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One year spread and insight into ecology of invasive *Impatiens glandulifera* in Ljubljansko barje area (Central Slovenia)

Enoletna dinamika širjenja in vpogled v ekologijo invazivne tujerodne vrste *Impatiens glandulifera* na območju Ljubljanskega barja (osrednja Slovenija)

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Abstract: *Impatiens glandulifera* Royle (Himalayan balsam) is an annual plant, native to humid parts of the Himalayas. Brought to Europe in the XIX century, it has since successfully naturalized and spread throughout the continent, becoming one of the best-known invasive plants. Even though it has been thoroughly studied by many authors, some aspects of its biology and ecology remain unclear and debatable, such as its spreading dynamics, negative impacts in invaded ecosystems and ecological adaptability regarding moisture, nutrients, and light. This 2019 field study from the Ljubljana Marsh (Slovenia) has proved that Himalayan balsam successfully develops under mesophilic conditions, where it easily compensates moderate deviations from its ecological optimum. The species thrives in riparian zones, out-competing native vegetation, trait shown as potentially the biggest negative impact of chosen species in this context. This study additionally gave us a different insight into - usually highly emphasized - dynamics of species' spreading. Spreading was not either dependent on hydrochory or as drastic as mentioned in literary sources, giving it a secondary role in species' invasiveness on the chosen area. Lastly, we proposed rough estimates of eradication expenses for given area, based on our field results of species' abundance and distribution on chosen area.

Keywords: ecology, Himalayan balsam, *Impatiens glandulifera*, invasive species, plant invasions

Izvleček: *Impatiens glandulifera* Royle (žlezava nedotika) je enoletna rastlina, domorodna v vlažnih predelih območja Himalaj. Vrsta je bila vnešena v Evropo v XIX. stoletju, kjer je od takrat, kot ena izmed najbolj znanih tujerodnih vrst, postala uspešno naturalizirana in invazivna, ter razširjena po vsej celini. Nekatere njene biološke lastnosti še vedno ostajajo precej nejasne in vprašljive. To se nanaša predvsem na njeno invazivnost in morebitni vpliv v ekosistemih, dinamiko širjenja in možnost prilagajanja na različne okoljske dejavnike, kot so vlaga, hranila in svetloba. Terenska raziskava iz 2019, opravljena na območju Ljubljanskega barja v osrednji Sloveniji, je pokazala da žlezava nedotika uspeva v zmernih pogojih, kjer uspešno prenaša zmerna odstopanja od svojega ekološkega optimuma. Vrsta je najbolj uspešna v obrežnem pasu, kjer je precej bolj kompetitivna kot domorodna vlagoljubna vegetacija, kar bi v tem kontekstu lahko definirali kot največji negativni vpliv izbrane tujerodne vrste. V tej študiji smo tudi ugotovili, da ima dinamika širjenja sekundarni pomen v njeni invazivnosti na Ljubljanskem barju, ter da širjenje ni odvisno od hidrohorije, niti ni toliko uspešno kot navajajo nekateri drugi literaturni viri. Na podlagi rezultatov o razširjenosti in velikosti lokalnih populacij žlezave nedotike na Ljubljanskem barju smo pripravili ocene stroškov odstranjevanja vrste in predlog monitoringa stanja v prihodnjih letih.

Ključne besede: ekologija, *Impatiens glandulifera*, invazivne tujerodne rastlinske vrste, žlezava nedotika

Introduction

Short introduction to biological and plant invasions

Biological invasions are one of the most covered topics in modern science and an important negative consequence of globalization (Lambdon et al. 2008, Perglová et al. 2009, Vilà et al. 2010, Vilà et al. 2011, Bieberich et al. 2020). Invasive species are diverse and known for their specific biological traits, which make them stronger competitors in comparison to native species and facilitate their success in newly invaded habitats (Čuda et al. 2014, Enders et al. 2020). Many studies have proven negative impacts of invasive species on environment and society, which are derived from their disruption of ecosystem services. The disruption comes from changes in native species' diversity, trophic networks, biogeochemical cycles, and habitat structure in invaded ecosystems, all of which are confirmed consequences of biological invasions (Hejda et al. 2009, Vilà et al. 2011, Pyšek et al. 2012, Blackburn et al. 2014). Impacts of invasive species are however context-dependent and determined by various aspects of individual case of species' invasion, such as its residence time and naturalization status, biological traits of given species and biotic and abiotic conditions found in ecosystem they invade (Richardson and Pyšek 2006, Pyšek et al. 2012, Blackburn et al. 2014). Different ecosystems show different levels of vulnerability regarding biological invasions. Generally, it is proposed that ecosystems with higher number of endemic species are more susceptible to the negative impacts of biological invasions. On the other hand, ruderal vegetation is often predominantly composed of neophytes, to which frequent disturbances found in urban areas are suitable (Zelnik 2012). Due to both natural disturbances and human pressures put on them - such as building dams, flow regulations, degradation, eutrophication or draining, riparian habitats are exceptionally sensitive to biological invasions (Schnitzler et al. 2006, Richardson et al. 2007, Nobis et al. 2017). Additionally, permanent presence of water is reducing drought stress, which is an important limiting factor for some alien plants from more humid climates.

General traits of Himalayan balsam

One of the invasive species commonly found in riparian habitats, where it triggers conservation issues, is Himalayan balsam, *Impatiens glandulifera* Royle (Hejda and Pyšek 2006). Himalayan balsam is a summer therophyte, up to 2.5 (4) meters tall and known as the tallest annual plant in Europe. It is easily distinguished by its zygomorphic, pinkish-purple flowers and opposite, lanceolate-shaped, serrated leaves. Complex, multicellular, dark-purple tipped glands develop at the leaf base and serve as extrafloral nectaria, to which the species owns its scientific name. In Europe, seeds of Himalayan balsam start germinating in early spring, usually in March (Balogh, 2008), and according to the experimental study by Perglová et al. (2009), they require stratification for germination. Seedlings are very vulnerable to late frosts, snails, and fungal infections, as seen in a study by Prowse (1998), in which only about 5-10% of observed young plants survived. Flowering begins 13 weeks after the germination and it is the most intense in July and August, even though it can last until October or November. Individual flowers last for 2-3 days. Fruit and seed development end approximately 13 weeks after the flowering and are followed by plant maturation and seed dispersal, which take place in autumn and last until November. Fruit type is a capsule which can contain up to 16 seeds, so whole plant can produce up to 2500 seeds. Upon maturation, capsules burst explosively, shooting seeds up to 7 meters away from the parent-plant (Balogh, 2008). This mechanism is known as ballistochory (Elst et al. 2016). By this natural mechanism, local populations spread their range by 3-5 meters per year on average, even though spreading is often enhanced by human activities, animals, or waters (Balogh 2008). Often cited study by Perrins et al. (1993) reports on Himalayan balsam's spread by rivers in England. Authors have calculated the maximum downstream spreading rate of 38 km/year, although they note that the realistic enhancement by hydrochory is around 2.6 km/year. Čuda et al. (2017a) additionally state that flooding might have an important role in species' spreading. In the soil seed bank, some seeds can survive for 4 (Skalová et al. 2019) or even 6 years (Schuldes 1995).

Himalayan balsam is often found in humid and half-shaded habitats, in both its native and non-native range. In Europe, it usually inhabits temperate areas with rainfall values of at least 250 mm/year, optimally 1000 mm/year, with an average annual temperature between 6 and 12 ˚C. Species avoids direct sunlight, unless provided with adequate sources of water, since it is defined as hydrolabile. It is commonly found in riparian zones and damp ruderal communities (Balogh 2008), but it can also be found in other types of ecosystems, like forest fringes, arable fields, and meadows (Čuda et al. 2017a). Species is found growing in alluvial soils, loam, and humic clay, avoiding both acidic and alkaline soils (Balogh 2008). Species is often regarded as nitrophilous (Hejda and Pyšek 2006). According to Beerling and Perrins (1993), optimum soil nitrate values for Himalayan balsam range from 0.5±0.3 µg/g to 5.5±1.3 µg/g. Andrews et al. (2005) have confirmed that species has an ability of nitrates accumulation, what possibly stimulates species' extensive growth in shaded habitats, whereas Andrews et al. (2009) report on positive effect of higher nitrates value on seed germination, later confirmed again by Skalová et al. (2019).

Often-used methodology used for describing species' ecological preferences are indicator values (see Bartelheimer and Poschlod 2016, Chytrý et al. 2018). In this study, we present and use modified, Ellenberg-type indicator values (shortened as EV in continuation) by Chytrý et al. (2018), which describe Himalayan balsam as transitional between the plants of half-shade and half-light, rarely found on less than 20% of full light intensity (EV for light 6), transitional between mesothermic and thermophilous plant species (EV for temperature 6), transitional between indicators of wet and moist soils (EV for moisture 8), indicator of neutral soils, avoidant of extremely acid soils (EV for pH 7) and the favourer of fertile soils (EV for nutrients 7).

Introduction of Himalayan balsam in Europe and its current invasiveness status

Native to the Western Himalayas, species was introduced to Europe in 1839 as an ornamental plant, whose seeds were sent to Kew Garden from Kashmir by dr. J. F. Royle. Soon after the introduction in 1848, Himalayan balsam escaped the cultivated area and was proclaimed as successfully naturalized in United Kingdom by 1855. In the continental Europe, first records on naturalization date from 1897, although the species probably didn't become invasive in Europe until the last three decades of previous century (Balogh 2008). Today, Himalayan balsam is widely distributed across the Northern Hemisphere, in zone between 40˚ and 65˚ of geographic latitude, which includes most parts of temperate Europe and North America, along with some parts of Asia where it's not native, such as Russia and Japan (Drescher and Prots 2003). Results of DAISIE project report on its presence in more than 30 European countries, out of which 25 consider it as at least naturalized allochthonous species, what puts Himalayan balsam on the list of 150 mostly widespread alien plants in Europe (Lambdon et al. 2008). Due to its progressive spreading and impacts on biodiversity and subsequently economy, it was included in the first edition of the List of invasive species of Union concern (European Commission 2017). Therefore, all member states of the European Union must act towards preventing its further introductions and spreading, while simultaneously working on adequate management and monitoring methodology (ibid.; Commission, 2017). In Slovenia, it was first reported in 1935 (Petkovšek 1966), whereas oldest findings on northern margins of capital city Ljubljana date from Zalokar, from 1939 (data from University of Ljubljana's Herbarium). Species has been successfully spreading since, mostly along main water bodies, as seen in older publication by Prekoršek (1964), who claimed its presence by rivers Sava, Savinja, Drava and Mura, and is today widespread across the country (Jogan et al. 2001). Zelnik (2012) lists it as one of the most invasive alien plants in Slovenia, found in an array of habitat types, such as riparian zones, floodplains and swamps, forests, urban areas, and managed ecosystems.

Studies of Himalayan balsam's invasiveness

Although much is known about the species, some aspects of its ecology and invasiveness are still insufficiently understood and sometimes debatable. For instance, while some authors report on its negative impact in invaded habitats (Hulme and Bremner 2006, Kiełtyk and Delimat 2019), other studies deny it (Hejda and Pyšek 2006, Hejda et al. 2009, Diekmann et al. 2016, Čuda et al. 2017b, Bieberich et al. 2020). Notably, studies were carried out in different habitats and biogeographic regions, so the impact should be interpreted as context-dependent. For instance, Hulme and Bremner (2006) found that Himalayan balsam's worst negative impact was on the native heliophytes in its undergrowth in riparian zones, whose development was disturbed due to Himalayan balsam's rapid growth and height. Kiełtyk and Delimat (2019) confirmed species' impact on reduced native biodiversity in temperate meadows, while its impact was negligible in mesophilic forests (Čuda et al. 2017b). Apart from invasiveness, other questionable traits of the species are its nitrophily - considering the fact that it survives in wider range of nutrients availability in soil (Beerling and Perrins 1993, Hejda and Pyšek 2006, Clements et al. 2008), and its dependence on moisture and riparian zones. Some authors hypothesise that latter might be an evolutionary adaptation which would enhance spreading along the watercourses (Čuda et al. 2014). Results of study by Elst et al. (2016) have shown that Himalayan balsam could be pre-adapted to invasions, since both native and non-native population express phenotypic plasticity, regardless of environmental conditions they grew in.

Aims of the study

Aim of this study was to get a clearer insight into dynamics of species' seasonal spreading in chosen area, since it corresponds with its described ecological optimum and it might show potential impact of water bodies in seed spreading. Additionally, due to differing literary sources on ecological traits of chosen species, we studied its ecology throughout its accompanying flora, for which we hypothesised that it would include widespread, ruderal species and neophytes. Due to the state of Himalayan balsam's widespread and continuously growing populations in Europe and stance of European conservation politics on it, we proposed simplified eradication expenses estimation, based on field findings, along with an adequate eradication plan for initial and following upcoming management actions.

Materials and methods

Study area

Field sampling was performed during the summer of 2019, in area of Nature Park Ljubljana Marsh (in continuation: Ljubljana Marsh; in Slovenian: Krajinski park Ljubljansko barje), which holds the basic level of nature protection as a nature park. Almost the entire area of Ljubljana Marsh was included in Natura 2000 network in 2004 and it has had a status of a protected area since 2008. It is a floodplain of river Ljubljanica and some of its tributaries, noted for its irregular, seasonal flooding and mosaic of different habitats including wetland meadows, riparian forests, and remains of peat bogs. The area has been under heavy human pressures, which include river flow regulation, peat excavation, intense agriculture, and prolonged draining in recent times (Zorn and Šmid Hribar 2012). Human activities have also contributed to spreading of invasive species. Based on official reports on the distribution of Himalayan balsam in the previous season (Lozej 2018), we designed a systematic census of Himalayan balsam's population in 2019, to compare states of populations between the two consecutive seasons and to see, whether theoretical claims of species' spreading could be applied to chosen area. Our methodologies differed slightly: our inventory distinguished each locality its by size and shape, followed by partial or complete inventory of accompanying flora, whereas previous report focused mostly on geographic mapping of entire population (Lozej 2018).

Field work

We sampled throughout July, August, and September of 2019, at the peak of the species' development. Field data (geographical coordinates) from previous report (Lozej 2018) were used, which were all reviewed for presence of Himalayan balsam, along with the other potential localities near them, or elsewhere considered suitable for the species based on its biological traits. Entire road and cart-track network of the study area has been systematically monitored. Every confirmed locality was marked as either a point - when less than 50 meters long, or as either linear or polygon – both longer/wider than 50 m, typified according to the spatial traits (shape) of a given local stand. Two stands (localities, populations *s.l.*) were distinguished as separated, if there was approximately 10 meters between them without any flowering individuals of Himalayan balsam. Size of each stand was roughly estimated on a scale which consisted of 4 size classes: 1-10, 10-100, 100-1000 and over 1000 fully developed plants. Fully developed, flowering individuals were considered for localities' distinguishment and size estimations, since Himalayan balsam is an annual therophyte which spreads primarily by its seeds. Therefore, flowering individuals represent adequate basis for population size estimations and stand as a reference for discussions regarding population dynamics in forthcoming vegetation seasons. To get a better insight in species' ecology, the general habitat type was also determined, based on the predominant vegetation type, proximity to agricultural areas, travel infrastructure and water bodies. No detailed analysis (mapping) of habitat types were carried out, due to the complexity of study area, interconnectedness of its many habitat types and changes in their structure, whose causation goes beyond this specific study. Each locality was described as accessible, inaccessible, or partially accessible, for purposes of further monitoring propositions and calculations of potential eradication expenses. Qualitative inventory of Himalayan balsam's accompanying flora was carried out on 67.5% (370 of 548 in total) of the locations (following nomenclature in Martinčič et al. 2007), whereas no cover/abundance examination was carried out for those species. Inventories of accompanying flora were carried out based on accessibility and the general state of given stand (for example, overgrown by Himalayan balsam, or small plant stands where only few plant individuals of any species were present). In case of presence of any other invasive alien plant species within stands of Himalayan balsam, those were always documented, regardless of whether the inventory of the entire accompanying flora was carried out or not.

Data analysis

Spatial data was processed in QGIS programme, version 3.18.1 (QGIS.org 2022), which was used to create maps of species' current distribution and to compare Himalayan balsam's population dynamics between two consecutive seasons. Distribution map in form of population hotspots was created using the built-in function in QGIS, which considers both the density of stands on a certain area, as well as their maximum size, as described above in the field work methodology. For ecological analyses, we used modified Ellenberg-type indicator values (Chytrý et al. 2018), applied to significantly abundant taxa, found at 11 or more locations where qualitative vegetation surveys were carried out ($f \geq 11$). Species which occurred sporadically in Himalayan balsam's accompanying flora ($f \leq 10$) were omitted from analysis, due to their low abundance in microsites where Himalayan balsam was growing, so their co-existence wasn't considered a possible indicator of Himalayan balsam's ecological preferences. Average values for Ellenberg-type indicator values in Himalayan balsam's accompanying flora for light (L), temperature (T), moisture (M), pH reaction (R) and nutrients (N) were calculated, along with percentages of each individual value for each ecological condition. Average values were then compared to the Himalayan balsam's theoretical optimum for given ecological factor, following Chytrý et al. (2018). Observed average values in Himalayan balsam's accompanying flora were then compared to the average values for each ecological condition for dataset of entire flora Ljubljana Marsh flora (data from Jogan et al. 2001). Comparisons between Himalayan balsam's stands and Ljubljana Marsh flora were carried out to get a robust estimations of species' possible ecological niche profiling on chosen area, since no similar studies of Himalayan balsam's accompanying flora ecology were carried out previously in Slovenia. Additionally, general ecology of Ljubljana Marsh fits into basic ecology of Himalayan balsam (described above), so its distribution and co-existence with specific species might provide additional information on species' biology. Due to those reasons, all species in Ljubljana Marsh flora dataset were included in analysis. Species without modified Ellenberg values were left out of calculations. Distribution of significantly abundant accompanying flora on Ljubljana Marsh was used to create a simple model of Himalayan balsam's prospective distribution in Slovenia. Occurrence of those species in floristic quadrants at Ljubljana Marsh was extrapolated to entire Slovenia, using data from Slovenian Centre for fauna and flora cartography, available at Bioportal.si (2022). Suitability of conditions was simply estimated as portion of present taxa of accompanying flora in quadrants of Slovenia.

Eradication expenses were estimated from our field results, based on values calculated from combinations of local populations' accessibility and sizes. We assumed that partially accessible and inaccessible populations would require solely manual eradication work, whilst accessible ones could be managed by machines. Hypothetical wage of 10 EUR/hour was used in both cases, fair for the work effort needed for theoretical hand-eradication of one plant per minute. For accessible stands, we made a simple calculation by multiplying their frequency with hypothetical wage of 10 EUR/hour. Partially accessible and inaccessible stands were analysed in more detail, taking into consideration their frequencies combined with Himalayan balsam's stands size for each stand category, multiplying both minimum, maximum sizes of stands (10, 100, 1000 and 10 000 for stands for over 1000), along with combinations of minimum and maximum sizes in intermediate stands. Minimum stand size wasn't considered only for populations of size range 1-10, due to low probability of finding single individual of Himalayan balsam in a stand, whilst stands with over 1000 were defined with hypothetical upper stand size of 10000. Those numbers were then divided with 60, resulting in hypothetical hours needed for manual eradication, then multiplied with hypothetical 10 EUR/hour wage. Numbers were added to the value of eradication expenses for accessible stands, resulting in price ranges. To achieve the completely effective prevention of future flowering of a local population, consecutive approaches are needed in the following years, due to soil seed-bank persistency (Schuldes 1995, Skálová et al. 2019). We predicted the rough estimate needed to cover those expenses in future growing seasons, which would in practice depend on the success of the previous eradication and should be significantly lower than the starting price point.

Results

Distribution and estimation of spreading

In 2019, Himalayan balsam was found on 548 localities in Ljubljana Marsh. Most of the localities were situated in the northern part of area, by the water bodies - usually streams, creeks and drainage ditches. Some of the biggest stands (written as numbered on Fig. 1) were found in villages Vnanje Gorice and Notranje Gorice by the stream Drobtinka (1), in Plešivica by the stream Veliki Graben (2), in Brezovica by the stream Radna (3), in area of Rakova Jelša by the stream Curnovec (4) and in village Črna vas, by the rivers Iška and Ižica, and streams Lahov graben and Prošca (5). On the southern parts of Ljubljana Marsh, Himalayan balsam occurrence is sparse, in form of scattered localities by rivers Borovniščica and Iška, by the the stream Draščica and in the Draga area, by the pond Veliki Ribnik. Due to uneven distribution and highlighted concentrated in the northern part of the area, we have decided to present species' distribution in forms of both common map and hotspots map, as shown below on Fig. 1 (locations are numbered as written above). We would additionally emphasise local stands 6*, located near the old riverbed of Ljubljanica river (in Slovenian: Stara struga Ljubljanice), and 7*, situated at the very border of Ljubljana Marsh, by the waste collecting and management centre Barje (in Slovenian: Zbirni center Barje). Those aren't shown as true hotspots though, due to their smaller size compared to other stands which expand over larger area.

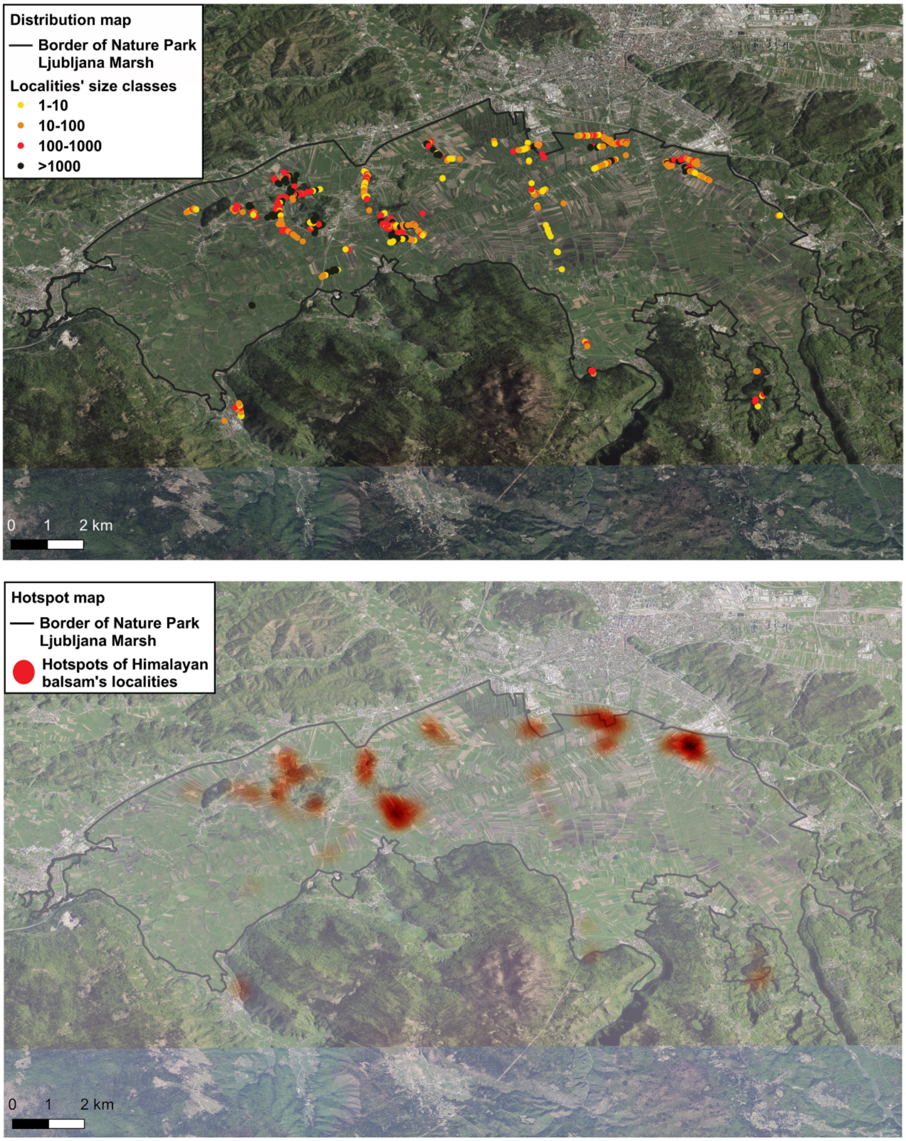

Figure 1: Distribution of Himalayan balsam on Ljubljana Marsh (bordered with black) in season 2019, given in form of individual population locations, categorized by size classes (**A**) and hotspots (**B**). Hotspots are numbered as: Notranje and Vnanje Gorice (1), Podplešivica (2), Brezovica (3), Rakova Jelša (4) and Črna vas (5). Additional mention goes to smaller areas with densely distributed populations, by the oldriver bed of Ljubljanica river (6*), and by the waste collecting and management center Barje (7*).

Slika 1: Razširjenost žlezave nedotike na območju Ljubljanskega barja (omejeno s črnim poligonom) v letu 2019, prikazana v obliki posamičnih nahajališč populacij, razdeljenih po velikostnih razredih (**A**) in vročih točk (**B**). Vroče točke so označene kot: Notranje in Vnanje Gorice (1), Podplešivica (2), Brezovica (3), Rakova Jelša (4) in Črna vas (5). Poudarjamo še dve manjši lokaliteti z večjo gostoto lokalnih populacij, kot sta Stara struga Ljubljanice (6*) in Zbirni center Barje (7*).

Majority of the localities – 442, (80.7%) were marked as points - stands smaller than 50 meters. We recorded 82 linear ones (15%) and 24 polygons (4.3%). Around 90% of all localities had up to 1000 individuals, whereas the most frequent size class was the second one (10-100), with 223 localities (40.7%), followed by the first one (1-10), with 152 (27.7%) and the third one (100-1000) with 122 localities (22.2%). Fifty-one localities counted more than 1000 individuals (9.4%). We found Himalayan balsam in 9 different habitats, listed according to their frequency: roads, ditches, fields, hedges, forests, grasslands, riparian zones, banks, and embankments. About a half (49.8%) of the stands were located by roads, followed by drainage ditches, where around a quarter (26.8%) of stands were found. Other common habitat types included fields (8%), where we found species as either a weed growing among crops or at the field margins, and hedges (7.1%), fragments of bush vegetation specific for study area, which usually divide individual parcels. Himalayan balsam grew in other habitat types on Ljubljana Marsh only sporadically.

Comparison of 2018 and 2019 spatial data showed that the general pattern of Himalayan balsam's population on study area in two consecutive seasons was very similar, without observed long-distance spreading. Our study has shown that Himalayan balsam can successfully spread up to 150 meters in one year (Fig. 2), whereas the average distance of newly recorded populations from the nearest localities known in 2018 was 122 meters.

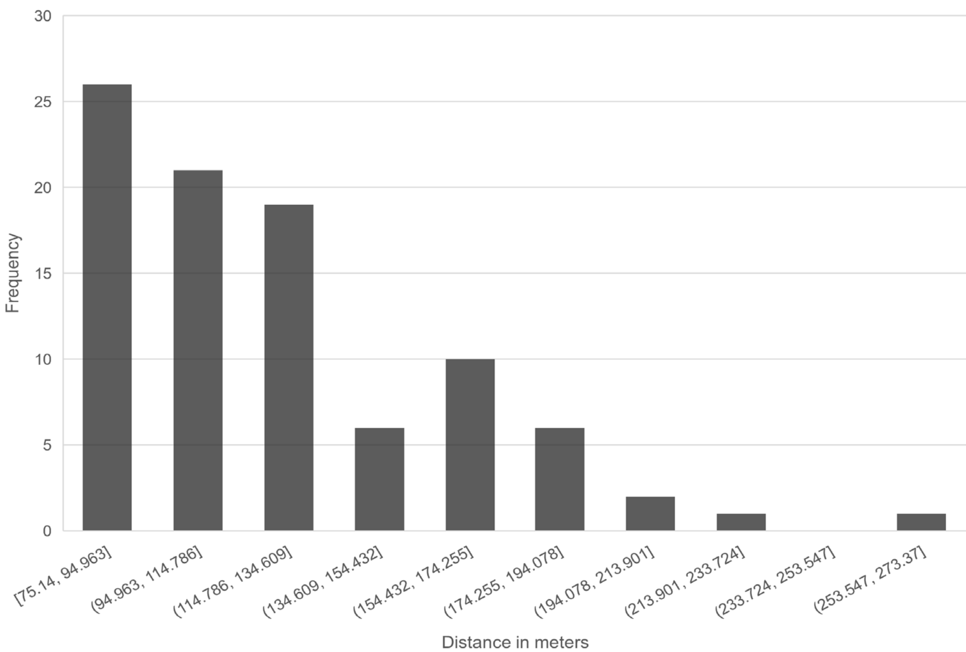

Figure 2: Frequency distribution of measured distances between the newly recorded locations and the nearest previously known populations, regarding the spreading of Himalayan balsam in 2018-2019 period.

Slika 2: Porazdelitev pogostosti izmerjenih razdalj med na-novo zabeleženimi populacijami v letu 2019 in njim najbližjimi populacijami, zabeleženimi v letu 2018, s ciljem ugotavljanja dinamike širjenja žlezave nedotike v obdobju 2018-2019.

Accompanying flora, statistical and ecological analysis

Inventory of Himalayan balsam's accompanying flora resulted in presence of 238 other plant taxa. Identification was to the species-level, unless specimens were unreachable or underdeveloped. On average, there were 11 other taxa in communities beside Himalayan balsam, whereas the maximum number was 53. Five of the most common accompanying species were European dewberry *Rubus caesius* L. (on 250 locations), common nettle *Urtica dioica* L. (221), cock's-foot *Dactylis glomerata* L. [s.str.] (200), giant goldenrod *Solidago gigantea* Aiton (139) and large-flowered hemp-nettle *Galeopsis speciosa* Mill. (114). The most common woody species were common alder *Alnus glutinosa* (L.) Gaertn. (93), white willow *Salix alba* L. (76), European ash *Fraxinus excelsior* L. (49), brittle willow *Salix fragilis* L. (36), goat willow *Salix caprea* L. (17) and black poplar *Populus nigra* L. (14). Alongside Himalayan balsam, on 285 of its stands (52 % in total), at least one of 26 other alien plants species was present (27 taxa, if we include inconclusively determined goldenrods, due to inacessibility). Apart from the already mentioned *S. gigantea* – which was the most common allochthonous species, other significantly abundant alien plants were Canadian goldenrod *S. canadensis* L. (80), small balsam *Impatiens parviflora* DC. (62), Japanese knotweed *Fallopia japonica* (Houtt.) Ronse Decr. (56) and annual fleabane *Erigeron annuus* (L.) Pers. (52).

Ecological analysis of Himalayan balsam's accompanying flora showed that average values of four of the observed environmental variables (temperature, pH reaction, light, and nutrients) were approximate to the given theoretical optimum (Ellenberg-type ecological indicator value) of Himalayan balsam for each variable (according to Chytrý et al., 2018), as seen in Tab. 1 below. Values for temperature and pH reaction had the lowest variance of all the results (0.45 in both cases), whereas the variance was the highest for moisture (2.15). In Tab. 1 are also presented values of Ellenberg-type indicator values for entire flora of Ljubljana Marsh.

Table 1: Analysis of Ellenberg-type indicator values for temperature, pH reaction, light, nutrients, and moisture, for Himalayan balsam's accompanying flora and Ljubljana Marsh flora (Jogan et al., 2001), following Chytrý et al. (2018). Corresponding values of Himalayan balsam are highlighted with an asterisk (*).

Tabela 1: Analiza modificiranih Ellenbergovih indikatorskih vrednosti za temperaturo, pH reakcijo, svetlobo, količino hranil in vlago v spremljevalni flori žlezave nedotike na Ljubljanskem barju in za celotno floro Ljubljanskega barja (Jogan in sod., 2001), prirejena po Chytrý in sod. (2018). Vrednosti za žlezavo nedotiko so v preglednici označene z zvezdico (*).

Short description of Ellenberg-type indicator values for temperature	**Himalayan balsam's accompanying flora**		**Ljubljana Marsh flora**	
	Numerus of observations	Percentage (%)	Numerus of observations	Percentage (%)
1 – cold indicator (alpine and nival belt)	0	0	0	0
2 – between 1 and 3	0	0	0	0
3 – cool indicator (mostly in subalpine areas)	0	0	5	0.6
4 – between 3 and 5	0	0	55	6.9
5 – moderate heat indicator	41	59.4	321	39.9
6* – between 5 and 7 (lowland and colline species)	23	33.3	323	40.2
7 – heat indicator	4	5.8	83	10.3

8 – between 7 and 9	1	1.5	16	2.0
9 – extreme heat indicator	0	0	1	0.1
Average value	5.5	/	5.5	/
Variance	0.45	/	0.74	/

Short description of Ellenberg-type indicator values for pH reaction	**Himalayan balsam's accompanying flora**		**Ljubljana Marsh flora**	
	Numerus of observations	Percentage (%)	Numerus of observations	Percentage (%)
1 – indicator of strong acidity	0	0	4	0.5
2 – between 1 and 3	0	0	12	1.5
3 – acidity indicator	0	0	29	3.6
4 – between 3 and 5	1	1.4	48	6.0
5 – indicator of moderate acidity	3	4.4	74	9.2
6 – between 5 and 7	32	46.4	205	25.5
7* – indicator of slightly acidic to slightly basic conditions	32	46.4	325	40.4
8 – between 7 and 9	1	1.4	104	12.9
9 – base and lime indicator	0	0	3	0.4
Average value	6,4	/	6.2	
Variance	0.45	/	1.9	

Short description of Ellenberg-type indicator values for light	**Himalayan balsam's accompanying flora**		**Ljubljana Marsh flora**	
	Numerus of observations	Percentage (%)	Numerus of observations	Percentage
1 – deep shade plants	0	0	0	0
2 – between 1 and 3	0	0	2	0.2
3 – shade plant	0	0	29	3.6
4 – between 3 and 5	5	7.3	68	8.5
5 – semi-shade plant	7	10.1	66	8.2
6* – between 5 and 7	19	27.5	151	18.8
7 – half-light plant	32	46.4	296	36.8
8 – light plant	6	8.7	164	20.4
9 – full light plant	0	0	28	3.5
Average value for accomp. flora	6.4	/	6.5	
Variance	1.06	/	2.02	

Short description of Ellenberg-type indicator values for nutrients	**Himalayan balsam's accompanying flora**		**Ljubljana Marsh flora**	
	Numerus of observations	Percentage (%)	Numerus of observations	Percentage (%)
1 – occurring on nutrient-poorest sites	0	0	5	0.6
2 – between 1 and 3	0	0	57	7.1
3 – occurring on nutrient-poor sites more frequently than at average sites	0	0	112	13.9
4 – between 3 and 5	2	2.9	109	13.6
5 – occurring at moderately nutrient-rich sites	10	14.5	141	17.5
6 – between 5 and 7	20	29.0	180	22.4
7* – occurring at nutrient-rich sites more often than on average sites	25	36.2	141	17.5
8 – pronounced nutrient indicator	11	15.9	55	6.8
9 – concentrated at very nutrient-rich sites	1	1.5	4	0.5
Average value for accomp. flora	6.5	/	5.1	
Variance	1.13	/	3.03	

Short description of Ellenberg-type indicator values for moisture	**Himalayan balsam's accompanying flora**		**Ljubljana Marsh flora**	
	Numerus of observations	Percentage (%)	Numerus of observations	Percentage (%)
1 – strong drought indicator	0	0	1	0.1
2 – between 1 and 3	0	0	7	0.9
3 – missing on damp soil	1	1.45	64	8.0
4 – between 3 and 5	6	8.7	165	20.5
5 – indicator of average moisture and fresh soils	25	36.2	225	28.0
6 – between 5 and 7	16	23.2	105	13.0
7 – humidity indicator	5	7.3	53	6.6
8* – between 7 and 9	13	18.8	69	8.6
9 – wetness indicator	2	2.9	64	8.0
10 – aquatic plant which survives long periods without flooding	1	1.45	25	3.1
11 – aquatic plant rooted under water	0	0	10	1.2
12 – (almost) permanently submerged aquatic plant	0	0	16	2.0
Average value for accomp. flora	6.0	/	5.8	
Variance	2.15	/	4.6	

Values for Himalayan balsam's accompanying flora from Tab. 1 are summarized graphically on box and whisker plot, seen on Fig. 3.

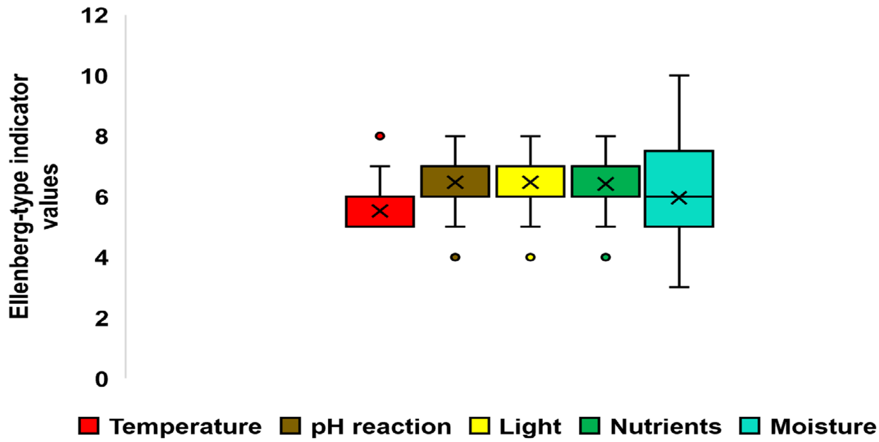

Figure 3: Ellenberg-type indicator values of Himalayan balsam's accompanying flora on Ljubljana Marsh, shown with outliers for each ecological condition. x represents average value.
Slika 3: Ellenbergove indikatorske vrednosti za spremljevalno floro žlezave nedotike na Ljubljanskem barju, s prikazom odstopajojočih vrednosti. x predstavlja povprečno vrednost.

Similarly, for accompanying flora, variance across Ljubljana Marsh flora dataset was the highest for moisture, but the difference between average values between accompanying flora and entire dataset was the highest for nutrients (Tab. 1 above). Comparisons between observed values of Ellenberg-type indicator factors for accompanying flora and Ljubljana Marsh flora are shown graphically on box and whisker plot below, on Fig. 4., showing that the species primarily fell into middle, mesophilic range for many conditions on large-scale area, except regarding nutrients.

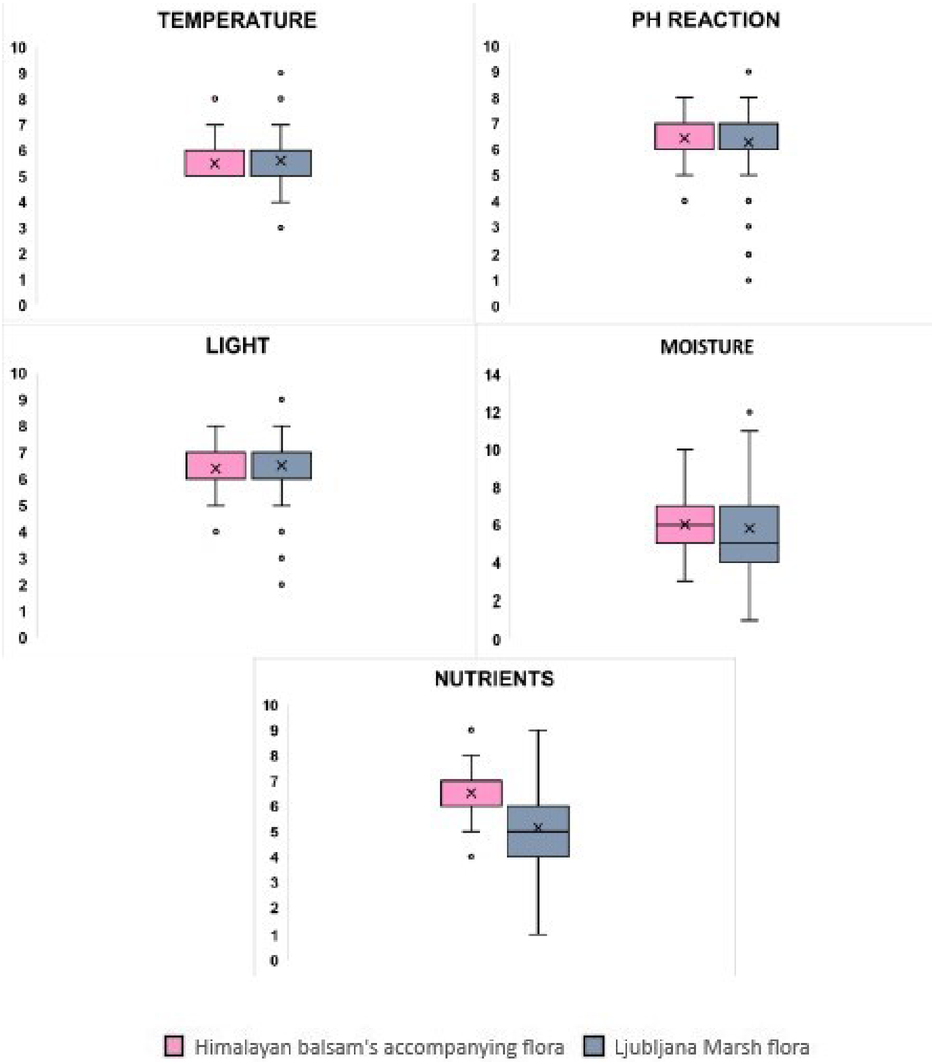

Figure 4: Box and whisker plots with comparisons between Ellenberg-type indicator values for temperature, pH reaction, light, nutrients and moisture between Himalayan balsam's accompanying flora and Ljubljana Marsh flora. x represents average value.

Slika 4: Grafična primerjava Ellenbergovih modificiranih indikatorskih vrednosti za temperaturo, pH, svetlobo, nutriente in vlago med spremljevalno floro žlezave nedotike in floro Ljubljanskega barja.

Analysis of species' potential future spreading, based on existing data on distribution of its accompanying flora has shown that it is highly likely for Himalayan balsam to continue spreading across temperate regions of Slovenia. The only parts which are ecologically unsuitable are Alps, Dinarides (both with higher altitudes) and Sub-Mediterranean region (with higher temperatures and longer summer drought period) (below on Fig. 5).

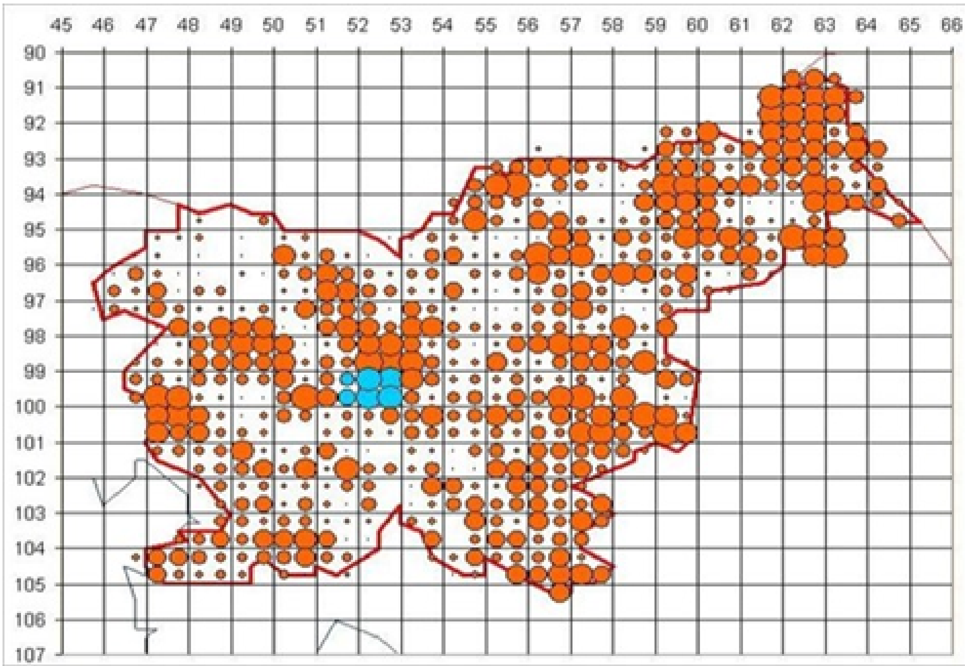

Figure 5: Simplified model of possible Himalayan balsam's distribution in Slovenia, based on distribution of its accompanying flora on Ljubljana Marsh. Color code: blue, area of Ljubljana Marsh; orange, predicted distribution.

Slika 5: Poenostavljen model predvidenega areala žlezave nedotike v Sloveniji, narejen na podlagi razširjenosti spremljevalne flore vrste na Ljubljanskem barju. Barvna shema: modro, območje Ljubljanskega barja; oranžno, predviden ustrezen areal vrste v prihodnosti.

Eradication expenses

According to our calculations (Tab. 2), expenses for eradication on the entire area would run around 20.000 EUR per year. Eradication on accessible localities costs less since they would – theoretically - require only machine work. In our case, that cost was estimated approximately to 3.300 EUR, evaluated as number of accessible sites (330), multiplied by hypothetical wage of 10 EUR/h. Larger effort and budget will be needed for eradication of the inaccessible populations hidden in deep drainage ditches, on steep banks, in thickets, below hedgerows and on private properties, which would require manual processing and therefore. Final costs depend on stands' sizes and density - number of individuals that need to be pulled out, cut down and properly handled. Combining different possibilities of sizes (minimum, minimum and maximum and just maximum sizes), expected prices range from ~ 5.000 EUR to ~ 50.000 EUR, which are both extremes with smallest possible and highest possible number of individuals included. Intermediate value, with the highest probability of combination of smaller and bigger populations (as observed on field), comes to a price point of 16.000 EUR, which combined with mechanical work, gives a final estimate of ~ 20.000 EUR per year. If the first-year eradication approach was proven as effective, repetition of the same approach in the consecutive years would be less expensive and after about 6 years, when the soil seedbank of existing populations would be exhausted, only regular monitoring of sites and hand pulling of individual plants (when needed) would suffice.

Table 2: Himalayan balsam's eradication expenses' estimation for Ljubljana Marsh, calculated on the basis of field results from 2019, by methodology explained in Methods.
Tabela 2: Ocena stroškov odstranjevanja žlezave nedotike na Ljubljanskem barju, narejena na podlagi rezultatov terenske študiji po metodologiji opisani v zgornjem delu besedila, v poglavju Metod.

Stands classification by size classes and accessibility					
Stand size classes	**Number of accessible stands**	**Number of partially accessible stands**	**Number of inaccessible stands**	**∑ of stands by size classes**	
1-10	97	9	46	152	
10-100	151	13	59	223	
100-1000	58	34	30	122	
Over 1000	27	14	10	51	
	333	70	145	548	
x10 EUR/h	3330				
	∑ partially accessible and inaccessible stands	Minimum sizes of stands considered in calculations	Min. and max. stand sizes combined in calculations	Min. and max. stand sizes combined (2) in calculations	Maximum stand sizes considered in calculations
1-10	55	550	550	550	550
10-100	72	720	7200	7200	720
100-1000	64	6400	6400	64000	64000
Over 1000	24	24000	24000	24000	240000
∑	215	31670	38150	95750	311750
	In hours	527.83	635.83	1595.83	5195.83
	x10 EUR/h	5278.33	6358.33	15958.3	51958.3
	Total estimated cost in EUR (+ acc.)	8608.33	9688.33	19288.33	55288.33

Discussion

Spreading dynamic and species' ecology

Scattered distribution of Himalayan balsam in the given area is very likely a result of many circumstances, such as area's geographical and hydrological structure, complex conservational system, intensive agriculture, and several other human activities. Dominance of point-type stands is not surprising, since those included an array of different sized stands, including either handful of individuals or up to 1000. Those smaller stands were found in a range of different habitats - predominantly dispersed alongside the roads, but were also located in fields, meadows, by the forest edges or along the waters. Linear and polygon-type stands were mostly located on larger, often less accessible areas, such as alongside drainage ditches, where linear stands were predominant, or on abandoned fields or properties, dominated by polygon-type stands with over 1000 individuals. Those are likely older stands, which successfully maintain their size by local spreading. Between the two seasons, Himalayan balsam has spread across the Ljubljana Marsh only moderately and to relatively short distances: mostly up to 150 meters away of existing populations, what confirms its hypothesised successful spreading capabilities by water only partially. Based on our results and our field observations, we assume that water bodies of Ljubljana Marsh are not the main vector of species' spreading on chosen area. Firstly, there were only few populations located near the biggest water course - river Ljubljanica, while the rest were mostly found by the streams or along ditches. Secondly, their main hydrological characteristic: slow water flow due to minimum elevation differences, could not carry out long-distance spreading as seen in some other studies (Perrins et al. 1993), which report on spreading dynamics in British Isles of 38 km/year. We did confirm successful short distance spreading in the nearby area of the parent plants, which reaches up to 7 meters by the ballistochory mechanism (Balogh 2008). The main spreading mechanism in these instances was more effective than just ballistochory, but situation is not clear-cut. We can assume that various anthropogenic factors on Ljubljana Marsh have had a significant role in species' spreading, along with limited hydrochory. Thus, we presume that the primary role of water bodies in drainage ditch network of Ljubljana Marsh might be maintenance of local populations, by enabling favourable moist conditions, regular opening of bare soils due to ditch maintenance and reduced accessibility for the agricultural activities (mowing, pasturing, trampling). Čuda et al. (2014) hypothesized that existence of Himalayan balsam in riparian zones represents an evolutionary adaptation which would reinforce the hydrochory. Our results cannot confirm that either. Another note was the absence of typical winter floods in given period. Floods were reportedly mentioned as a contributing factor in invasiveness of the species (Čuda et al. 2017a). For additional insight into spreading dynamic, we checked Flood Warning map of Ljubljana Marsh (data from Slovenian INSPIRE metadata system, 2022). The southwest part of Ljubljana Marsh is the one primarily exposed to regular flooding (Fig. 6), Himalayan balsam is mostly absent there, as seen in Fig. 1, except for parts of Podplešivica and some parts of Notranje Gorice and Vnanje Gorice. Hereof, we conclude that hydrochory should not be considered as the main pathway in spreading of given species on Ljubljana Marsh, especially in such short time interval. Further research, which would incorporate the possible impact of flooding, is therefore highly appreciated.

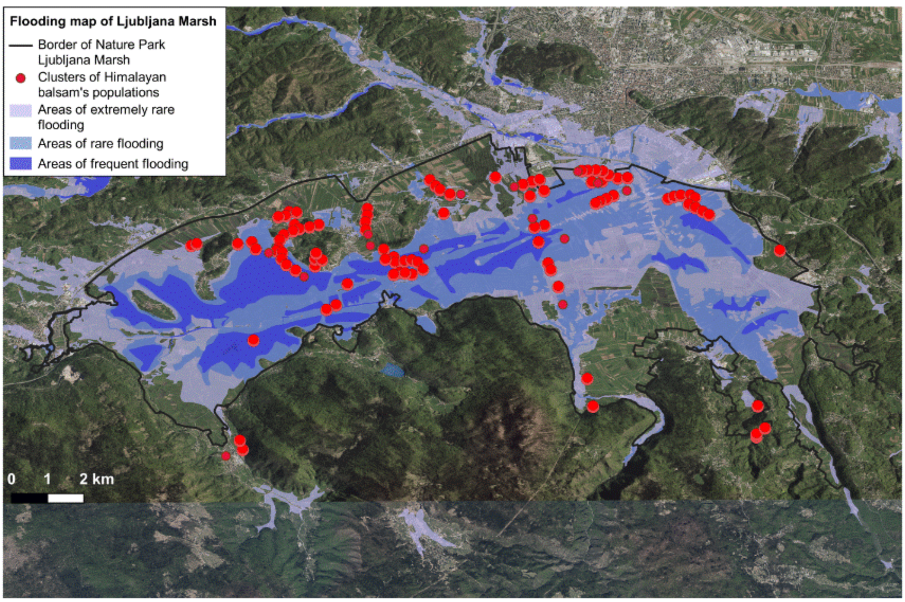

Figure 6: Flooding areas of Ljubljana Marsh (bordered with black line), which are divided into areas of extremely rare flooding (lightest blue on map), which include floods with return period of 50 years and more, areas of rare flooding (medium blue on map), which include floods with return period between 10 and 20 years, and areas of frequent flooding (darkest blue on map), which include floods with return period of 2 to 5 years. GIS layers and correspoding legend descriptions are found at publicly available server of Slovenian INSPIRE metadata system, as Flood warning map (2022). Red points represent clusters of Himalayan balsam's populations found at Ljubljana Marsh, grouped by built-in function Point Cluster in QGIS 3.18.1.

Slika 6: Območja poplavljanja na Ljubljanskem barju (omejeno s črno linijo), razdeljena v območja zelo redkih poplav (svetlo modra na karti), ki vključujejo poplave s povratno dobo 50 ali več let, območja redkih poplav (srednje temno modra na karti), ki vključujejo poplave s povratno dobo od 10 do 20 let, ter območja pogostih poplav, ki vključujejo poplave s povratno dobo od 2 do 5 let. Uporabljene GIS datoteke in njihovi opisi so dostopni na spletni strani Slovenskega INSPIRE metapodatkovnega sistema, v zavihku Opozorilna karta poplav (2022). Rdeče pike na karti predstavljajo grupirane populacije žlezave nedotike, narejene s pomočjo sistemske funkcije Point Cluster v programu QGIS 3.18.1.

Accompanying flora was similar to the literature reports (Hulme and Bremner 2006, Balogh 2008, Diekmann et al. 2016, Kiełtyk and Delimat 2019), simoultaneously very heterogenous and reflective of Ljubljana Marsh's habitat diversity and its degradation. Even though over half (285) of our localities had at least one other alien plant or other elements of neophytic vegetation, on 263 localities Himalayan balsam was the only one. Those were usually the ditches with native riparian vegetation, most commonly willow thickets and occasional alder communities. Adequate ecological conditions allowed the Himalayan balsam to competitively exclude and supress native riparian forest vegetation, since black poplar, white willow and crack willow appeared to be ecologically most similar species to Himalayan balsam (see Chytrý et al. 2018). Those ecosystems have a crucial role as pionneers in the progressive succession of riparian forests (Garófano-Gómez et al. 2017), but due to their heavy invasion by alien species on entirety of Ljubljana Marsh, those natural processes seem to be significantly disturbed. Our observations and results therefore put focus on disturbance of riparian zones as the potentially biggest negative impact caused by Himalayan balsam on Ljubljana Marsh. Based on the results of robust ecological analysis of indicator values, we suggest that Himalayan balsam should be observed as a species with somewhat broader ecological niche than the one usually ascribed to it. Most surprising variation from its ecological optimum was for moisture, with accompanying flora's average resulting in 6.0. If we look at values of entire Ljubljana Marsh area and compare them with accompanying flora of Himalayan balsam, we see that Himalayan balsam falls into average ecological values of area, with a possibility of realized ecological niche profiling into its alleged nitrophily, since micro-sites where Himalayan balsam grew were by the results of indicator values analysis more suitable for nitrophilous species (averages 6.5 and 5.1, respectively). Those results were probably influenced by large presence of *Urtica dioica*, the second most common species in accompanying flora and only true nitrophilous species, with EV 9. Even though its accompanying flora didn't reflect hidrophily *per se* (with average value of 6.1 and theoretical optimum of 8), there were small differences between its stands and entire area (averages 6.0 and 5.8), hinting that it grows at areas slightly more hydrophilous than the entire area.

Species is probably more tolerant to moderate variations of ecological conditions and capable of surviving in different habitats, co-existing with a range of different species, what Bieberich et al. (2020) list as one of crucial traits which determine the success of invader. As an example, we point out Himalayan balsam's road populations. Even though those stands were usually smaller in size, species is obviously capable of existence in sites which are by default more open, bright and dry than the expected species' ecological optimum (see Chytrý et al. 2018). Accompanying flora at those sites consisted of different ruderal grasses, such as *Lolium perenne* L., *Setaria pumila* (Poir.) Roem. & Schult., *Setaria viridis* (L.) PB., *Panicum capillare* L. and *Digitaria sanguinalis* (L.) Scop., or ruderals like *Cichorium intybus* L. On the other hand, light and/or dryness weren't shown as possible limiting factors when stands were found in an optimum regarding water and/or nutrients, for example along ditches on an open field, where Himalayan balsam might have compensated exposure to open light with sufficient amount of water from ditches. On arable land, Himalayan balsam's stands probably have a dependable source of nutrients, coming from both water and soil. Thus, our results – at least partially - refute findings of Čuda et al. (2014), which indicate that species avoids fully open sites, but agree with the later study (Čuda et al. 2017a), whose results hint that species successfully grows in open areas, when appropriately supplied with water. Optimal conditions for Himalayan balsam (see Chytrý et al. 2018) can therefore be achieved in micro-ecological sites and niches, what is not unusual for Himalayan balsam (see Bieberich et al. 2020 – different approach with a similar final result). In those (relatively) optimal conditions, negative impact of species could come to its peak.

Eradication suggestions

For successful supression of Himalayan balsam's further invasion, we suggest regular and proper eradication, followed by continuous monitoring. Proper eradication methodology is mostly dependent on knowledge of species' phenology, so it is important to choose the right moment for the first summer eradication. In this case, it would be recommended to start in July. If we start priorly, we risk the re-establishment of the population from seeds or by resprouting. If we start later - towards the fall season, we might assist in the seed spreading from ripe capsules whilst handling the plants. Therefore, we suggest one removal in July and one later in the season, to remove potentially regenerated individuals (Hartmann et al. 1995). Skalová et al. (2019) have confirmed the viability of seed bank lasting up to 4 years, so we highly suggest the continuation of proper monitoring and prospective repeated removal in 4-year period at shortest, preferrably longer, since there are also reports on seed viability after 6 years (Schuldes 1995). With regular removal and control, eradication costs (proposed in Results) will probably decrease in the consecutive years. To terminate the invasion process, we must also prevent further importation and re-introduction, which in case of Himalayan balsam would be prohibition of horticultural and beekeeping usage.

Conclusions

This study has confirmed the importance of context-dependence in research field of invasion ecology. Despite great number of studies on Himalayan balsam (*Impatiens glandulifera*), species is still somehow overlooked and trivialized. On Ljubljana Marsh, Himalayan balsam has shown more ecological plasticity than usually considered, surviving in wider range of mesophilic conditions which deviate from its theoretical optimum – moist, fertile and shady places. As long as any of species' critically impactful ecological conditions – light, moisture and nutrients – are at least near its theoretical optimum, deviations of other ecological conditions don't pose as the limiting factor in species' persistance, especially regarding moisture. We have found that species doesn't spread as drastically by water bodies on Ljubljana Marsh in two consecutive seasons as mentioned in other literary sources, meaning that specific hydrology of Ljubljana Marsh cannot contribute to its invasiveness, as other factors – presumably anthropogenic – might. Hydrology of Ljubljana Marsh therefore probably has a role in maintenance of already existing populations and spreading dynamics is not the basis of species' invasiveness in given circumstances. We propose competitive exclusion of native riparian vegetation as the main mechanism of species invasiveness, along with flexibility and adaptability to wide range of ecological conditions. As species of Union concern, Himalayan balsam should be regularly eradicated and monitored at adequate period, dependent on its phenology. At chosen site, in approximately five-year period, species can be successfully controlled with moderate expenses, although prevention of further introductions is crucial.

Povzetek

Biološke invazije so, zaradi negativnega vpliva na biotsko pestrost in ekosistemske storitve eden izmed največjih izzivov, s katerimi se soočajo sodobno naravovarstvo, družba in gospodarstvo. Zaradi velike raznolikosti tujerodnih vrst, povzročajo tudi različne vplive v različnih ekosistemih, kar je odvisno od njihovih bioloških lastnosti, vitalnosti in odpornosti avtohtonih združb. V tem članku so predstavljeni rezultati terenske študije z Ljubljanskega barja iz leta 2019, ko smo primerjali stanje populacij žlezave nedotike (*Impatiens glandulifera*) med letoma 2018 in 2019. Glede na to, da se v literaturi pogosto poudarja sposobnost hitrega širjenja te vrste z vodami, smo predvsem vzdolž vodotokov pričakovali velike razlike stanja populacij med dvema sezonama. Izkazalo

pa se je, da hidrološke in poplavne razmere na Ljubljanskem barju ne omogočajo hitrega širjenja žlezave nedotike, ker med dvema sezonama ni bilo izrazitih razlik. Rezultatov tujih študij razširjanja žlezave nedotike ob hitro tekočih vodah torej ne moremo preprosto uporabiti pri napovedovanju širjenja ob počasi tekočih ali skoraj stoječih voda Barja. Za te se je v študiji pokazalo, da imajo predvsem pomen v vzdrževanju primernih razmer za obstoj populacij nedotike. Ta študija nam je pokazala, da je vrsta ekološko bolj plastična, kot si jo morebiti predstavljamo iz posplošenih navedb iz literaturnih virov, ki jo praviloma obravnavajo kot vlagoljubno, sencoljubno in nitrofilno. Vse dokler je vsaj eden izmed kritičnih okoljskih dejavnikov (svetloba, hranila in vlaga) zunaj pesimuma ali vsaj blizu optimuma, drugi okoljski dejavniki za vrsto očitno niso izrazito omejujoči. Zaradi velikega števila spremljevalnih drugih tujerodnih vrst na rastiščih nedotike in splošnega degradiranega stanja Ljubljanskega barja tudi ni bilo mogoče govoriti o konkretnem vplivu žlezave nedotike na ta ekosistem, vendar naši rezultati kažejo, da vrsta vrhunec svoje invazivnosti kaže v obrežnih gozdovih vrbe in jelše, kjer kompetitivno izključuje avtohtono obrežno floro in moti naravni tok sukcesije. Ker so rezultati naše in drugih študij o žlezavi nedotiki dokaj raznoliki, poudarjamo pomen vsake individualne in primerjalne raziskave. Le tako bomo lažje razumeli biologijo teh vrst v širšem kontekstu, kar je izjemno pomembno pri raziskavah invazivnih tujerodnih vrst v raznolikem in zanje novem okolju, kar nam bo kot biologom omogočilo zaznati ključne momente biologije posamezne invazivne vrste, na katere bomo lahko oprli naravovarstvene ukrepe.

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