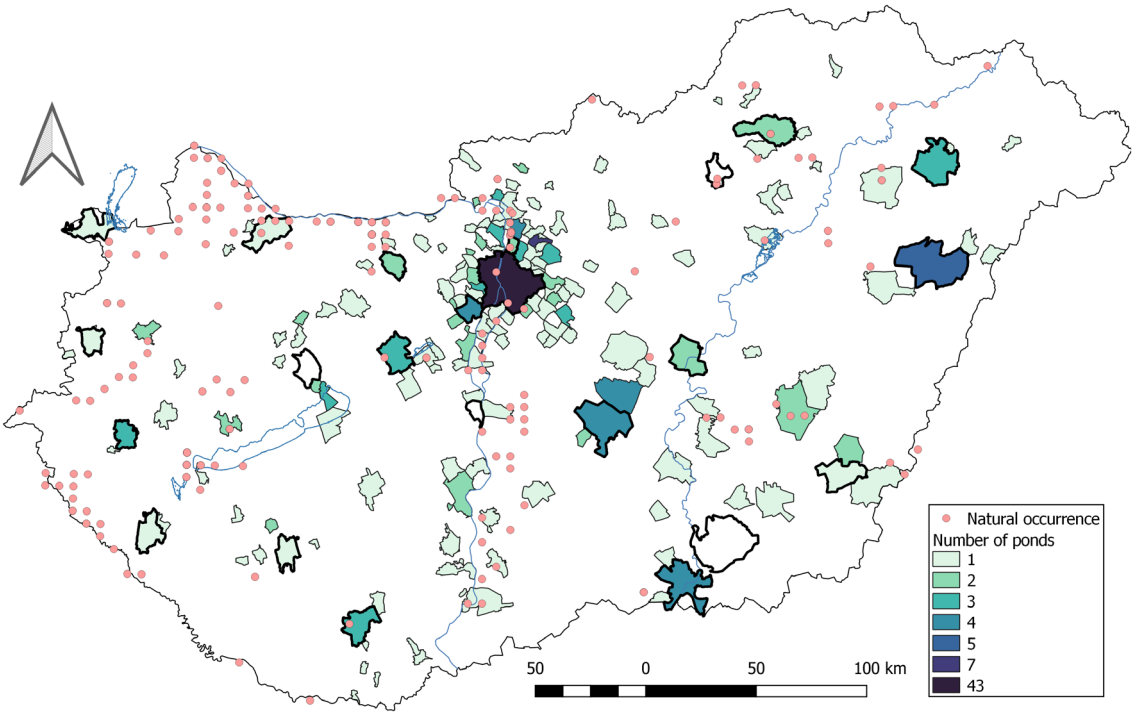


FIGURE 2 | The number of ponds with invasive plant presence within the administrative boundary of each town based on paper-based and online survey results ($n = 288$ of total 560 ponds, presence only). Pink circles indicate the locations of the invasive plants detected in nature, based on the GBIF and the Hungarian Flora Mapping databases. Bold outlines show cities with a population > 40,000 (Hungarian Central Statistical Office 2024).

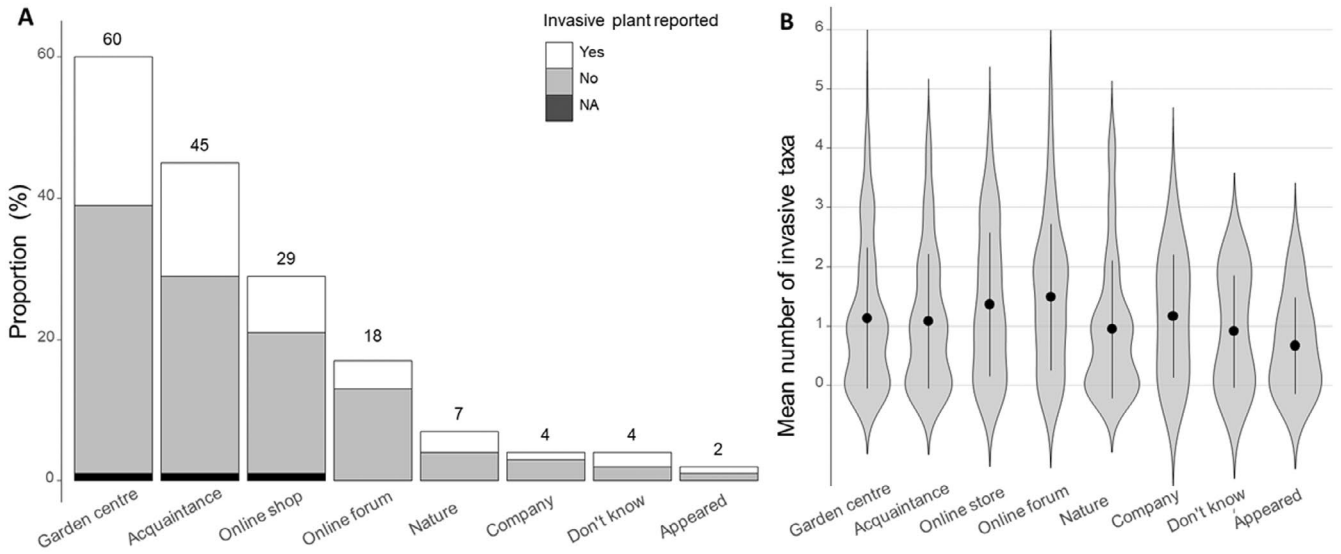


FIGURE 3 | (A) The percentage of pond owners according to the sources of plant acquisition for their garden ponds, based on the online survey. (B) The number of invasive taxa (mean +/− SD, max = 6) present in a pond and the source from which the pond owner acquires plants ($n = 268$ ponds).

positively with algae treatment. Additionally, *Ludwigia*, and *Elodea* were more common in ponds with circulation systems. The presence of *Eichhornia* was linked to the use of fertilisers and insecticides in the garden, while *Ludwigia* and *Elodea* were associated with fish introduced by the owner. *Myriophyllum* was associated with younger ponds that were not drained, leaves were removed and where crayfish were present. *Pistia* was also more likely to be present in younger ponds. Ponds with *Elodea* were more likely to have been created for aesthetic purposes (Table 2). Pond size in terms of surface area and depth did not differ between ponds with and without invasive plants (Table S3).

10% of all ponds contained at least one of the six invasive taxa and were also visited by wading birds (i.e., herons, egrets, storks) or waterfowl according to the observations of pond owners (Figure 4). Individually, it ranged between 1% and 5% being lowest in *Ludwigia* and *Vallisneria*, followed by

TABLE 2 | The relationship between the presence of invasive plant taxa and pond characteristics based on chi-square and Fisher tests. Blue shading represents positive and red represents negative associations. Darker colours indicate stronger associations. $n = 305$ ponds.

		 *Eichhornia*	 *Elodea*	 *Ludwigia*	 *Myriophyllum*	 *Pistia*	 *Vallisneria*	Any of the six taxa
Animal added by owner	Fish		*	*				*
	Snail							
	Mussel							*
	Turtle			*				
	Crayfish				*			
Physical characteristics	Age				*	***		***
	Surface area							
	Depth							
Wild animal observed by owner	Odonates							
	Adult amphibians							
	Tadpoles							
Reason for creating the pond	Aesthetic		*					*
	Nature conservation							
	Education							
New function of pond described by the owner	Aesthetic							
	Nature conservation							
	Education							
Management	Insecticide use in the garden	•						
	Fertiliser use in the garden	•						
	Circulation		*	*				**
	Draining				*			
	Cleaning bottom							
	Removing leaves				*			
	Pruning							
	Algae treatment		**	*	*	**		***

•$p < 0.06$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Eichhornia, *Myriophyllum* and *Pistia* and being the highest for *Elodea*.

3.2 | Occurrence in Nature and Habitat Suitability

The results show that the species originating from warm climates (*Eichhornia, Ludwigia, Myriophyllum and Vallisneria*) will likely be able to establish in the southwestern part of the country. At the same time, the temperate-zone species *Elodea* is more likely to occur in the mountainous, colder parts (Figure 5). The taxa most commonly detected in natural waters were *Elodea* while *Myriophyllum* and *Eichhornia* have only been detected in three places. In contrast with the predictions by the species distribution models, most detections (known occurrences in Figure 5; black dots) occurred in and along the large rivers (Danube, Tisza) and larger lakes (e.g., Balaton).

The presence of *Elodea* spp. is best predicted by urban green space and habitat suitability, while the presence of *Vallisneria* spp. was best predicted by urbanisation (all urban surfaces including urban green space) and habitat suitability. The presence of *Pistia* and *Ludwigia* is best predicted by the proportion of urban green space (Figure 6 and Table S4).

4 | Discussion

The current rapid loss of freshwater habitats may partly be compensated by the creation of secondary, artificial habitats such as urban ponds which have many benefits for both biodiversity and ecosystem services (Hassall 2014; Horváth et al. 2025). Citizens are increasingly contributing to this by building ponds in their own, private gardens (Hill et al. 2021; Márton et al. 2025), but we still know little about how these are created and managed, including any potential negative effects for native biodiversity.

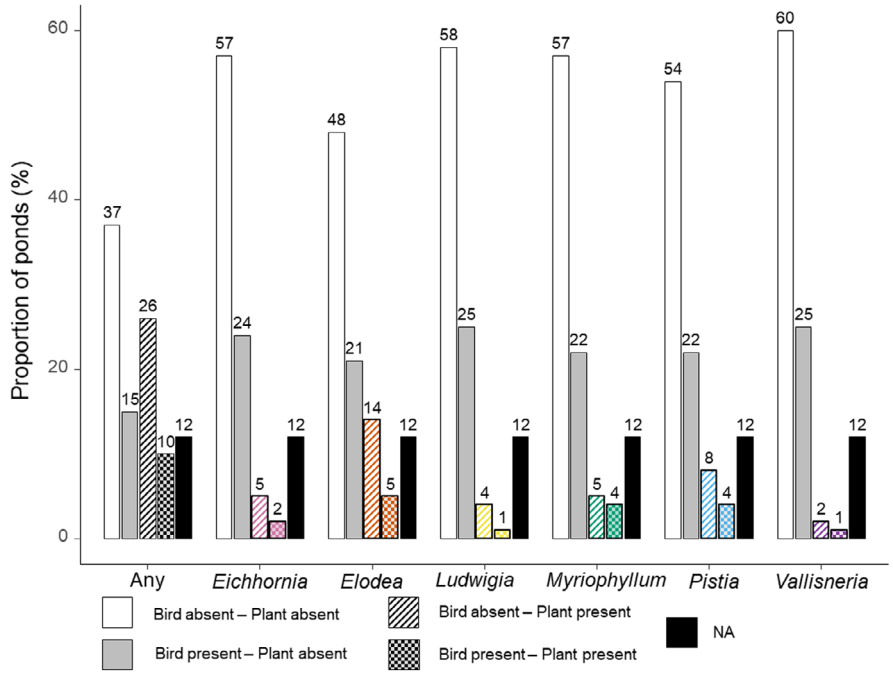


FIGURE 4 | Percentage of garden ponds reported by owners to have invasive plants, wading bird visits, both or neither ($n = 305$).

We found that alien invasive plants are frequently introduced by pond owners and these taxa are not only capable of but are already established in natural waters in Hungary where they could potentially cause serious environmental and economic damage.

In Hungary, garden ponds are very popular, as indicated by the large online community and the number of active participants in our citizen science programme (Hamer et al. 2024; Márton et al. 2025). The largest active group on social media has over 30,000 members. If each member owned a garden pond, it would mean that the number of garden ponds is seven times more than standing waterbodies (4000) officially registered in the country (Barreto et al. 2017). While they can benefit native biodiversity (Hassall 2014; Hill et al. 2021; Márton et al. 2025), their role as sources of alien plant invasions cannot be neglected. Indeed, we found that from around half of the 560 ponds, the owners reported at least one of the six investigated alien macrophyte taxa, with *Elodea* spp. being the most common. Among the studied species, *Elodea* taxa are the most widespread in the region, with *E. nuttallii* emerging as the most frequent and abundant species within the genus over the last 10–15 years (Bartha et al. 2024).

Even though the issues associated with invasive macrophytes have been known for a long time and their origin in Europe can be traced back to the ornamental trade (Hussner 2012; Hussner et al. 2010; Kay and Hoyle 2001), many of them are still available for purchase. Alarmingly, even those pond owners who tend to buy plants from professional (garden centres or plant nurseries) and semi-professional sources (online stores, pond building companies) reported having invasive plants. It is common to find invasive and even banned macrophytes for sale in many countries (June-Wells et al. 2012; Martin and Coetzee 2011; Peres et al. 2018) and even specialised garden pond architects and builders offer these harmful species (Patoka et al. 2017). Vendors themselves may not be aware of the adverse impact or they may not know the species they sell as mislabelling and misidentification do occur (June-Wells et al. 2012; Keller and Lodge 2007; Martin and Coetzee 2011). In other EU member states, such as Germany and Poland, surveys of invasive species trade found that the online trade is also booming (Dickey et al. 2023; Lenda et al. 2014; Mazza et al. 2015). Similar to our findings, there was no significant difference in the proportion of invasive species between physical and online stores (Dickey et al. 2023). The problem of e-commerce has been reported from outside of the EU, including Brazil, the United States, Australia and many other countries (Humair et al. 2015; Maher et al. 2023; Olden et al. 2021; Peres et al. 2018), highlighting that the challenges of regulating invasive species trade appear largely unrelated to whether vendors operate online or as physical stores.

Finally, almost half of the participants reported acquiring plants from acquaintances and 18% on online fora, similar to how anglers and aquarists exchange invasive fish (Hirsch et al. 2021). This represents a largely hidden, and in many cases, longer distance dispersal route (Lenda et al. 2014), especially in the absence of broad public awareness and willingness to report invasive species.

Environmental consciousness and prior knowledge may increase the chance of people recognising invasive taxa and the need to remove them (Cordeiro et al. 2020; Novoa et al. 2017; Sharp et al. 2011). In contrast, we found that there was no significant difference in the proportion of pond owners planting invasive macrophytes between those who considered conservation and education when building their pond and those who did not. Similarly, there was no significant association between the answers for the question of what functions the owners observed the pond to fulfill once it was built (aesthetic, conservation, education) and macrophyte planting.

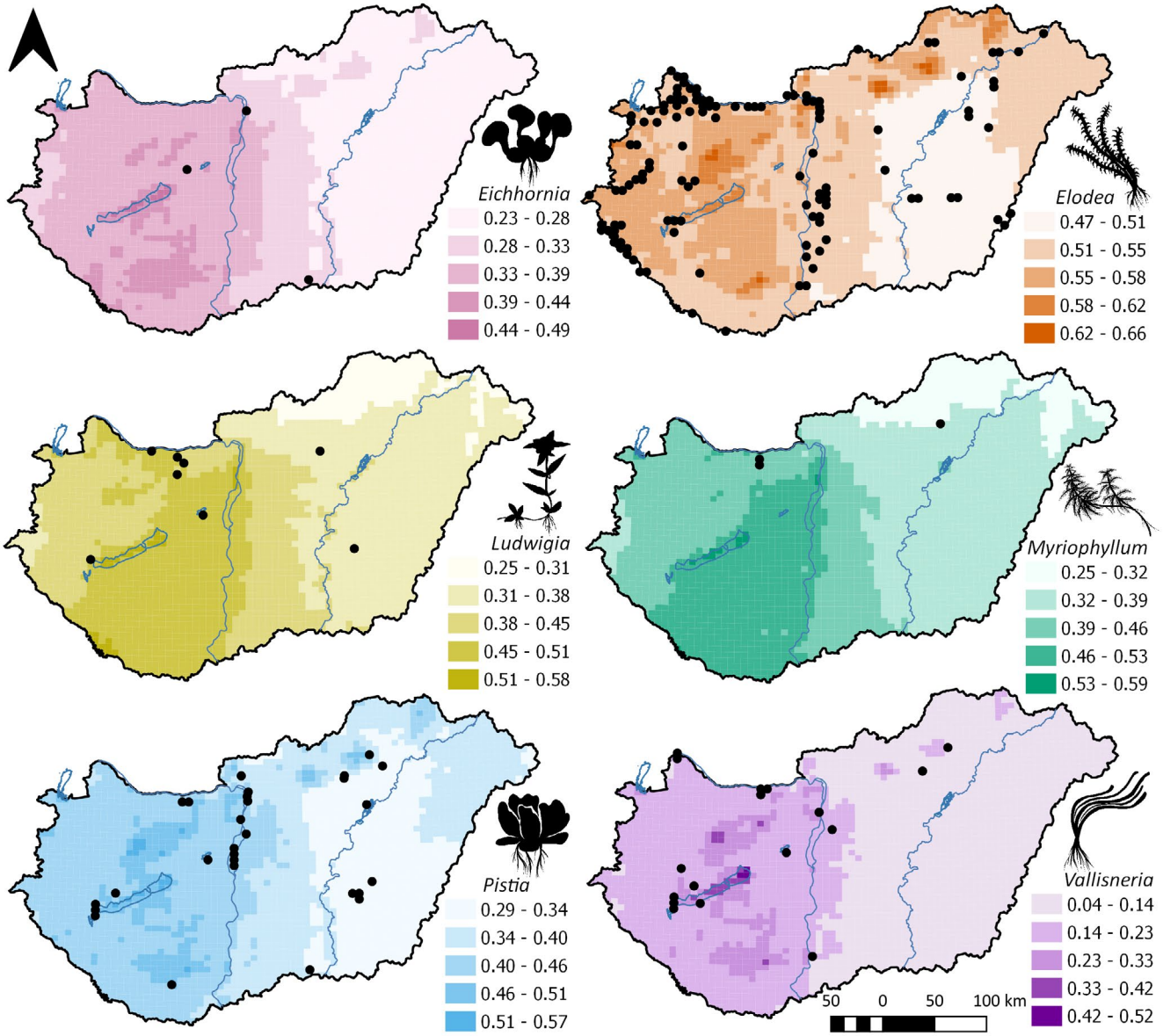


FIGURE 5 | The habitat suitability for the six taxa based on species distribution modelling using two bioclimatic variables (minimum temperature of the coldest month and the temperature annual range) and the global occurrence from the GBIF database. Higher values with darker colours indicate higher suitability. Black dots indicate the location of known occurrences in nature, based on the GBIF database and the Hungarian Flora Mapping Database.

We found that the presence of invasive macrophytes was often associated with animals introduced to the pond by the owner. These potentially invasive animals, for example the highly fecund goldfish (Lorenzoni et al. 2010; Tarkan et al. 2010) and various invertebrates are commonly traded (Dickey et al. 2023; Patoka et al. 2017), similar to the plants. Their co-occurrence might be the reason for the association between the macrophytes and various pond management practices. For example, the feeding of fish may lead to higher nutrient levels which necessitates the use of algae treatment, water filtration and circulation systems. Fish may also disturb the sediment thereby resuspending nutrients and uprooting and damaging the aquatic plants (Richardson et al. 1995). This contributes further to high algal biomass production as the nutrient levels increase and shading decreases.

Garden ponds could affect biodiversity adversely in two ways. Firstly, by providing suboptimal conditions for wild organisms that arrive at the pond (e.g., due to high predation of tadpoles by introduced fish) (Dickey et al. 2022; Lejeune et al. 2024; Monello and Wright 2001). Here, we found no negative correlation between invasive macrophytes and odonates, adult amphibians or tadpoles although the presence of these animal groups was reported at a very crude level. Furthermore, macrophyte density might be low to have such an effect in garden ponds as the owners tend to control the vegetation (e.g., they mentioned cutting back reed and sedge, removing dead leaves, thinning overgrown vegetation, removing a portion of submerged macrophytes if overgrown).

Secondly, invasive species, including plants, pose a significant threat due to their potential spread into natural waterbodies. All taxa investigated in the present study can reproduce vegetatively, facilitating dispersal through various means. Broken-off plant fragments may be transported via animal vectors or human activity from one pond to another or from

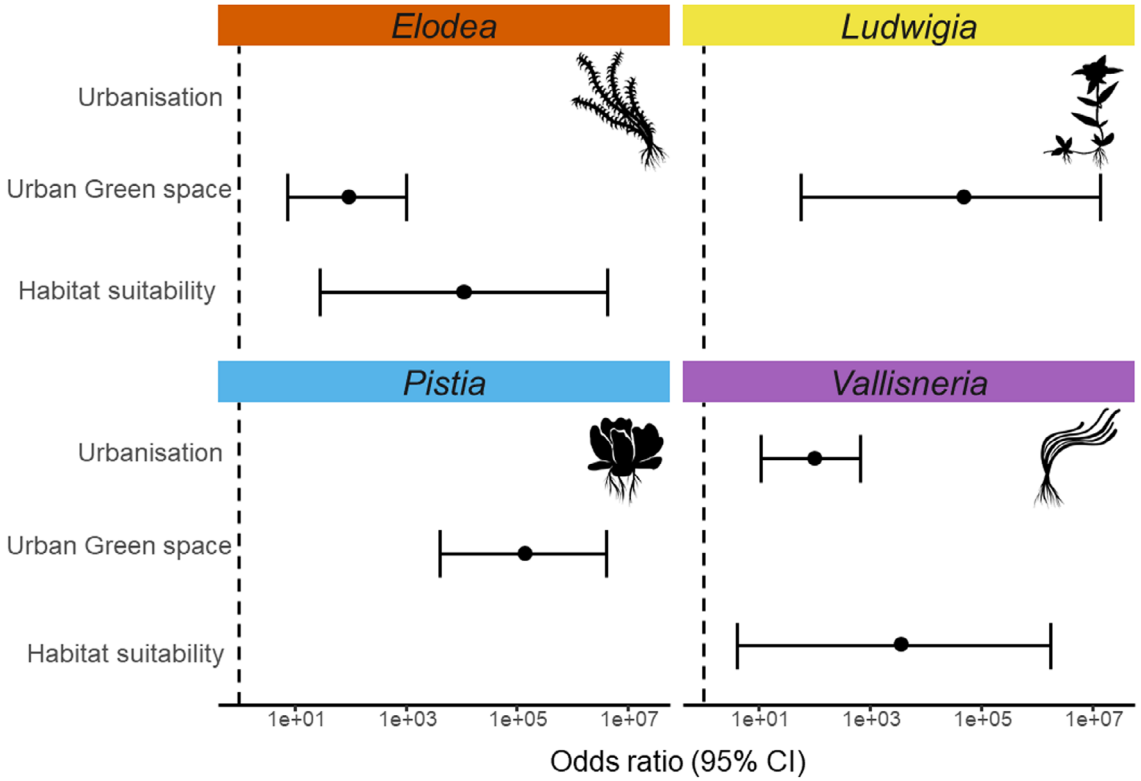


FIGURE 6 | Occurrence of the four invasive taxa predicted by urbanisation (i.e., proportion of urban land cover), urban green space (i.e., proportion of urban green space cover) and habitat suitability based on SDM models. The best fitting generalised linear models (family = binomial, link = logit) were selected using AIC scores.

the gardens to natural waterbodies. In our dataset, 2% of pond owners reported unexpected plant appearances, suggesting unintentional introductions. In the Netherlands, *Elodea* species were found to be the most frequently translocated alien plant, with an average dispersal distance of 10.6 km (Prins et al. 2024). *Ludwigia* species and *Myriophyllum aquaticum* have been found in natural waterbodies likely due to dumping (Nehring and Kolthoff 2011; Pliszko 2024). The appearance of *Pistia stratiotes* and *Eichhornia crassipes* is similarly assumed to be the result of recurrent dumping by pond owners, as evidenced by several North American and European studies (Adebayo et al. 2011; Boršić 2021; Brundu et al. 2012; Prokopuk et al. 2021; Šajna et al. 2023). In Hungary, anglers admitted releasing aquarium plants in nature (Löki et al. 2021; Nagy et al. 2025). Aquarists and anglers are two shared hobbyist groups whose practices are particularly likely to translocate non-native aquatic species (Hirsch et al. 2021; Nagy et al. 2025).

Zoochory may also contribute to dispersal as wading birds and waterfowl frequently visit garden ponds (Márton et al. 2025) and they are known to facilitate plant movement between ponds and natural waterbodies (Green et al. 2023; Lovas-Kiss et al. 2019). For example, grey herons are known to transport various organisms, including plants (Navarro-Ramos et al. 2022) and they are often observed by pond owners in the region (Márton et al. 2025). With an increasing number of ponds being built and the constantly expanding selection of alien species traded, such dispersal events might become more frequent. However, as our questionnaire did not ask pond owners whether exotic plants were intentionally introduced or appeared spontaneously, we cannot exclude the possibility that some occurrences already resulted from alternative pathways, such as zoochory.

Once in natural waters, the ability of alien aquatic plants to reproduce vegetatively and disperse via water enables rapid colonisation of connected aquatic systems. However, this may depend on environmental constraints, such as temperature, water chemistry (pH, nutrient levels), substrate type, and hydrological regime. While the study species exhibit broad ecological tolerances, climatic conditions are still expected to act as the main limiting factors for their growth and spread in cold climates. Alien species adapted to non-thermal waters are considered a more serious invasion risk than those still restricted mostly to thermal habitats in Hungary (Lukács et al. 2016). Theoretically, all the studied species are considered frost-sensitive with the exception of *Elodea* (Zehnsdorf et al. 2015), which is already widespread in Hungary (Mesterházy et al. 2019). The applied distribution model, which considers climatic conditions linked to frost sensitivity, identifies eastern Hungary with lower suitability for most species. Observations from natural waters, however, show that plants are able to survive in other regions, which may indicate the importance of microclimatic and specific local conditions (e.g., thermal waters). Additionally, increasing winter temperatures under climate change are altering climatic constraints. This may have led to the recent invasion of *Pistia stratiotes* along major irrigation canals and rivers in eastern Hungary (Molnár V. et al. pers. comm.). *Ludwigia* is in range extension along canals in western Hungary (Mesterházy et al. 2019), while *Myriophyllum* is invasive in Britain, the Netherlands and Belgium (Schou et al. 2023) suggesting capability to spread in Hungary.

Yet, the current patterns indicate that human-mediated translocation remains the main driver of spread, as occurrences are concentrated in and around urban areas in Hungary. This aligns with a European-scale study, which showed that the number of non-indigenous aquatic macrophyte species was significantly correlated with population size (Hussner et al. 2010).

5 | Caveats

Using citizen science in the current study provided invaluable data that was otherwise inaccessible for researchers but it is important to highlight some of the potential limitations arising from this approach. We aimed to choose macrophyte taxa that are easily recognisable and distinguishable from other taxa for laypeople. In other studies, participants were able to identify invasive species correctly, but it can be highly context dependent (e.g., participants' education or prior knowledge, country of survey, taxa under investigation) (Cordeiro et al. 2020; Novoa et al. 2017). Yet, with such a robust dataset, a small number of misidentifications is unlikely to influence the overall findings.

In the online version of the questionnaire, we allowed participants to select 'I don't know' as the answer in case they were unsure if they owned a plant or not. The number of these answers was low, ranging from 0 to 11 corresponding to 0% and 4%. The floating *Eichhornia crassipes* and *Pistia stratiotes* were likely to be correctly identified as these species are very distinct from other species present in Hungary. *Elodea, Vallisneria* and *Myriophyllum* are submerged which makes their identification more difficult. In addition, there are other native and also alien *Myriophyllum* species that can potentially make it more difficult to correctly identify *Myriophyllum aquaticum*. Interestingly, there was some level of uncertainty about *Ludwigia* spp. as well, even though there are no native species or even morphologically similar taxa in Hungary, especially when it is flowering.

There were clear misunderstandings in the instructions in the case of the paper-based questionnaire, which we tried to evaluate objectively and correct on a case-by-case basis. However, this represents a very small number of cases and only in the paper-based questionnaire. Further limitations may be if some participants failed to answer honestly due to fear of the consequences of owning banned plants. Finally, duplicate answers may be present, but only in the online dataset, as we had detailed information on the participants filling out the paper-based questionnaire. We assess the number of potential duplicates to be negligible, as there were only two cases where answers came from the same town within minutes of each other.

Additionally, it is possible that the distribution of the questionnaires had some bias not reaching all the social groups owning garden ponds equally. This may have led to some bias towards online communities as the questionnaire was distributed in online groups on social media, potentially increasing the share of online vendors used by participants.

Finally, when interpreting the results of the associations between invasive plant presence and other pond characteristics, it is important to keep in mind that these do not represent ecological relationships but rather are related to the general attitude of the pond owners.

6 | Conclusion and Recommendations

Engaging the public in data collection and monitoring is essential for managing invasive species. It also helps to identify and track the spread of invasive species, especially in overlooked habitats like urban garden ponds. Our country-wide citizen science survey revealed that more than half of the ponds hosted alien plant species, making them potential sources for invasion into natural habitats. This concern is reinforced by the fact that all identified alien species are already established in natural water bodies, suggesting a potential link between garden ponds and invasions. This issue seems widespread, given the number of ponds with invasive species and the availability of suitable habitats. Thus, stronger legislation would be needed, as well as strict enforcement in countries where these are lacking.

As pond owners also exchange plants among themselves, vendor bans alone may not prevent the further spread of these species. Raising awareness can increase public support for the management of these species (Haley et al. 2023; Novoa et al. 2017). This underscores the need for targeted education campaigns involving both the public and vendors (Ardoin et al. 2020; Verbrugge et al. 2021). Without intervention, these macrophytes might remain in circulation for a long time. Mobile phone applications can help pond owners identify species before purchase, improving prevention efforts, for example, The Flora Incognita App (Mäder et al. 2021), specifically designed for plant identification or iNaturalist (https://www.inaturalist.org/; iNaturalist, (n.d.) accessed on 29 September 2025), which is already widely used. More informed citizens, who are familiar with invasive species, can use apps to report invasive species to authorities, for example, the Invasive Alien Species Europe (Tsiamis et al. 2017) app in Europe or the MyPestGuide (Department of Primary Industries and Regional Development, Western Australia (DPIRD), n.d.) in Australia.

As invasive plants and animals often co-occur, joint campaigns could address both, including invasive ornamental animals like goldfish. New pond owners often have invasive plants, but also all pond owners seem to regularly manage their pond; thus information campaigns at garden centres could be effective. Additionally, as scientists are often seen as credible by the general public Cologna et al. (2025), they need to take a more active role. Citizen science offers the right channels and means for connecting them to the public, generating valuable data while facilitating public engagement and education. However, these efforts have to be planned carefully to achieve the desired outcomes, for example, by trying to understand where measurement errors could occur, striving for clear communication or exploring how to reduce uncertainty and bias Probert et al. (2022).

Author Contributions

Conceptualisation and developing methods: B.B., Z.H., B.A.L. Data analysis and preparation of figures and tables: B.B., B.A.L. Conducting the research, data interpretation, writing: B.B., Z.M., B.S., C.F.V., Z.H., B.A.L.

Acknowledgements

This work has been implemented by the National Multidisciplinary Laboratory for Climate Change (RRF-2.3.1-21-2022-00014) project within the framework of Hungary's National Recovery and Resilience Plan supported by the Recovery and Resilience Facility of the European Union. The research was funded by the Sustainable Development and Technologies National Programme of the Hungarian Academy of Sciences (FFT NP FTA). Barbara Barta was supported by the EKÖP-24 (EKÖP-24-3-II-ELTE-272) University Excellence Scholarship Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund and the Young Researchers' Grant by the HUN-REN. Zsófia Horváth and Beáta Szabó were supported by OTKA FK146095. Zsófia Horváth and Csaba F. Vad acknowledge further support from the János Bolyai Research Scholarship of the Hungarian Academy of Sciences (grant number BO/00418/24/8 and number BO/00239/24/8). The authors are grateful to all citizen scientists who participated in the project. We acknowledge the help of Virág Csiszár and Vivien Kardos in designing the project homepage and questionnaire. We thank Csilla Laskai for her assistance in data collection and entry.

Funding

The work was supported by the National Multidisciplinary Laboratory for Climate Change (RRF-2.3.1-21-2022-00014) project within the framework of Hungary's National Recovery and Resilience Plan supported by the Recovery and Resilience Facility of the European Union. The project was further supported by the Hungarian Academy of Sciences via the projects: BO/00418/24/8; BO/00239/24/8 and the Sustainable Development and Technologies National Programme (FFT NP FTA). The project received further support from the National Research, Development and Innovation Fund via the project OTKA FK146095 and it was supported by the EKÖP-24 University Excellence Scholarship Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund (EKÖP-24-3-II-ELTE-272).

Ethics Statement

The handling and analyses of questionnaire data were in accordance with the GDPR regulations of the HUN-REN Centre for Ecological Research where the study was conducted following a Legitimate Interest Assessment. Participation in the project was voluntary and conditional upon acceptance of the GDPR guidelines to ensure meeting ethical standards.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data associated with the manuscript are available via the Figshare repository at https://doi.org/10.6084/m9.figshare.29645417.v1.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Appendix S1:** fwb70145-sup-0001-AppendixS1.pdf.