

Distribution and pathways of introduction of invasive alien plant species in Romania

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Abstract

Biological invasions are one of the main drivers of modern human-induced species losses. Research on the distribution of alien species and their pathways of introduction is essential for understanding and tackling the invasion process. A comprehensive overview on invasive alien plant (IAP) species in Romania is lacking. With this paper, we aim to contribute to filling this gap and to provide a visualization of national patterns regarding plant species invasions, geographical origins and pathways of introductions. Based on plant species occurrence records in the published literature and herbaria we compiled a national database of 102 invasive and potentially invasive alien plant species. We georeferenced 42776 IAP species occurrences and performed an analysis of their spatial patterns. The spatial analyses revealed a biased sampling, with clear hotspots of increased sampling efforts around urban areas. We used chord diagrams to visualize the pathway of introduction and geographical origins of the IAP species, which revealed that species in Romania originate mainly in North and Central America, while the dominant pathway of plant introduction was horticulture. Our results provide an important baseline in drafting management and action plans, as invasive alien plant species represent a priority for the European Union through the Biodiversity Strategy for 2030, and a good starting point for various analyses as the database is further developed and regularly updated.

Keywords

Hotspot analysis, introduction pathways, national database, occurrence records, plant invasion, species richness

Introduction

Biological invasions are one of the main drivers of modern human-induced species losses (Li et al. 2016; Essl et al. 2020; Pyšek et al. 2020; Seebens et al. 2021). The establishment of invasive alien species (IAS) alters habitats, communities and ecosystems' functioning (Hulme 2015; Bellard et al. 2016), the effects ranging from changes in the physio-chemical environment to increasing the risk of disturbances, such as fires, and contributing to the loss of native biodiversity (Ehrenfeld 2010; Schirmel et al. 2016; Catford et al. 2018). In time, many IAS lead to the decline of abundance of native species (Alyokhin and Sewell 2004) or even to local extinctions, especially when the competition for resources is high (Gallardo et al. 2019).

Invasive alien plants (IAPs) can impact the environment in multiple ways (Barney et al. 2013) and contribute to a wide range of impacts on the economy and human well-being (Diagne et al. 2020). Some IAPs have been shown to disrupt community assemblages (Pyšek et al. 2009) or to alter the biogeochemical processes in an area (Ehrenfeld 2003). In agriculture, IAPs can lead to the loss of crops and productive land (Ruiz and Carlton 2003). Furthermore, they can lead to disease outbreaks for people and wildlife (Kumar Rai and Singh 2020). In past decades, the risks associated with invasive species have increased because human activities altering the environment have escalated rapidly (Keller et al. 2011). In Europe alone, the costs associated with damage and control of the IAP species ragweed (*Ambrosia* spp.) and water-primrose (*Ludwigia* spp.) are estimated to be around 20 USD billion (Haubrock et al. 2021). Most costs are supported by agriculture and forestry, as IAPs are considered agricultural or forestry weeds. However, highly allergenic species to humans, such as the ragweed *Ambrosia artemisiifolia*, lead to high medical costs (Richter et al. 2013).

A good practice in reducing the ecological and social-economic impacts of alien species is to prevent their introduction (Keller et al. 2011). To do this, monitoring species movements and their geographic distribution is necessary to understand and track the effects of biological invasions (McGeoch et al. 2012; McGeoch and Latombe 2015). Occurrence databases represent one of the most simple tools to identify and monitor the distribution of alien plants (Latombe et al. 2017). Reports on biodiversity targets and trends in biological invasions have also been developed using lists of alien and invasive alien species with the aim of informing policy (Hulme et al. 2009). Compiling inventories of alien taxa including details on status and distribution are important for biological invasion research. An up-to date inventory represents an essential tool for conducting risk assessments as well as for guiding policy, management and action plans regarding biological invasions (Hulme et al. 2009).

Globally, the emphasis has been put on the identification and analysis of introduction pathways of IAS as a key step for managing invasive species based on the precautionary principle (Pyšek et al. 2011). The main pathways of introduction and transport of alien species are directly or indirectly associated with anthropogenic activities; the species being introduced intentionally (deliberately) or unintentionally (accidentally). The main introduction pathways of IAS are strongly associated with international trade. The intensification and diversification of commercial activities, and the intensification of transports increase the likelihood of introducing IAS on the territory of certain states (Keller et al. 2011). They can be brought as goods subject to trade or transported by chance on a certain type of goods involuntarily (Hulme 2009; Seebens et al. 2017). To address this issue, decision-makers from various institutions identified the need to develop policies to prevent the spread of IAS, focusing on transcontinental transport and trade (Wołkowycki and Banaszuk 2016).

Due to its geographical position in the center of Europe (Rey et al. 2007) and intensive trade with other states, Romania is prone to biological invasions (Anastasiu and Negrean 2007; Sirbu et al. 2011; Skolka and Preda 2011; Preda et al. 2012; Anastasiu et al. 2017; Stanescu et al. 2020; Urziceanu et al. 2020). According to the Biodiversity Strategy for 2030, managing IAPs is a priority for the European Union (European Commission 2020). As a result, Regulation (EU) No. 1143/2014 focuses on invasive alien species and aims to prevent and limit their negative effects on the environment. Despite the urgency of managing biological invasions, current knowledge on the distribution of alien species in Romania is limited. There are several regional or species-specific studies (Sirbu and Oprea 2010; Szatmari 2012; Zimmermann et al. 2015; Kucsicsa et al. 2018); however, a comprehensive database of alien plant species occurrences at national level is lacking. In order to contribute to filling this gap, the present study aims to review the published records of invasive and potentially invasive plant species in Romania and provide an open-access spatial database, including an overview of the main pathways of introduction.

Methods

To compile a database with invasive and potentially invasive plants species in Romania, we conducted an extensive literature review covering the 1778–2018 time-period. We identified almost 800 alien plant species in Romania but selected only a set of species for the current study (see Suppl. material 1: Appendix S1 for a detailed list). Following the terminology used by Richardson et al. (2000) and Pyšek et al. (2004), our selection refers to alien plants considered invasive, i.e., a subset of naturalized plants that have the potential to spread over large areas, or potentially invasive i.e., naturalized and casual alien plants that may become invasive in Romania. The potentially invasive category refers to alien plants that have established self-sustaining populations (i.e., naturalized) or whose presence has been casually recorded in Romania, without forming such populations (i.e., casual) according to Anastasiu and Negrean (2009) and

Sirbu and Oprea (2011b). Nevertheless, having a history of invasiveness in other European countries, the latter category was considered important for detailed assessments by national experts (e.g., based on the input of all academic botanists in the country, covering all university centers), during a workshop aiming at identifying alien species of national concern, as a part of a national program to support the implementation of Regulation (EU) 1143/2014 on invasive alien species. Therefore, invasive and potentially invasive are considered a single group (hereafter IAP species).

Information regarding the occurrence records of alien plant species included in the database was extracted from 1174 published documents, i.e., 980 articles, 150 books, 29 PhD theses, six research reports, six conferences proceedings, and three herbarium data (see Suppl. material 3: Appendix S3 for a detailed list). The occurrence records were checked for taxonomic and geographic quality. The records that could not be georeferenced (e.g., occurrences assigned only to mountain ranges, historical provinces, and hydrographic basins) or records with unspecified taxa within genera, were not included in the current version of database. The species taxonomy considered in the present paper is based on GBIF Backbone Taxonomy (GBIF Secretariat 2021).

For each species included in our database, we added information on taxonomy, the native range and the pathways of introduction according to Sirbu and Oprea (2011a). The introduction pathways were standardized based on the main categories described in the Convention on Biological Diversity (CBD 2014): release in nature, escape from confinement, transport-contaminant, transport-stowaway, corridor, and unaided. Each main category includes several sub-categories. For example, the intentional release of alien species in nature can be due to various reasons such as erosion control and dune stabilization or landscape/flora/fauna “improvement” in the wild. The categories used in this study are detailed in Table 1. Finally, we used a chord diagram (Gu et al. 2014; Turbelin et al. 2017) to visualize the introduction pathways and geographical origin of the alien plant species included in the database.

To aggregate IAP species occurrence records, we followed the approach established by Cogălniceanu et al. (2013). Valid occurrence records were aggregated at a Universal Transverse Mercator (EPSG 9807) spatial resolution of 25 km² (UTM 5 × 5 km) using the UTM index of localities and Google Maps/Google Earth (Alphabet Inc., Santa Clara CA). Georeferenced data points were transferred to ArcGIS 10.3 (ESRI, Redlands CA) and visually inspected for errors.

Spatial patterns in IAP species occurrences were analyzed using spatial autocorrelation of species records per 5 × 5 km grid cell at the national level. We used Global Moran’s I test to evaluate the overall spatial pattern of occurrences reported from Romania (Fortin and Dale 2005). The test indicates if reported occurrences at grid cell level are significantly clustered ($Z > 0$), to random ($Z = 0$) and dispersed ($Z < 0$) across Romania. To assess the local patterns of sampling bias, we used the Getis Ord Gi* spatial statistic. This analysis identifies clusters of occurrence records with values numerically higher than expected by chance within a specified searching distance (Ord and Getis 1995). The distance threshold for the aggregation patterns was set up to 7100 m to include the neighboring eight grid cells for each UTM grid of interest (Cogălniceanu

Table 1. List of abbreviations used to describe the geographical origins of the alien plant species and their pathways of introduction.

| Acronym | Description of acronym |
|--|--|
| <i>Geographical origins</i> | |
| A+P | Asia + Pacific |
| E | Europe |
| M | Mediterranean |
| A N+C | America (North + Central) |
| A S | America (South) |
| T | Tropics |
| A | Americas (North + Central + South) |
| O | Other regions and/or unknown origin |
| <i>Pathways of introduction</i> | |
| RE_eros | RELEASE IN NATURE: Erosion control/ dune stabilization (windbreaks, hedges, ...) |
| RE_land | RELEASE IN NATURE: Landscape/flora/fauna “improvement” in the wild |
| RE_othr | RELEASE IN NATURE: Release in nature for use (other than above, e.g., fur, transport, medical use), or other intentional release |
| ES_agri | ESCAPE FROM CONFINEMENT: Agriculture (including Biofuel feedstocks) |
| ES_fore | ESCAPE FROM CONFINEMENT: Forestry (including afforestation or reforestation) |
| ES_hort | ESCAPE FROM CONFINEMENT: Horticulture, Ornamental purpose other than horticulture |
| ES_faci | ESCAPE FROM CONFINEMENT: Pet/aquarium/terrarium species (including live food for such species), Botanical Garden/zoo/aquaria (excluding domestic aquaria), Research and ex situ breeding (in facilities) |
| ES_othr | ESCAPE FROM CONFINEMENT: Other escape from confinement |
| TR_habi | TRANSPORT CONTAMINANT: Transportation of habitat material (soil, vegetation, ...) |
| TR_seed | TRANSPORT - CONTAMINANT: Seed contaminant |
| TR_mult | TRANSPORT - STOWAWAY: Vehicles (car, train, ...), Ship/boat ballast water or other means of transport |
| UN_intr | UNAIDED: Interconnected waterways/basins/seas |
| UN_natu | UNAIDED: Natural dispersal across borders of invasive alien species that have been introduced through pathways 1 to 5 |

et al. 2013). The Getis Ord Gi* test returns a Z-score for every cell, which, depending on the level of aggregation, describes spatial clusters of high or low sampling effort. We identified clusters of grid cells where the sampling effort was significantly higher (hot-spots of occurrence, GiZScore > 1.96) or lower (cold spots of occurrence, GiZScore < 1.96). IAP species richness was mapped at a spatial resolution of 50 × 50 km UTM grid cells. Aggregating species richness at a coarser resolution reduced the potential bias in sampling effort and allowed for a better understanding and visualization of regional patterns (Graham and Hijmans 2006).

The altitudinal distribution of each species was assessed by extracting the range and mean altitude per grid cell from the SRTM digital topographic database (Jarvis et al. 2008) using ArcGIS Desktop Zonal Statistics geoprocessing tool. Due to the size of grid cell (25 km²), the altitudinal distribution of a given record might be over- or underestimated. Grid cells intersecting the Romanian border were excluded from the analysis.

The data underpinning the analysis reported in this paper are deposited at GBIF, the Global Biodiversity Information Facility, and are available at <https://doi.org/10.15468/gg846v>.

Results

Distribution and taxonomy of invasive and potentially invasive alien plant species in Romania

Following the extensive literature review, we identified 102 alien plant species to be included in the invasive or potentially invasive categories, as described in the Methods section (invasive, naturalised, casual cf. Richardson et al. 2000; Pyšek et al. 2004; Anastasiu and Negrean 2009; Sirbu and Oprea 2011b). The rate of accumulation of IAP species occurrence records shows a slow increase between 1778 and 1940s, with peaks in 1866 (29 occurrences) and 1898 (25 occurrences), followed by a steady increase with a maximum in 2009 (82 occurrences) (Fig. 1). Regarding the new IAP species discovered in Romania, we observed a maximum of nine new plant species reported in 1816, followed by seven new plant species reported in 1866 (Fig. 2). In the 20th century, the data in the literature indicates a maximum of four new alien species recorded per year in the 1950s and one species per year in the 2000s.

The documented IAP species cover 41 families, with most species belonging to Asteraceae (23%), followed by Amaranthaceae (12%), Poaceae (6%) and Fabaceae (5% of species) families. Eight species in our database had more than 1000 occurrence records each (i.e., *Erigeron canadensis*, *Erigeron annuus* subsp. *annuus*, *Ambrosia artemisiifolia*, *Amaranthus retroflexus*, *Xanthium orientale* subsp. *italicum*, *Robinia pseudoacacia*, *Galinsoga parviflora*, and *Xanthium spinosum*), while eight species had less than ten occurrence records (i.e., *Verbesina encelioides*, *Grindelia squarrosa*, *Ambrosia tenuifolia* – previously

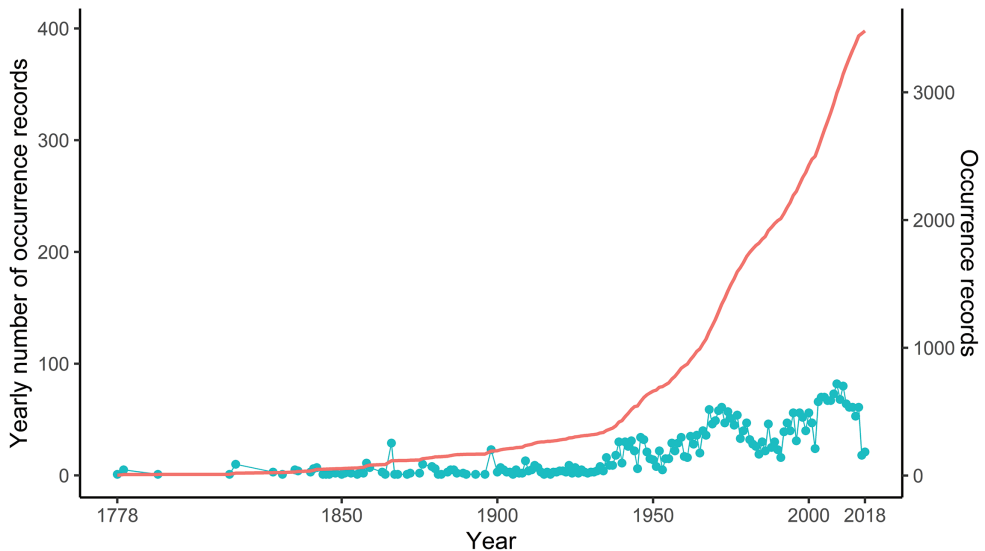


Figure 1. Yearly number of invasive and potentially invasive alien plant species occurrence records reported from Romania (blue) and accumulation of occurrence records (red).

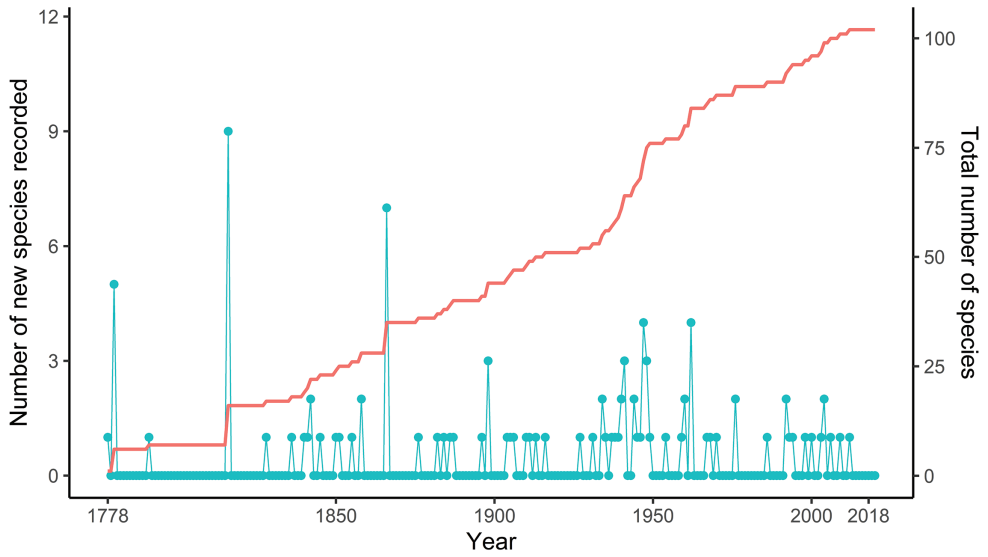


Figure 2. Number of new invasive and potentially invasive alien plant species reported during the 1778–2018 period from Romania (blue) and accumulation of species (red).

erroneously reported as *Ambrosia psilostachya*, according to Karrer et al. (2021), *Heracleum sosnowskyi*, *Heracleum mantegazzianum*, *Cabomba caroliniana*, *Myriophyllum aquaticum*, *Rhaponticum repens*). Most occurrence records were registered for species belonging to the Asteraceae family (see Suppl. material 1: Appendix S1 for a detailed list).

Furthermore, eight of the IAP species whose presence was recorded in Romania up to (and including) 2018, are listed as invasive alien species of Union concern according to the Regulation (EU) No. 1143/2014 of the European Parliament and of the Council (i.e., *Ailanthus altissima*, *Asclepias syriaca*, *Cabomba caroliniana*, *Elodea nuttallii*, *Heracleum sosnowskyi*, *Humulus japonicus*, *Impatiens glandulifera* and *Myriophyllum aquaticum*). *Cabomba caroliniana* and *Myriophyllum aquaticum* were reported from one location, a Nature 2000 site, the thermal lake Peța in Bihor County (the western part of Romania), currently without water. Only one record of *Heracleum sosnowskyi* in the wild was available from the literature, but recent field work efforts confirmed the presence of the species.

The current version of the database includes 42776 occurrence records belonging to 102 taxa. The altitudinal range of IAP species recorded in Romania (average altitude in 25 km² grid) varied between 0 and 2288 m. Only eight IAP species (e.g., *Bidens frondosa*, *Erigeron canadensis*, *Erigeron annuus* subsp. *annuus*, *Galinsoga quadriradiata*, *Impatiens parviflora*, *Juncus tenuis*, *Robinia pseudoacacia* and *Rudbeckia laciniata*) occur in grid cells with average altitude above 2000 m, while most species were recorded in grid cells with average altitude between 0 and 500 m (Fig. 3). The number of IAP species decreased with increasing altitude, the correlation being negative and statistically significant ($r = -0.099$, $p < .000$).

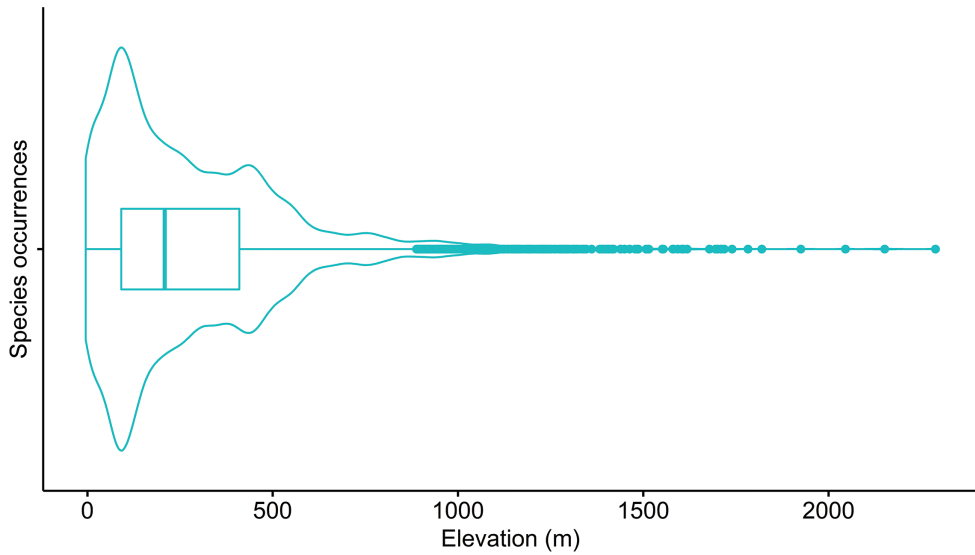


Figure 3. Altitudinal range of IAP species recorded in Romania (mean altitude of UTM 5 × 5 km grid cell). Box = interquartile range, horizontal line = median, whiskers = 1.5 × interquartile range, points = outliers, the vertical width of violin = density of the data.

Spatial patterns in invasive and potentially invasive alien plant species occurrences

Almost half (47%, i.e., 4764 grid cells) of the 9978 UTM 5 × 5 km grid cells covering the Romanian territory include reports of IAP species sightings. Global Moran's I test revealed a clustered pattern in the number of IAP species ($Z = 30.50$, $p < 0.001$) and of species occurrences ($Z > 1.96$, $p < 0.05$) per UTM 5 × 5 grid cell, thus suggesting a strong bias in the sampling effort at national level.

Results of the Getis Ord Gi* spatial statistic revealed three hotspots of recorded IAP species. We observed a strong clustering of records in cities and surroundings (e.g., Iasi, Sibiu, Bucharest, Cluj-Napoca, Zalau, Constanta and Galati). Among these hotspots, the highest sampling effort was recorded in Iasi city and its surrounding area (mean $Z = 24.17$), followed by Bucharest (mean $Z = 12.71$) and Sibiu (mean $Z = 12.40$) (Fig. 4). Additionally, there are several smaller hotspots in Salaj County (in the northwestern part of Romania), in Vaslui and Galati counties (the eastern part of Romania), and around the cities of Cluj-Napoca (in the western part of Romania) and Constanta (southeastern Romania).

Species richness aggregated at a 5 × 5 km grid, ranged from 2 to 59 species. The highest number of IAP species was recorded around cities, namely Bucharest, Iasi, and Sibiu (59 species per grid cell), followed by Cluj-Napoca (55 species per grid cell), Constanta and Sulina (53 species per grid cell) (Fig. 5). Most of the grid cells with high IAP species richness recorded are concentrated in particular regions of Romania i.e., the eastern part (e.g., Iasi, Vaslui, Galati and Neamt counties), the center (e.g., Sibiu County), northwest (e.g., Salaj County), and the southern part of Romania (Bucha-

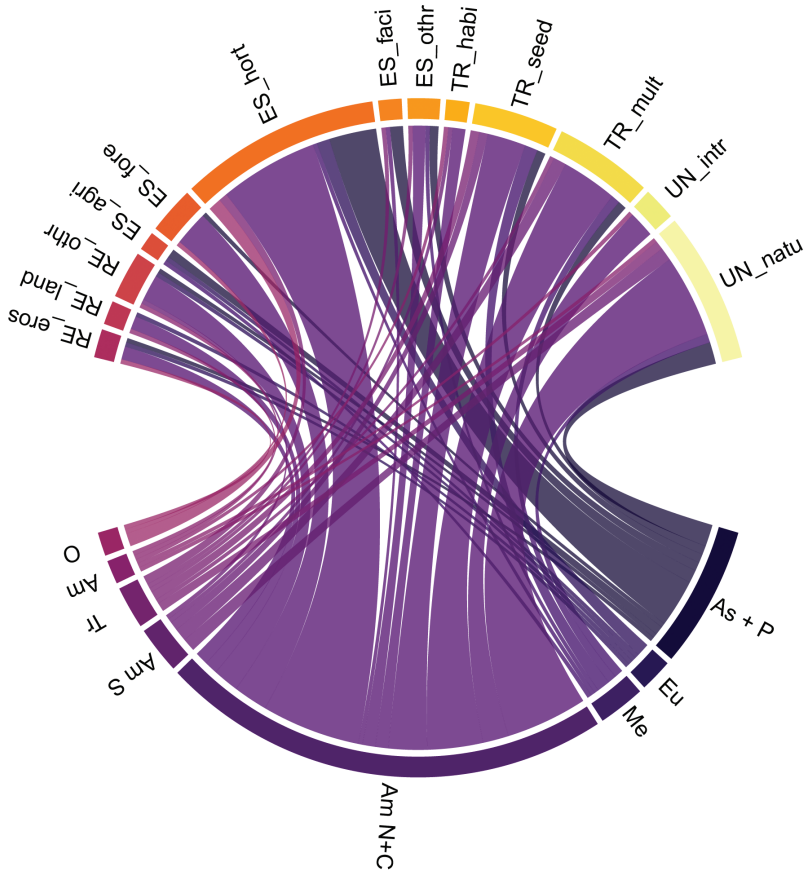


Figure 4. Hotspots of invasive and potentially invasive alien plant species sampling in Romania (in red). The p-value was < 0.05 when Z scores took values between 1.96 and 33.87, suggesting a highly clustered pattern in the number of IAP species occurrences per UTM 5×5 km grid cell.

rest), suggesting a more intensive sampling of IAP species when compared to other regions. Grid cells with low richness values are mostly distributed in the southern and western parts of the country, reflecting an under sampling of IAP species. When represented at a lower spatial resolution (50×50 km), IAP species richness ranged from 3 to 70 species per grid cell (Fig. 6). The same patterns can be observed on the map, lower IAP species richness in the southern and western parts of the country and higher in the eastern and central parts of Romania.

Geographical origins and pathways of introduction

The analysis on the pathways of introduction and the geographical origins of the IAP species is illustrated in Fig. 7 (see Table 1 for abbreviations). For example, the introduction pathway Escape from confinement – Forestry (ES_fore) contributed to the

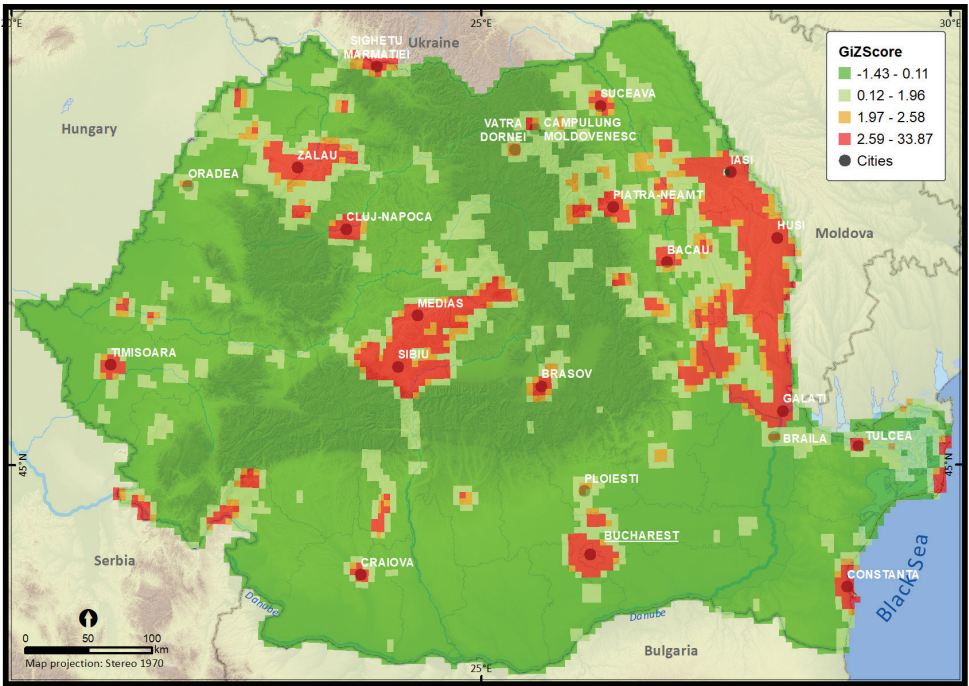


Figure 5. Invasive and potentially invasive alien plant species richness in Romania (5 × 5 km grid resolution).

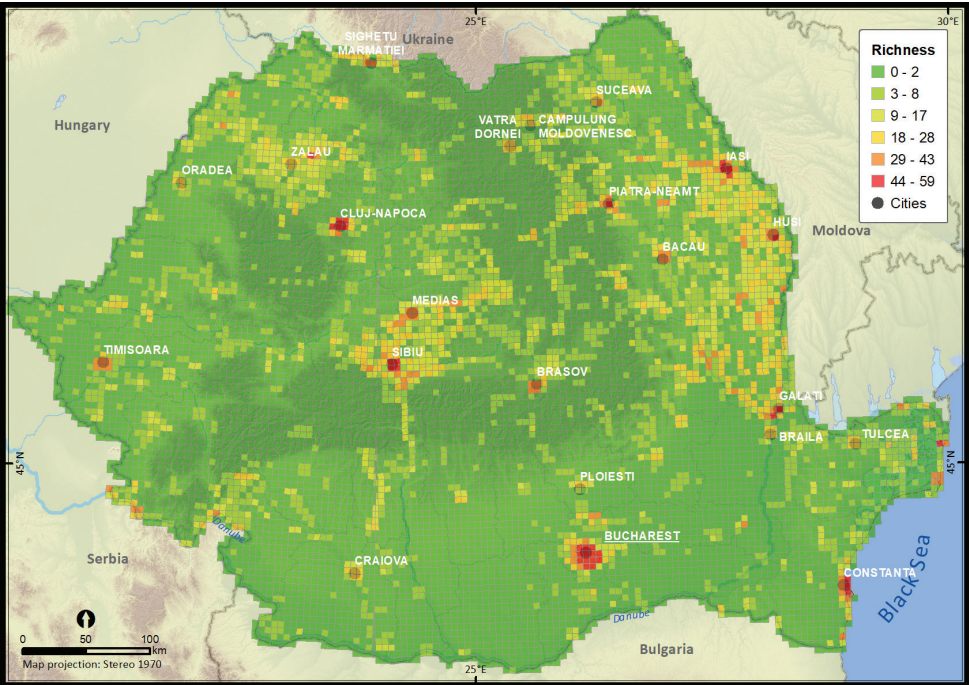


Figure 6. Invasive and potentially invasive alien plant species richness in Romania (50 × 50 km grid resolution).

introduction of ten species in Romania, while the pathway Escape from confinement – Agriculture (ES_agri) is responsible for only four species ($n = 102$). The majority of the species in our database (62.7% species) had one pathway of introduction documented, while for two species, *Ailanthus altissima* (Mill.) Swingle, and, *Acer negundo* L., we identified six and seven pathways respectively.

The data shows that the geographical origin of most IAP species included in our database is in Northern and Central America (56.1% of the species), followed by Asia and Pacific (17.3% of the species) (Fig. 7). Most species (24.9% of the recorded species) were introduced intentionally for horticulture or ornamental purposes (ES_hort in Fig. 7). Examples are *Prunus cerasifera*, used in horticulture, and the species *Ailanthus altissima*, *Amorpha fruticosa* and *Fraxinus americana* used for ornamental purposes. Out of the 102 recorded IAP species, 32 species entered Romania by natural dispersal across borders (UN_natu), after being introduced to Europe through various other ways, mainly from North and Central America. Examples of plants that dispersed naturally are *Symphytotrichum ciliatum* and *Veronica persica*. Other important pathways of introduction are transportation as stowaway (TR_mult) and seed contaminant (TR_seed), with 12.1%, and 10.4% of species being introduced through these pathways respectively.

Discussion

In this article we advance an important step towards establishing a comprehensive national database of invasive and potentially invasive alien plant species occurrences in Romania along with their distribution and pathways of introduction. The distribution of species was compiled from documents published between 1778 and 2018. We included in the database the records that fulfilled taxonomic and location quality criteria, and provide an analysis of the accumulation rate of species and occurrences, a spatial analysis of alien species diversity and a summary of introduction pathways.

The accumulation rate of invasive and potentially invasive alien plant species occurrences showed a steady increase after the 1950s, peaking in three time periods (1968–1974, 1995–2000, and 2009). This pattern is likely due to local initiatives focused on biological invasions, that led to the publishing of scientific papers and books, improving the knowledge of alien plants in Romania (Mititelu and Barabaş 1972; Negrean 1972; Ciocârlan et al. 1997; Coroi and Coroi 1997; Costea 1997; Ştefan and Oprea 1997; Anastasiu et al. 2009). However, since 1955, the number of occurrences reported has more than doubled and it is unlikely it will decrease in the future (Seebens et al. 2017, 2021). A similar rapidly increasing tendency after the 1950s has been reported by Nikolić et al. (2013) for Croatia. Peaks in the number of new recorded species have also been reported by other studies, with some variation in the time moment of the peak, for example the peak reported to take place during the 1940s and 1960s in eastern Africa (Witt et al. 2018).

The number of occurrences varies among species. Asteraceae with 26 species represented the most dominant family in the IAP species list. Furthermore, the majority of

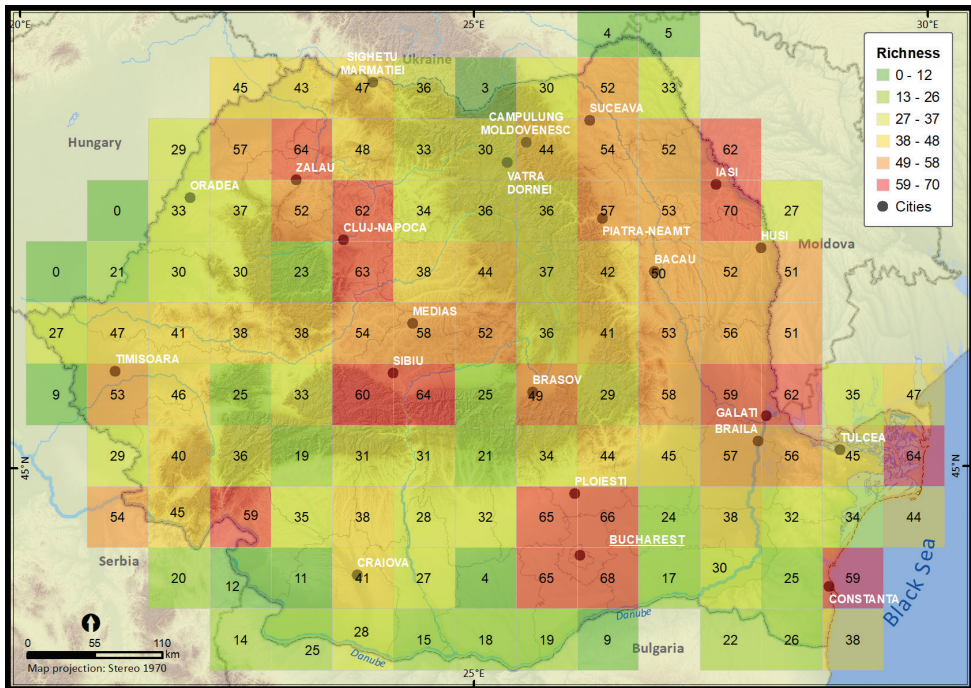


Figure 7. Proportion of invasive and potentially invasive alien plant species' introductions by pathway and geographic origins (see Table 1 for abbreviations).

the reported species are able to colonize disturbed and/or urbanized ecosystems in their native range (see Suppl. material 1: Appendix S1). The horseweed, *Erigeron canadensis*, is the species with the largest number of reported occurrences (3717 reported occurrences) at national level, having an altitudinal range varying between 3 and 2153 m. Also frequently recorded are the common ragweed, *Ambrosia artemisiifolia*, and the annual fleabane, *Erigeron annuus* subsp. *annuus* (more than 2000 occurrence records each). These species have a wide altitudinal range (between 0 and 1252 m the former, and between 0 and 2288 m the latter), inhabiting both lowlands and highlands. However, most IAP species from our database have been recorded between 0 and 500 m altitude (see Suppl. material 2: Appendix S2).

The number of newly reported species varies greatly among years (see Fig. 2), and, at least in the case of species reported in the 19th century, are linked to the publishing of monographical works. For example, the high number of new IAP species reported in 1816 is due to the works of Baumgarten (1816), who devoted his time to botanical research and published four volumes on Transylvanian flora. In 1866, seven new IAP species were added to the recorded flora of Transylvania by two other botanists (Fuss 1866; Schur 1866).

Most IAP species recorded in Romania originate in North and Central America (56.1%), followed by Asia and the Pacific (17.3%). Intentional introductions

contributed only slightly more (52.0%) than unintentional introductions (48.0%) to the presence of the IAP species in Romanian flora. Findings are in contrast with observations made by Lambdon et al. (2008) for Europe, where he pointed out that intentional introductions prevail over unintentional introductions. However, our findings are in agreement with the study by Hulme et al. (2008) with respect to the fact that horticulture and the use of alien plant species for ornamental purposes is the main pathway of introduction for the largest and most diverse group of species.

Unintentional introductions by transportation of plants as contaminants and stowaways play an important role in Romania. Globalization and economic development facilitated the local, regional, and global transfers of invasive alien species (Hulme 2009). For example, Lemke et al. (2019) demonstrated that the traffic volume significantly affected dispersal distances and the lateral deposition of seeds of *Ambrosia artemisiifolia* on the roadsides in Germany. The same IAP species was repeatedly reported in Romania, probably because it is conspicuous and highly allergenic. The important role of the high traffic roads in the dispersal of IAP species (Mortensen et al. 2009; Rauschert et al. 2017) is evident in Romania, as most of the 5×5 km grid cells in which IAP species were recorded are crossed by, or have roads with, high traffic volumes nearby (e.g., European routes E85, E81 and E60).

The horticulture industry, notably the ornamental horticulture, is also considered an important pathway for introducing and dispersing alien species (Drew et al. 2010). Botanical gardens and dendrological parks can also contribute to introducing and spreading invasive alien species, especially in case of defective management and design (Reichard and White 2001; Simberloff 2010). Our results revealed hotspots of IAP species near major academic and research facilities, for example, Iasi (eastern Romania), Sibiu (central Romania), Bucharest (southern Romania), and Timisoara (western Romania) (Fig. 4). In these areas, the higher-than-expected number of IAP species occurrences per grid cell can be explained by the presence of major academic and research facilities with biology/botany departments and large botanical gardens and dendrological parks. Similar biased sampling effort explained by the work of local researchers is Salaj County (Zalau, center of Romania).

Our analysis suggests data collection was conducted opportunistically rather than systematically, an issue noticed before in Romania (Cogălniceanu et al. 2013) and in other parts of the world (Hortal et al. 2007). To better capture the IAP species distribution in Romania and avoid the botanist effect on data (Pautasso and McKinney 2007), researchers should start sampling more intensively areas away from major academic and research facilities, and outside of popular protected areas.

Conclusions

The present study provides a systematic analysis of invasive and potentially invasive plant species in Romania. Our findings based on the review of existing literature, show the presence of 102 IAP species pertaining to 41 families. The number of occurrences

has increased steadily after 1950s, with new species being continuously introduced. Species originating mainly in North and Central America have been introduced almost equally through intentional and unintentional pathways. Mapping the species occurrences has revealed several hotspots of IAP species which concentrate in urban areas and their surroundings. The data collected in this study is made available through an open-access spatial database. We suggest that this database is maintained, regularly updated and used to build upon e.g., include all alien plants naturalized in Romanian flora and also other taxa. We consider it a valuable tool in biological invasions management at national level, as well as regionally, and for setting conservation priorities for species and sites, but also for further studies on impacts. In agreement with Regulation (EU) No. 1143/ 2014 (EU Regulation 2014), data about the distribution and pathways of introduction is necessary in order to establish a surveillance system.

Ahrends et al. (2011) highlighted how resources for descriptive taxonomy and biodiversity inventories have substantially declined in the last decades. Limited financial and logistic resources for field botany and taxonomy translated into a decrease in quality of biodiversity data, emphasizing that the funds oriented towards biodiversity research and conservation are rather insufficient or inefficiently spent. Future inventory activities must be oriented predominantly towards those counties/regions for which the data in the published literature is lacking.

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References

- Ahrends A, Rahbek C, Bulling MT, Burgess ND, Platts PJ, Lovett JC, Kindemba VW, Owen N, Sallu AN, Marshall AR, Mhoro BE, Fanning E, Marchant R (2011) Conservation and the botanist effect. *Biological Conservation* 144(1): 131–140. <https://doi.org/10.1016/j.biocon.2010.08.008>
- Alyokhin A, Sewell G (2004) Changes in a lady beetle community following the establishment of three alien species. *Biological Invasions* 6(4): 463–471. <https://doi.org/10.1023/B:BINV.0000041554.14539.74>

- Anastasiu P, Negrean G (2007) Invadatori vegetali in Romania. Editura Universitatii din Bucuresti, Bucharest.
- Anastasiu P, Negrean G (2009) Neophytes in Romania. In: Rákossy L, Momeu L (Eds) Neobiota din România. Editura Presa Univ. Clujeană, Cluj-Napoca, 66–97.
- Anastasiu P, Negrean G, Făgăraș M, Samoilă C, Cogălniceanu D (2009) Constanța Harbour (Romania) as a major gateway and reservoir for alien plant species. *Acta Horti Botanici Bucurestiensis* 36: 41–60.
- Anastasiu P, Preda C, Bănăduc D, Cogălniceanu D (2017) Alien Species of EU Concern in Romania. *Transylvanian Review of Systematical and Ecological Research* 19(3): 93–106. <https://doi.org/10.1515/trser-2017-0024>
- Barney JN, Tekiel DR, Dollete ESJ, Tomasek BJ (2013) What is the “real” impact of invasive plant species? *Frontiers in Ecology and the Environment* 11(6): 322–329. <https://doi.org/10.1890/120120>
- Baumgarten JCG (1816) *Enumeratio Stirpium Magno Transsilvaniae Principatui, I–III, Vindobonae*.
- Bellard C, Cassey P, Blackburn TM (2016) Alien species as a driver of recent extinctions. *Biology Letters* 12(2): e20150623. <https://doi.org/10.1098/rsbl.2015.0623>
- Catford JA, Bode M, Tilman D (2018) Introduced species that overcome life history trade-offs can cause native extinctions. *Nature Communications* 9: e2131. [7 pp.] <https://doi.org/10.1038/s41467-018-04491-3>
- CBD (2014) Pathways of Introduction of invasive species, their prioritization and management. Convention on Biological Diversity: 1–18. <https://www.cbd.int/doc/meetings/sb-stta/sbstta-18/official/sbstta-18-09-add1-en.pdf>
- Ciocărlan V, Sârbu I, Ștefan N, Marian T (1997) *Elodea nuttallii* (Planchon) St. John - specie nouă în flora României. *Buletinul Grădinii Botanice Iași* 6(1): 213–215.
- Cogălniceanu D, Székely P, Samoilă C, Iosif R, Tudor M, Plăiașu R, Stănescu F, Rozyłowicz L (2013) Diversity and distribution of amphibians in Romania. *ZooKeys* 296: 35–57. <https://doi.org/10.3897/zookeys.296.4872>
- Coroi AM, Coroi M (1997) Contribuții la studiul buruienilor din culturile agricole și viile județului Vrancea. *Lucr. Ști., Ser. Agron. USAMV Iași* 40: 98–105.
- Costea M (1997) The genus *Amaranthus* L. section *Amaranthus* in Romania. *Acta Horti Botanici Bucurestiensis* 25: 105–120.
- Diagne C, Leroy B, Gozlan RE, Vaissière AC, Assailly C, Nuninger L, Roiz D, Jourdain F, Jarić I, Courchamp F (2020) InvaCost, a public database of the economic costs of biological invasions worldwide. *Scientific Data* 7: e277. [12 pp.] <https://doi.org/10.1038/s41597-020-00586-z>
- Drew J, Anderson N, Andow D (2010) Conundrums of a complex vector for invasive species control: A detailed examination of the horticultural industry. *Biological Invasions* 12(8): 2837–2851. <https://doi.org/10.1007/s10530-010-9689-8>
- Ehrenfeld JG (2003) Effects of Exotic Plant Invasions on Soil Nutrient Cycling Processes. *Ecosystems* (New York, N.Y.) 6(6): 503–523. <https://doi.org/10.1007/s10021-002-0151-3>
- Ehrenfeld JG (2010) Ecosystem consequences of biological invasions. *Annual Review of Ecology, Evolution, and Systematics* 41(1): 59–80. <https://doi.org/10.1146/annurev-ecolsys-102209-144650>

- Essl F, Lenzner B, Bacher S, Bailey S, Capinha C, Daehler C, Dullinger S, Genovesi P, Hui C, Hulme PE, Jeschke JM, Katsanevakis S, Kühn I, Leung B, Liebhold A, Liu C, MacIsaac HJ, Meyerson LA, Nuñez MA, Pauchard A, Pyšek P, Rabitsch W, Richardson DM, Roy HE, Ruiz GM, Russell JC, Sanders NJ, Sax DF, Scalera R, Seebens H, Springborn M, Turbelin A, van Kleunen M, von Holle B, Winter M, Zenni RD, Mattsson BJ, Roura-Pascual N (2020) Drivers of future alien species impacts: An expert-based assessment. *Global Change Biology* 26(9): 4880–4893. <https://doi.org/10.1111/gcb.15199>
- European Commission (2020) EU Biodiversity Strategy for 2030. Bringing nature back into our lives. Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions. <https://ec.europa.eu/research/environment/index.cfm?pg=nbs>
- EU Regulation (2014) Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species. *Official Journal of the European Union* 57(317/35): 1–21.
- Fortin M, Dale M (2005) *Spatial Analysis. A Guide for Ecologists*. Cambridge University Press, Cambridge, 365 pp. <https://doi.org/10.1017/CBO9780511542039>
- Fuss M (1866) *Flora Transsilvaniae excursoria*. Typis Haeredum Georgii de Closius, Cibinii.
- Gallardo B, Bacher S, Bradley B, Comín FA, Gallien L, Jeschke JM, Cascade CJ, Vilà M (2019) InvasiBES: Understanding and managing the impacts of invasive alien species on biodiversity and ecosystem Services. *NeoBiota* 50: 109–122. <https://doi.org/10.3897/neobiota.50.35466>
- GBIF Secretariat (2021) GBIF Backbone Taxonomy. Checklist dataset. <https://doi.org/10.15468/39omei> [accessed via GBIF.org on 2021-06-07]
- Graham CH, Hijmans RJ (2006) A comparison of methods for mapping species ranges and species richness. *Global Ecology and Biogeography* 15(6): 578–587. <https://doi.org/10.1111/j.1466-8238.2006.00257.x>
- Gu Z, Gu L, Eils R, Schlesner M, Brors B (2014) Circlize implements and enhances circular visualization in R. *Bioinformatics (Oxford, England)* 30(19): 2811–2812. <https://doi.org/10.1093/bioinformatics/btu393>
- Haubrock PJ, Turbelin AJ, Cuthbert RN, Novoa A, Taylor NG, Angulo E, Ballesteros-Mejia L, Bodey TW, Capinha C, Diagne C, Essl F, Golivets M, Kirichenko N, Kourantidou M, Leroy B, Renault D, Verbrugge L, Courchamp F (2021) Economic costs of invasive alien species across Europe. *NeoBiota* 67: 153–190. <https://doi.org/10.3897/neobiota.67.58196>
- Hortal J, Lobo JM, Jiménez-Valverde A (2007) Limitations of biodiversity databases: Case study on seed-plant diversity in Tenerife, Canary Islands. *Conservation Biology* 21(3): 853–863. <https://doi.org/10.1111/j.1523-1739.2007.00686.x>
- Hulme PE (2009) Trade, transport and trouble: Managing invasive species pathways in an era of globalization. *Journal of Applied Ecology* 46(1): 10–18. <https://doi.org/10.1111/j.1365-2664.2008.01600.x>
- Hulme PE (2015) Invasion pathways at a crossroad: Policy and research challenges for managing alien species introductions. *Journal of Applied Ecology* 52(6): 1418–1424. <https://doi.org/10.1111/1365-2664.12470>
- Hulme PE, Bacher S, Kenis M, Klotz S, Kühn I, Minchin D, Nentwig W, Olenin S, Panov V, Pergl J, Pyšek P, Roques A, Sol D, Solarz W, Vilà M (2008) Grasping at the routes of

- biological invasions: A framework for integrating pathways into policy. *Journal of Applied Ecology* 45(2): 403–414. <https://doi.org/10.1111/j.1365-2664.2007.01442.x>
- Hulme PE, Roy DB, Cunha T, Larsson T-B (2009) A pan-European Inventory of Alien Species: Rationale, Implementation and Implications for Managing Biological Invasions. *Handbook of Alien Species in Europe*. Springer Netherlands, Dordrecht, 1–14. https://doi.org/10.1007/978-1-4020-8280-1_1
- Jarvis A, Guevara E, Reuter HI, Nelson AD (2008) Hole-filled SRTM for the globe : version 4 : data grid — University of Twente Research Information. CGIAR Consortium for Spatial Information. <https://research.utwente.nl/en/publications/hole-filled-srtm-for-the-globe-version-4-data-grid>
- Karrer G, Sirbu C, Oprea A, Doroftei M, Covaliov S, Georgescu MI (2021) *Ambrosia tenuifolia*, instead of *A. psilostachya*, in Romania. *Scientific Annals of the Danube Delta Institute* 26: 17–26.
- Keller RP, Geist J, Jeschke JM, Kühn L (2011) Invasive species in Europe: Ecology, status, and policy. *Environmental Sciences Europe* 23(1): e23. <https://doi.org/10.1186/2190-4715-23-23>
- Kucsicsa G, Grigorescu I, Dumitrascu M, Doroftei M, Nastase M, Herlo G (2018) Assessing the potential distribution of invasive alien species *Amorpha fruticosa* (Mill.) in the Mures Floodplain Natural Park (Romania) using GIS and logistic regression. *Nature Conservation* 30: 41–67. <https://doi.org/10.3897/natureconservation.30.27627>
- Kumar Rai P, Singh JS (2020) Invasive alien plant species: Their impact on environment, ecosystem services and human health. *Ecological Indicators* 111: 106020. <https://doi.org/10.1016/j.ecolind.2019.106020>
- Lambdon PW, Pyšek P, Basnou C, Hejda M, Arianoutsou M, Essl F, Jarošík V, Pergl J, Winter M, Anastasiu P, Andriopoulos P, Bazos I, Brundu G, Celesti-Grapow L, Chassot P, Delipetrou P, Josefsson M, Kark S, Klotz S, Kokkoris Y, Kühn I, Marchante H, Perglová I, Pino J, Vilà M, Zikos A, Roy DB, Hulme PE (2008) Alien flora of Europe: Species diversity, temporal trends, geographical patterns and research needs. *Preslia* 80: 101–149.
- Latombe G, Pyšek P, Jeschke JM, Blackburn TM, Bacher S, Capinha C, Costello MJ, Fernández M, Gregory RD, Hobern D, Hui C, Jetz W, Kumschick S, McGrannachan C, Pergl J, Roy HE, Scalera R, Squires ZE, Wilson JRU, Winter M, Genovesi P, McGeoch MA (2017) A vision for global monitoring of biological invasions. *Biological Conservation* 213: 295–308. <https://doi.org/10.1016/j.biocon.2016.06.013>
- Lemke A, Kowarik I, von der Lippe M (2019) How traffic facilitates population expansion of invasive species along roads: The case of common ragweed in Germany. *Journal of Applied Ecology* 56(2): 413–422. <https://doi.org/10.1111/1365-2664.13287>
- Li X, Liu X, Kraus F, Tingley R, Li Y (2016) Risk of biological invasions is concentrated in biodiversity hotspots. *Frontiers in Ecology and the Environment* 14(8): 411–417. <https://doi.org/10.1002/fee.1321>
- McGeoch MA, Latombe G (2015) Characterizing common and range expanding species. *Journal of Biogeography* 43(2): 217–228. <https://doi.org/10.1111/jbi.12642>
- McGeoch MA, Spear D, Kleynhans EJ, Marais E (2012) Uncertainty in invasive alien species listing. *Ecological Applications* 22(3): 959–971. <https://doi.org/10.1890/11-1252.1>

- Mititelu D, Barabaş N (1972) Vegetația ruderală și segetală din interiorul și împrejurimile municipiului Bacău. Stud. Comun. Muz. Ști. Nat. Bacău 5: 127–148.
- Mortensen DA, Rauschert ESJ, Nord AN, Jones BP (2009) Forest Roads Facilitate the Spread of Invasive Plants. *Invasive Plant Science and Management* 2(3): 191–199. <https://doi.org/10.1614/IPSM-08-125.1>
- Negrean G (1972) Câteva plante adventive din flora județului Prahova. Com. Ref. Muz. Ști. Nat. Ploiești: 77–80.
- Nikolić T, Mitić B, Milašinović B, Jelaska SD (2013) Invasive alien plants in Croatia as a threat to biodiversity of South-Eastern Europe: Distributional patterns and range size. *Comptes Rendus Biologies* 336(2): 109–121. <https://doi.org/10.1016/j.crv.2013.01.003>
- Ord JK, Getis A (1995) Local Spatial Autocorrelation Statistics: Distributional Issues and an Application. *Geographical Analysis* 27(4): 286–306. <https://doi.org/10.1111/j.1538-4632.1995.tb00912.x>
- Pautasso M, McKinney ML (2007) The botanist effect revisited: Plant species richness, county area, and human population size in the United States. *Conservation Biology* 21(5): 1333–1340. <https://doi.org/10.1111/j.1523-1739.2007.00760.x>
- Preda C, Memedemin D, Skolka M, Cogălniceanu D (2012) Early detection of potentially invasive invertebrate species in *Mytilus galloprovincialis* Lamarck, 1819 dominated communities in harbours. *Helgoland Marine Research* 66(4): 545–556. <https://doi.org/10.1007/s10152-012-0290-7>
- Pyšek P, Richardson DM, Rejmánek M, Webster GL, Williamson M, Kirschner J (2004) Alien plants in checklists and floras: Towards better communication between taxonomists and ecologists. *Taxon* 53(1): 131–143. <https://doi.org/10.2307/4135498>
- Pyšek P, Lambdon PW, Arianoutsou M, Kühn I, Pino J, Winter M (2009) Alien Vascular Plants of Europe. In: DAISIE (Ed.) *Handbook of Alien Species in Europe*. Springer, Dordrecht, 43–61. <https://doi.org/10.1007/978-1-4020-8280-1>
- Pyšek P, Jarošík V, Pergl J (2011) Alien plants introduced by different pathways differ in invasion success: Unintentional introductions as a threat to natural areas. *PLoS ONE* 6(9): e24890. <https://doi.org/10.1371/journal.pone.0024890>
- Pyšek P, Hulme PE, Simberloff D, Bacher S, Blackburn TM, Carlton JT, Dawson W, Essl F, Foxcroft LC, Genovesi P, Jeschke JM, Kühn I, Liebhold AM, Mandrak NE, Meyerson LA, Pauchard A, Pergl J, Roy HE, Seebens H, Kleunen M, Vilà M, Wingfield MJ, Richardson DM (2020) Scientists' warning on invasive alien species. *Biological Reviews of the Cambridge Philosophical Society* 95(6): 1511–1534. <https://doi.org/10.1111/brv.12627>
- Rauschert ESJ, Mortensen DA, Blosler SM (2017) Human-mediated dispersal via rural road maintenance can move invasive propagules. *Biological Invasions* 19(7): 2047–2058. <https://doi.org/10.1007/s10530-017-1416-2>
- Reichard SH, White P (2001) Horticulture as a Pathway of Invasive Plant Introductions in the United States. *Bioscience* 51(2): 227–234. [https://doi.org/10.1641/0006-3568\(2001\)051\[0103:HAPOI\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2001)051[0103:HAPOI]2.0.CO;2)
- Rey V, Ianos I, Groza O, Patroescu M (2007) *Reclus Atlas de la Roumanie* Nouvelle édition. Montpellier, 208 pp.

- Richardson DM, Pysek P, Rejmanek M, Barbour MG, Panetta FD, West CJ (2000) Naturalization and invasion of alien plants: Concepts and definitions. *Diversity & Distributions* 6(2): 93–107. <https://doi.org/10.1046/j.1472-4642.2000.00083.x>
- Richter R, Berger UE, Dullinger S, Essl F, Leitner M, Smith M, Vogl G (2013) Spread of invasive ragweed: Climate change, management and how to reduce allergy costs. *Journal of Applied Ecology* 50(6): 1422–1430. <https://doi.org/10.1111/1365-2664.12156>
- Ruiz GM, Carlton JT (2003) *Invasive species: vectors and management strategies*. Island Press, Washington DC, 520 pp.
- Schirmel J, Bundschuh M, Entling MH, Kowarik I, Buchholz S (2016) Impacts of invasive plants on resident animals across ecosystems, taxa, and feeding types: A global assessment. *Global Change Biology* 22(2): 594–603. <https://doi.org/10.1111/gcb.13093>
- Schur JF (1866) *Enumeratio Plantarum Transsilvaniae, Vindobonae*.
- Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, Winter M, Arianoutsou M, Bacher S, Blasius B, Brundu G, Capinha C, Celesti-Grapow L, Dawson W, Dullinger S, Fuentes N, Jäger H, Kartesz J, Kenis M, Kreft H, Kühn I, Lenzner B, Liebhold A, Mosena A, Moser D, Nishino M, Pearman D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R, Schindler S, Štajerová K, Tokarska-Guzik B, Van Kleunen M, Walker K, Weigelt P, Yamanaka T, Essl F (2017) No saturation in the accumulation of alien species worldwide. *Nature Communications* 8(1): 1–9. <https://doi.org/10.1038/ncomms14435>
- Seebens H, Bacher S, Blackburn TM, Capinha C, Dawson W, Dullinger S, Genovesi P, Hulme PE, van Kleunen M, Kühn I, Jeschke JM, Lenzner B, Liebhold AM, Pattison Z, Pergl J, Pyšek P, Winter M, Essl F (2021) Projecting the continental accumulation of alien species through to 2050. *Global Change Biology* 27(5): 970–982. <https://doi.org/10.1111/gcb.15333>
- Simberloff D (2010) Invasive species. In: Sodhi NS, Ehrlich PR (Eds) *Conservation biology for all*. Oxford University Press, 131–152. <https://doi.org/10.1093/acprof:oso/9780199554232.003.0008>
- Sirbu C, Oprea A (2010) Contribution to the knowledge of the alien flora of Romania: *Rudbeckia triloba* L. and *Senecio inaequidens* DC. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 38: 33–36.
- Sirbu C, Oprea A (2011a) *Flora adventivă din România*. Edit. Universității “Alexandru Ioan Cuza”, Iasi.
- Sirbu C, Oprea A (2011b) *Plante adventive în flora României*. “Ion Ionescu de la Brad”, Iasi.
- Sirbu C, Oprea A, Elias P, Ferus P (2011) New contribution to the study of alien flora in Romania. *Journal of Plant Development* 18: 121–134.
- Skolka M, Preda C (2011) Alien invasive species at the Romanian Black Sea coast - Present and perspectives. *Travaux du Muséum National d'Histoire Naturelle*. Grigore Antipa 53: 443–467. <https://doi.org/10.2478/v10191-010-0031-6>
- Stanescu F, Rozyłowicz L, Tudor M, Cogalniceanu D (2020) Alien Vertebrates in Romania – A Review. *Acta Zoologica Bulgarica* 72(4).
- Ștefan N, Oprea A (1997) A contribution to the weeds phytocoenology with *Sorghum halepense* (L.) Per. *Studii și Cercetări de Biologie. Seria Biologie Vegetală* 49(1–2): 37–43.

- Szatmari P-M (2012) Alien and invasive plants in Carei Plain natural protected area, western Romania: Impact on natural habitats and conservation implications. *South Western Journal of Horticulture, Biology and Environment* 3: 109–120.
- Turbelin AJ, Malamud BD, Francis RA (2017) Mapping the global state of invasive alien species: Patterns of invasion and policy responses. *Global Ecology and Biogeography* 26(1): 78–92. <https://doi.org/10.1111/geb.12517>
- Urziceanu M, Camen-Comănescu P, Nagodă E, Raicu M, Sirbu IM, Anastasiu P (2020) Updated list of non-native ornamental plants in Romania. *Contributii Botanice* 55: 59–82. <https://doi.org/10.24193/Contrib.Bot.55.4>
- Witt A, Beale T, van Wilgen BW (2018) An assessment of the distribution and potential ecological impacts of invasive alien plant species in eastern Africa. *Transactions of the Royal Society of South Africa* 73(3): 217–236. <https://doi.org/10.1080/0035919X.2018.1529003>
- Wołkowyci D, Banaszuk P (2016) Railway routes as corridors for invasive plant species. The case of NE Poland. *The International Academic Conference on The New Silk Road Connectivity*, NSRC, 162–169.
- Zimmermann H, Loos J, Von Wehrden H, Fischer J (2015) Aliens in Transylvania: Risk maps of invasive alien plant species in Central Romania. *NeoBiota* 24: 55–65. <https://doi.org/10.3897/neobiota.24.7772>

Supplementary material I

Appendix S1. List of invasive and potentially invasive alien plant species in Romania

Authors: Culita Sirbu, Iulia V. Miu, Athanasios A. Gavriliadis, Simona R. Gradinaru, Iulian M. Niculae, Cristina Preda, Adrian Oprea, Mihaela Urziceanu, Petronela Camen-Comanescu, Eugenia Nagoda, Ioana M. Sirbu, Daniyar Memedemin, Paulina Anastasiu

Data type: (docx. file)

Explanation note: List of invasive and potentially invasive alien plant species in Romania (* denotes an invasive alien species of Union concern pursuant to Regulation (EU) No 1143/2014 of the European Parliament and of the Council).

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Link: <https://doi.org/10.3897/neobiota.75.84684.suppl1>

Supplementary material 2

Appendix S2. Altitudinal range of invasive and potentially invasive alien plant species recorded in Romania

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Data type: (docx. file)

Explanation note: Appendix S2. Altitudinal range of invasive and potentially invasive alien plant species recorded in Romania (mean altitude of UTM 5 × 5 km grid cell).

Box = interquartile range, horizontal line = median, whiskers = 1.5 × interquartile range, points = outliers); The species ID corresponds to the IDs provided in Suppl. material 1: Appendix S1.

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Link: <https://doi.org/10.3897/neobiota.75.84684.suppl2>

Supplementary material 3

Appendix S3. Publications used to compile distribution of alien plant species in Romania.

Authors: Culita Sirbu, Iulia V. Miu, Athanasios A. Gavrilidis, Simona R. Gradinaru, Iulian M. Niculae, Cristina Preda, Adrian Oprea, Mihaela Urziceanu, Petronela Camen-Comanescu, Eugenia Nagoda, Ioana M. Sirbu, Daniyar Memedemin, Paulina Anastasiu

Data type: (docx. file)

Explanation note: Appendix S3. Publications used to compile distribution of alien plant species in Romania.

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Invasive round goby shows higher sensitivity to salinization than native European perch

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Abstract

Salinity is an influential abiotic environmental factor in aquatic species, specifically in freshwater, where salinization causes ecosystem degradation. Secondary salinization, that is increases in salinity due to anthropogenic activities, can affect both osmoregulation and behaviour in freshwater fishes. It is generally believed that invasive species handle climatic change and environmental degradation better than native species, which is one reason for their invasion success. However, how invasive and native species cope with salinity changes remains little understood. Therefore, we investigated how low (500 $\mu\text{S}/\text{cm}$) and high salinity (2000 $\mu\text{S}/\text{cm}$) conditions affected oxygen consumption and behaviour in the invasive round goby (*Neogobius melanostomus*) and the native European perch (*Perca fluviatilis*). Our results showed that in round goby oxygen consumption increased and swimming and non-swimming movements changed in response to salinity increments, whereas European perch was not affected by salinity. Thus, it seems as if the invasive round goby is more sensitive to changes in salinity than the native European perch. Our results fit with the minority of studies indicating invasive species being less tolerant than some native species to environmental changes. This finding could be explained by the adaptation of round goby to low salinity due to its long establishment in River Rhine. Further, our results are also confirming that the effect of salinity is species-specific. In addition, European perch and round goby show diametrically different behavioural response to disturbance which could be an effect of holding different ecological niches as well as their anatomical differences.

Keywords

European perch, exploratory behaviour, general activity, metabolic rate, risk behaviour, round goby

Introduction

Salinization is one of the major causes of biological changes in river ecosystems (Vander Laan et al. 2013). Salinity is a very important abiotic environmental factor influencing aquatic species, to the extent that aquatic species are normally divided into groups based on living environment concerning salinity, such as freshwater, brackish water, or seawater species. Increases in salinity can occur via natural accumulation of salts. This is called primary salinization and the time-scale is typically very long (~100 000 years with some variances) (Herbert et al. 2015). Secondary salinization, on the other hand, is caused by anthropogenic activities such as vegetation clearance, intensive irrigation, river regulation, mining and extraction, and de-icing salts, and for secondary salinization the time-scale is much shorter than for primary salinization (decades or shorter) (Herbert et al. 2015).

Secondary salinization can have adverse effects on aquatic animals because changing salinities could affect the metabolic cost of the organism (Hart et al. 1991). For instance, many freshwater fish species have their optimal growth and typically lower metabolic rates when exposed to intermediate salinities, while increased salinities seem to reduce food intake and growth in fish (Bœuf and Payan 2001). However, fish condition has been observed to increase in spite of the reduced food consumption rate (Hintz et al. 2017). Increased riverine salinities as a result of road salt have been shown to be toxic for fathead minnows (*Pimephales promelas*) (Corsi et al. 2010) and anthropogenic increases of salinity in the Great Menderes Basin in Turkey have led to the extinction of the previously most abundant fish, namely carp (*Cyprinus carpio*) and also Wels catfish (*Silurus glanis*) (Koç 2008).

Various behavioural traits of freshwater fish are affected by salinity, although no pattern seems apparent. For instance, with increasing salinity Eastern mosquitofish (*Gambusia holbrooki*) decreased their aggressive behaviour and needed more time to capture prey (Alcaraz et al. 2008). By contrast, in an invasive cichlid aggression increased when exposed to brackish water compared to freshwater (Lorenz et al. 2016). Exposure to increased salinity increased swimming activity in pikeperch (*Sander lucioperca*) (Scott et al. 2008), and reduced anti-predator responses in fathead minnows (Hoover et al. 2013). However, there are studies showing no effects of salinity upon behaviour in other freshwater fish, such as in the Iberian barbel (*Luciobarbus bocagei*) (Leite et al. 2019).

In general, it is considered that invasive aquatic species can handle environmental change better than native species in freshwater ecosystems (Bates et al. 2013), with invasive species being more tolerant to temperature fluctuation. The pattern seems to be true for temperature tolerance in the River Rhine, because native fishes in the Rhine seem to be more negatively affected by the temperature changes during the last century (lower minimum and higher maximum) than invasive fishes (Leuven et al. 2011). Salinity sensitivity difference between invasive and native freshwater fishes has not been studied extensively. Invasive freshwater suckermouth armoured catfish (Loricariidae: *Pterygoplichthys*) has been shown to tolerate brackish water in south-

eastern Mexico (Capps et al. 2011), indicating that it could spread to a larger area. There are also some reports concerning invasive species being less tolerant to salinity than native species. For instance, the *Aphanius iberus* seems to handle salinity better than Eastern mosquitofish, but it is however also sensitive and grows worse in higher salinity environment (Sgarzi et al. 2020).

Based on this background, we wanted to investigate how an invasive fish and a native fish from River Rhine responded to different salinities. The species, the native European perch (*Perca fluviatilis*) and the invasive round goby (*Neogobius melanostomus*), were chosen based on their prevalence in the Rhine, where secondary salinization via mine water emission is extant (Wisotzky et al. 2018; Schulz and Cañedo-Argüelles 2019). Earlier studies have shown that both European perch (Overton et al. 2008; Christensen et al. 2019a) and round goby have a wide range of salinity tolerance (Karsiotis et al. 2012; Hempel and Thiel 2015). Further, European perch has a higher standard metabolic rate, that is minimum metabolic rate needed to sustain life for a specified temperature, (Ern et al. 2014; Christensen et al. 2019b), and round goby has a lower standard metabolic rate (Behrens et al. 2017) in brackish water compared to fresh water. Thus, we hypothesized that round goby would be less sensitive than European perch to an environmentally relevant increase of salinity. Specifically, we tested if oxygen consumption and/or exploratory behaviour, general activity and risk behaviour of both species were affected by salinity increments that could occur both naturally and following anthropogenic influences in the Rhine River.

Materials and methods

Experimental animals

The species chosen for this study, round goby and European perch, are not only invasive and native respectively. The round goby is typically a benthivore and the European perch a benthivore as juvenile and a piscivore as adult, thus having different ecological niches (Herlevi et al. 2018). European perch and round goby were caught by electrofishing in the Rhine River system (the tributary river Lahn at a conductivity [salinity] of 611 $\mu\text{S}/\text{cm}$ and the actual river Rhine at a conductivity [salinity] of 493 $\mu\text{S}/\text{cm}$) in September 2020 near Koblenz (50°21'12.85"N, 7°34'43.79"E) in Germany, and brought in oxygenated containers to the holding facilities of University Koblenz-Landau (electrofishing was done by The German Federal Institute of Hydrology during fish stock assessments). During acclimation, the fishes were kept in two separate tanks (120 × 100 × 116 cm, filled to ~700 L) with de-ionized tap water amended for aquarium use (Borgmann 1996; Richter et al. 2018) with addition of common table salt (NaCl, Aquasale Grobes Meersalz naturbelassen, Südwestdeutsche Salzwerke AG, Heilbronn, Germany) to have a conductivity (salinity) of ~500 $\mu\text{S}/\text{cm}$, and from hereon we will use salinity interchangeable for conductivity for our experiment to provide an easier comparison to other studies. The tanks were kept at ambient temperature with enrichment (stones

and plastic tubes), a photoperiod set to 14 h light/10 h dark, and fishes were fed with dry fish feed granules (sera Vipagran Nature, sera GmbH, Heinsberg, Germany). The fishes were kept in the tanks for at least 1 week before the experiment.

The methodology of this study was conducted in accordance with the Guidelines of the European Union Council (86/609/EU). The experiments were approved by the Federal Investigation Office (Landesuntersuchungsamt, Koblenz, Germany; approval number: 23 177-07/G 20-20-062) according to § 8a of the German law for animal welfare.

Experimental set-up

Fish for the experiment were randomly selected, lightly anaesthetised using Tricaine methanesulfonate (MS-222; ~25 mg/L), measured, weighed, marked individually via fin clip, which is typically temporary and thus would not affect the fish after the release (Delcourt et al. 2018), and put into one of two aquaria on day 1 (body mass and length; European perch: 6.51 ± 1.71 g and 7.49 ± 0.63 cm [mean \pm standard derivation (SD), N=24], round goby: 10.19 ± 4.91 g and 7.62 ± 1.04 cm [mean \pm SD, N=24]). The aquaria (120 \times 50 \times 50 cm, filled to ~150 L [25 cm] with the same de-ionized tap water amended for aquarium use as in the tanks) were divided into three separate compartments, one compartment was for filtration and oxygenation and the other two compartments for the fishes (one for each species). The compartments for fishes were the same size (48 \times 50 \times 25 cm, ~60 L de-ionized tap water amended for aquarium use) with gravel as substrate and additional enrichment (round goby: plastic tubes based on Hempel and Thiel (2015); European perch: plastic plants based on Magnhagen (2012)). Each compartment held 6 fish of similar size from the same species (10 L water per fish). Fishes were fed 5% of their bodyweight with dry fish feed (sera Vipagran Nature, sera GmbH, Heinsberg, Germany), and the aquaria had a photoperiod set to 14 h light/10 h dark.

The two aquaria were separated into two different acclimations, namely low salinity condition (LS; 500 μ S/cm) and high salinity condition (HS; 2000 μ S/cm) based on the normal level and expected level after mine water emission, and on day 2 salinity change was initiated in the HS aquarium, whereas the LS aquarium was kept at the original salinity of 500 μ S/cm. The salinity change was done by dissolving common table salt (NaCl, Aquasale Grobes Meersalz naturbelassen, Südwestdeutsche Salzwerke AG, Heilbronn, Germany) with water from the aquarium, and then pouring the solution into the compartment for filtration and oxygenation. A maximum change of 500 μ S/cm per day was used to minimize acute stress for the fishes, and the final salinity of 2000 μ S/cm for the high salinity condition was reached on day 4. Salinity, temperature and pH were measured regularly. The experimental set-up was run twice to acclimate 12 fish per group and species.

Oxygen consumption

After at least three days of habituation to the final salinity condition, oxygen consumption in fishes was measured using an automated intermittent flow respirometer (Q-Box

AQUA, Qubit Systems, Kingston, Canada). An individual fish was transferred to a respiration chamber (3.8×15.3 cm, 140 mL), which was submerged in an oxygenated acclimation water bath (LS or HS). The respiration chamber allowed the fish to move, but the fish were not able to swim freely. Oxygen consumption was then measured over eight 5-min periods when the chamber was closed (no circulation of water from the water bath) separated by eight 2.5-min periods when the chamber was opened (circulation of water from water bath leading to renewed oxygen), leading to a total time of 60 min. This means that, for practical reasons including trying to keep the fish holding as short as possible, we measure something between routine metabolic rate (RMR) and active metabolic rate (AMR) (White et al. 2016). After the oxygen consumption measurement, the fishes were put back into the aquaria for behavioural tests the following day. The oxygen consumption was measured on 4 fishes per day, and was done on day 3–5 under low salinity conditions and on day 6–8 under high salinity conditions between 08:00 and 15:00.

Behavioural tests

The day after the oxygen consumption measurement between 08:00 and 15:00, fishes were transferred individually to behavioural test arenas. The arenas ($66 \times 45 \times 23$ cm) were filled to ~ 25 L with treatment water from the aquarium and had an air stone in one corner. In the arenas several different behaviours were quantified in the following order:

1. Exploratory behaviour (EB)
Fishes were filmed with a Raspberry Pi with a camera module for 10 min immediately after the introduction of the fish into the tank (Cerqueira et al. 2016).
2. General activity (GA)
Fishes were filmed for 30 min after a 60 min habituation period after novel environment behaviour (70 min post introduction).
3. Risk behaviour (RB)
Fishes were filmed for 30 min after the disturbance (start 100 min post introduction). The disturbance was applied by dropping a 50 ml Falcon tube filled with gravel into one side of the test arena (Millot et al. 2009).

From the films of the different tests, 10 minutes of each was analysed for behaviour. The following was quantified in all of the videos: 1) percentage of time swimming, 2) percentage of time resting, 3) percentage of time hiding by the air stone or the falcon tube (only in RB), 4) percentage of time spent in non-swimming movement (moving less than a body length), 5) time to initiated swimming (s; with a maximum of 600 s), and 6) time to hiding (s; with a maximum of 600 s). The general activity and risk behaviour were quantified from the 10 minutes directly before and after the disturbance respectively. Each fish was registered as performing one of the 4 behaviours (swimming, resting, hiding, or non-swimming movement) at every moment. As in the oxygen consumption test, 4 fishes were tested each day, on day 4–6 under low salinity

conditions and day 7–9 under high salinity conditions. In total, two rounds were made to reach an N of 12 for each species and treatment (a total of 48 fish). After the end of the experiment, the fish were returned to the Rhine River system.

Statistical analyses

Normality of the data and homogeneity of variances were tested with Shapiro-Wilk tests, and data were analysed using parametric tests (ANOVA) or non-parametric tests (Kruskal-Wallis test or Wilcoxon signed rank test). Oxygen consumption was compared between salinity conditions using a two-way repeated measure ANOVA (dependent: oxygen consumption, factors: salinity and time) in each species. Behavioural parameters were tested using Kruskal-Wallis test for the differences between salinity conditions within a species, and using Wilcoxon signed rank test to test the difference between before and after disturbance. Since the behavioural parameters are percentages, only two parameters were tested per behavioural test and that were one of the active and one of the inactive parameters. For exploratory behaviour and general activity swimming and resting were tested, and for risk behaviour non-swimming movement and hiding, based on the expected importance of the behavioural parameters depending on situation. Finally, the treatment effect upon the difference between before and after disturbance was tested using Kruskal-Wallis test on the difference of behaviour before disturbance with the behaviour after disturbance subtracted (as example: percentage of swimming during general activity - percentage of swimming during risk behaviour). For 2 fishes (one of each species) the video recording before the disturbance was shorter than the recording after the disturbance (~ 20 s) because of not turning on the recording at the right time. These data were used in the statistical analysis anyway by using percentage. The free software R for statistical computing (R Core Team 2020) using the integrated development environment RStudio (RStudio Team 2019) was used for all analyses. All data, if not stated otherwise, are presented as mean \pm SD.

Results

Environmental data

During the experiment pH (LS: 7.52 ± 0.12 ; HS: 7.46 ± 0.04) and temperature (LS: 21.4 ± 1.0 °C; HS: 21.1 ± 0.4 °C) were similar between the salinity conditions, whereas salinity differed between the low salinity condition and high salinity condition (LS: 672 ± 30 μ S/cm; HS: 2130 ± 0 μ S/cm).

Oxygen consumption

Oxygen consumption decreased over time in both round goby (two-way repeated measure ANOVA; $F_{7, 154} = 9.187$, $P < 0.0001$; Fig. 1) and European perch (two-way repeated measure ANOVA; $F_{7, 147} = 17.770$, $P < 0.0001$; Fig. 2). In round goby there

was a significant effect of salinity condition (two-way repeated measure ANOVA; $F_{1,22} = 6.445$, $P = 0.019$; Fig. 1), with gobies under high salinity condition having a higher oxygen consumption than gobies under low salinity condition. However, in European perch there was no effect of salinity condition upon oxygen consumption (two-way repeated measure ANOVA; $F_{1,21} = 0.774$, $P = 0.398$; Fig. 2).

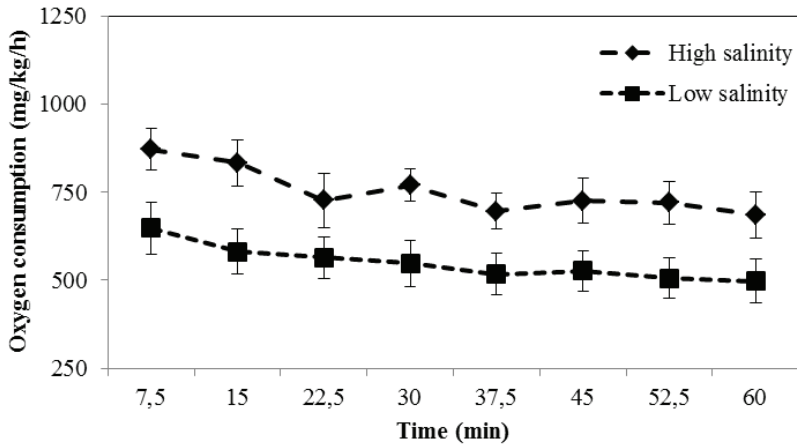


Figure 1. Oxygen consumption (mg/kg/h) in round goby from low salinity condition (square and densely dashed line) and high salinity condition (diamond and loosely dashed line) over time with a significant difference between conditions. Values are mean \pm S.E.M.

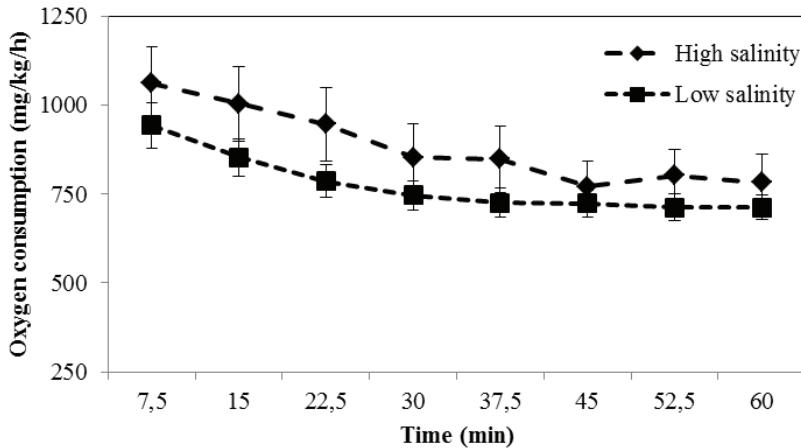


Figure 2. Oxygen consumption (mg/kg/h) in European perch from low salinity condition (square and densely dashed line) and high salinity condition (diamond and loosely dashed line) over time with no significant difference between conditions. Values are mean \pm S.E.M.

Behaviour

Salinity condition affected exploratory behaviour immediately after transfer to the test arena in invasive round goby but not in native European perch. This difference in exploratory behaviour was seen in percentage of swimming with gobies from high salinity condition swimming more than those from low salinity condition (LS: $6 \pm 12\%$, $N = 12$; HS: $12 \pm 13\%$, $N = 12$; Kruskal-Wallis chi-squared = 4.4622, $df = 1$, $P = 0.035$; Table 1). However, there were no other differences in hiding, resting, non-swimming movement apparent, time to initiated swimming or time to hiding (Table 1). European perch from the different salinity conditions did not differ in any behavioural parameters directly after transfer to the test arena (Table 1).

While general activity, measured 70 min after the transfer to the test arena, was not affected by salinity conditions in either of the species (Table 1), the risk behaviour, measured directly after a disturbance (100 min after transfer to the test arena), was affected by salinity condition in round goby but not in European perch. Round gobies from the high salinity condition were doing more non-swimming movement, that is moving less than a body length, than gobies from the low salinity condition (LS: $0 \pm 0\%$, $N = 12$; HS: $1 \pm 2\%$, $N = 12$; Kruskal-Wallis chi-squared = 6.4022, $df = 1$, $P = 0.011$; Table 1). Beyond non-swimming movement in round goby, the rest of the behavioural parameters were similar in both species during risk behaviour, regardless of salinity condition (Table 1).

To test if the additional disturbance in a stressful situation affected the behaviour in the fishes and whether that depended upon the salinity condition, the same behaviours were compared between before and after the disturbance. While for both species the effects of the disturbance were evident, only for round goby the salinity condi-

Table 1. Behaviour across different situational contexts under two different salinity conditions in European perch and round goby.

| Situation | Species | Condition | Swimming (%) | Resting (%) | Hiding (%) | Non-swimming movement (%) | Initiated swimming (s) | Time to hiding (s) | N |
|-----------------------|----------------|---------------|---------------|---------------|---------------|---------------------------|------------------------|--------------------|----|
| Exploratory behaviour | European perch | Low salinity | 3 ± 4 | 45 ± 48 | 52 ± 49 | 0 ± 0 | 0 ± 0 | 211 ± 288 | 12 |
| | | High salinity | 6 ± 10 | 62 ± 41 | 32 ± 38 | 0 ± 0 | 0 ± 0 | 260 ± 300 | 12 |
| | Round goby | Low salinity | 6 ± 12 | 45 ± 45 | 49 ± 44 | 0 ± 1 | 104 ± 198 | 265 ± 274 | 12 |
| | | High salinity | $12 \pm 13^*$ | 29 ± 34 | 58 ± 40 | 1 ± 1 | 25 ± 37 | 159 ± 208 | 12 |
| General activity | European perch | Low salinity | 0 ± 0 | 42 ± 51 | 58 ± 51 | 0 ± 0 | 600 ± 0 | 250 ± 309 | 12 |
| | | High salinity | 0 ± 0 | 58 ± 51 | 42 ± 51 | 0 ± 0 | 600 ± 0 | 350 ± 309 | 12 |
| | Round goby | Low salinity | 2 ± 5 | 23 ± 39 | 74 ± 41 | 1 ± 2 | 485 ± 207 | 131 ± 233 | 12 |
| | | High salinity | 9 ± 13 | 40 ± 44 | 49 ± 46 | 2 ± 2 | 280 ± 262 | 239 ± 293 | 12 |
| Risk behaviour | European perch | Low salinity | $1 \pm 2^*$ | 25 ± 45 | 74 ± 45 | 0 ± 0 | 301 ± 312 | 152 ± 270 | 12 |
| | | High salinity | 3 ± 4 | 49 ± 48 | 48 ± 49 | 0 ± 0 | 154 ± 269 | 206 ± 291 | 12 |
| | Round goby | Low salinity | 1 ± 1 | $16 \pm 38^*$ | $83 \pm 39^*$ | 0 ± 0 | 400 ± 295 | 51 ± 173 | 12 |
| | | High salinity | 2 ± 3 | 6 ± 20 | 91 ± 24 | $1 \pm 2^*$ | 150 ± 271 | 38 ± 124 | 12 |

Values are mean \pm S.D.
* Indicates that high salinity gobies behaviour is significantly higher compared to low salinity gobies ($P < 0.05$, Kruskal-Wallis test).
^ Indicates that there is a significant change in behaviour after disturbance (risk behaviour) for the low salinity and high salinity conditions combined compared to before disturbance (general activity) ($P < 0.05$, Wilcoxon signed rank test).

tion affected the behavioural responses. Round gobies from high salinity condition increased their resting after disturbance compared to gobies from low salinity condition (Kruskal-Wallis chi-squared = 4.4005, $df = 1$, $P = 0.036$). Following the disturbance, round gobies decreased resting (Wilcoxon signed rank test, $V = 78$, $P = 0.003$; Table 1) and increased hiding (Wilcoxon signed rank test, $V = 62$, $P = 0.038$; Table 1), while European perch increased swimming (Wilcoxon signed rank test, $V = 0$, $P < 0.001$; Table 1). No other behaviours were affected.

Discussion

Based on previous research, with lower standard metabolic rate in round goby (Behrens et al. 2017) and higher standard metabolic rate in European perch (Ern et al. 2014; Christensen et al. 2019b) in brackish water compared to fresh water, we had expected that the invasive round goby would be less sensitive to a higher salinity condition than the native European perch. However, round goby in high salinity condition showed an increase in oxygen consumption as well as changed behaviour compared to low salinity condition, and none of these differences were apparent in European perch. Thus, it seems as if the invasive round goby in the Rhine River system is more sensitive to increases in salinity than the native European perch.

Interestingly, it seems as if invasive species can differ in behaviour depending on time since colonization. For instance, in cane toad (*Rhinella marina*) anti-predatory responses differ between their native and invasive range with invasive toads being less likely to flee (Hudson et al. 2017). In addition, individuals from the invasive front were less likely to flee compared to toads from long-colonized areas and individuals even differed in morphology and locomotory traits between the invasive front and long-colonized areas (Hudson et al. 2017; Hudson et al. 2020). Further, native cane toad had higher stress responses than invasive cane toad at a similar climate (Kosmala et al. 2020a), and invasive cane toad had adapted to invasive areas abiotic challenges such as temperature (Kosmala et al. 2018), as well as moisture (Kosmala et al. 2020b). Round goby has also been reported to differ in several traits between the invasion front and long-colonized areas. Round goby at the invasion front were bolder, had a higher dispersal potential and higher resting metabolic rate (RMR) than gobies from long-colonized areas (present for approximately 10 years) (Myles-Gonzalez et al. 2015). Further, some studies also indicate that round goby have rapid adaptive traits in novel environments. For instance, it seems as if sperm velocity is adapting rapidly to novel salinity levels (Green et al. 2020). It has also been reported that genetic differentiation happened in fewer than ten generations of round goby in the southern Baltic Sea (Björklund and Almquist 2010). Further, there is evidence that round goby differs in demography, morphology and feeding behaviour between an invasion front and a long colonised area (Brandner et al. 2013). The sampling site for round gobies of this study (Rhine-km ~590) can be considered a long-colonised area, because this species had been detected in the Dutch Rhine delta 2004 and from higher up in Rhine (Rhine-km

718) in 2008 (Borcherding et al. 2011). Consequently, the round goby used in this study might be more sensitive to salinity because they are long established and therefore could have adapted to the environment as previously shown in cane toad. There are some studies indicating that round goby could be sensitive to freshwater salinity levels. For instance, heat shock protein 70 (hsp70) expression was highest in round goby in freshwater (0‰) compared to 10 and 30‰ salinities (Puntila-Dodd et al. 2021). However, it is still perplexing that European perch from the same area seem to be more tolerant towards salinity, but other factors than sensitivity to abiotic factors can also be important for the establishment of invasive species, such as sensory biology (Abrahams et al. 2017).

Our results that round goby increased oxygen consumption following high salinity condition were unexpected. Earlier studies have shown that round goby has a wide spectrum of tolerance for salinity (0–20‰ without problems) (Karsiotis et al. 2012) and growth rate did not change within the range of 0.1 to 15‰ (Hempel and Thiel 2015). Additionally, in contrast to our results, Behrens et al. (2017) reported that standard metabolic rate (SMR) was lower at 10‰ compared to 0‰ salinity, but found no differences in maximal metabolic rate (MMR) and aerobic scope (AS). There are, however, several differences between this study and our study concerning methodology. For instance, we used salinities of 500 and 2000 $\mu\text{S}/\text{cm}$, which are $\sim 0.25\text{‰}$ and 1.00‰ respectively, which led to a lesser difference between salinity conditions. Further, for practical reasons, we did not measure SMR or MMR, rather something between routine metabolic rate (RMR) and active metabolic rate (AMR) (White et al. 2016). Additionally, in our experiment, the gobies were acclimated for a short time (3–5 days) whereas in Behrens et al. (2017) the gobies were acclimated for at least 20 days. Thus, some of the different results could be attributed to methodological differences. However, in the desert goby (*Chlamydogobius eremius*) oxygen consumption was higher for gobies in higher salinities (35‰ and 70‰) compared to gobies in 0‰ (Thompson and Withers 2002), which is similar to our results.

Further, our results show that high salinity condition does not seem to have any significant effect on oxygen consumption in European perch. This result was unexpected because earlier reports have shown higher oxygen consumption, either in standard metabolic rate (SMR) or maximal metabolic rate (MMR), in perch exposed to higher salinities. For instance, European perch had a higher SMR in brackish water (10‰) compared to fresh water (0‰) (Ern et al. 2014). Further, SMR seems to be increased in 15‰ compared to 0 and 10‰ at 10 °C and 20 °C, but MMR seems to be lower at 5 °C in 15‰ compared to 0 and 10‰ (Christensen et al. 2017), however this was in perch from brackish water. Salinity did not affect MMR in European perch from low respectively high saline background (Christensen et al. 2019b), but SMR was higher at 10‰ than in 0‰ in perch from high saline background (Christensen et al. 2019b). There are again several differences between these studies and our study. For instance, we used a lesser difference between salinity conditions compared to the other studies. As mentioned above, we measured something between routine metabolic rate (RMR) and active metabolic rate (AMR) (White et al. 2016). This could make comparisons

difficult. However, we suggest that our results with no difference between treatments could be attributed to the freshwater origin of the perch as well as not measuring SMR, and thus fitting in with perch from low saline background showing no differences in SMR and MMR between 0‰ and 10‰ salinity (Christensen et al. 2019b).

In our study, we showed that oxygen consumption decreased during the exposure time in both European perch and round goby. This indicates that the initiation of the procedure, netting the fish from the aquarium and putting it into the respirometer chamber, was stressful and that the fishes acclimated to the situation over time. Our set-up was similar to White et al. (2016), which also had preliminary data suggesting the first measurements were higher based on a stress response following the transfer to the respirometer chamber. That respirometry can induce a stress response has also been reported in rainbow trout (*Onchorhynchus mykiss*) (Murray et al. 2017). Further, the respirometry chamber could also be considered to induce stress of confinement (Ellis et al. 2012). Thus, we believe that we have measured an initial stress response following the short chasing as well as confinement, but that the fishes acclimated and therefore decreased their oxygen consumption to normal levels.

We had expected that both species would change their behaviour following salinity increment. However, while in our study elevated salinity seemed to have no effect on behaviour in European perch, in round goby there were several significant differences between the salinity treatments. In general, the activity was increased at elevated salinity in round goby. This could be an increase of activity to avoid the salinity by changing location. Further, round goby has been proposed to use risky strategies during starvation and winter conditions (Fortes Silva et al. 2019). Consequently, it seems possible that they would also be using riskier strategy when exposed to elevated salinity, and thus have an overall increased activity. There are several studies indicating behavioural effects of salinity in freshwater fishes. For instance, male desert goby exert less aggressive behaviour but do not change courtship behaviour at elevated salinity (Lehtonen et al. 2016). Further, fathead minnows exposed to 8000 ppm salinity spent less time moving compared to 4000 and 1000 ppm salinity (Hoover et al. 2013). Additionally, the fathead minnows exposed to 4000 and 8000 ppm salinity could not distinguish between low and high alarm cues shown through anti-predator behaviour, which minnows exposed to 1000 ppm salinity could (Hoover et al. 2013). Furthermore, sailfin molly (*Poecilia latipinna*) prefer to remain in freshwater with predator cue in comparison to salt water (Tietze and Gerald 2016). Elevated salinity in combination with elevated temperature negates the increased interspecific aggression following only elevated temperature in Eastern mosquitofish and Australian bass juveniles (*Macquaria novemaculeata*) (Lopez et al. 2018). However, some fish do not change behaviour when exposed to salinity such as Iberian barbel (Leite et al. 2019). Thus, our results are confirming that the effect of salinity in freshwater fishes do give disparate results, and that each species should be studied to be able to predict how salinity would affect them, and that the specific salinities should also be considered thoroughly.

There were also distinct differences between European perch and round goby in their behavioural response to disturbance i.e., comparing risk behaviour with general

activity. European perch increased their swimming and tended to rest less after disturbance. On the other hand, round goby hid more and tended to swim less after disturbance. Thus, it seems as if the responses to disturbance between the two species are diametrically different, and could be interpreted as European perch trying to flee the disturbance and round goby trying to hide from the disturbance. This could be an effect of their differences in ecology such as being a benthivore and a piscivore, as well as their anatomical differences.

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References

- Abrahams MV, Bassett DK, Montgomery JC (2017) Sensory Biology as a Risk Factor for Invasion Success and Native Fish Decline. *Transactions of the American Fisheries Society* 146(6): 1238–1244. <https://doi.org/10.1080/00028487.2017.1353545>
- Alcaraz C, Bisazza A, García-Berthou E (2008) Salinity mediates the competitive interactions between invasive mosquitofish and an endangered fish. *Oecologia* 155(1): 205–213. <https://doi.org/10.1007/s00442-007-0899-4>
- Bates AE, McKelvie CM, Sorte CJB, Morley SA, Jones NAR, Mondon JA, Bird TJ, Quinn G (2013) Geographical range, heat tolerance and invasion success in aquatic species. *Proceedings. Biological Sciences* 280(1772): 20131958. <https://doi.org/10.1098/rspb.2013.1958>
- Behrens JW, van Deurs M, Christensen EAF (2017) Evaluating dispersal potential of an invasive fish by the use of aerobic scope and osmoregulation capacity. *PLoS ONE* 12(4): e0176038. <https://doi.org/10.1371/journal.pone.0176038>
- Björklund M, Almqvist G (2010) Rapid spatial genetic differentiation in an invasive species, the round goby *Neogobius melanostomus* in the Baltic Sea. *Biological Invasions* 12(8): 2609–2618. <https://doi.org/10.1007/s10530-009-9669-z>
- Bœuf G, Payan P (2001) How should salinity influence fish growth? *Comparative Biochemistry and Physiology. Toxicology & Pharmacology* : CBP 130(4): 411–423. [https://doi.org/10.1016/S1532-0456\(01\)00268-X](https://doi.org/10.1016/S1532-0456(01)00268-X)
- Borcherding J, Staas S, Krüger S, Ondračková M, Šlapanský L, Jurajda P (2011) Non-native Gobiid species in the lower River Rhine (Germany): Recent range extensions and densities. *Journal of Applied Ichthyology* 27(1): 153–155. <https://doi.org/10.1111/j.1439-0426.2010.01662.x>

- Borgmann U (1996) Systematic analysis of aqueous ion requirements of *Hyalella azteca*: A standard artificial medium including the essential bromide ion. Archives of Environmental Contamination and Toxicology 30(3): 356–363. <https://doi.org/10.1007/BF00212294>
- Brandner J, Cerwenka AF, Schliewen UK, Geist J (2013) Bigger Is Better: Characteristics of Round Gobies Forming an Invasion Front in the Danube River. PLoS ONE 8(9): e73036. <https://doi.org/10.1371/journal.pone.0073036>
- Capps KA, Nico LG, Mendoza-Carranza M, Arévalo-Frías W, Ropicki AJ, Heilpern SA, Rodiles-Hernández R (2011) Salinity tolerance of non-native suckermouth armoured catfish (Loricariidae: *Pterygoplichthys*) in south-eastern Mexico: implications for invasion and dispersal. Aquatic Conservation 21(6): 528–540. <https://doi.org/10.1002/aqc.1210>
- Cerqueira M, Rey S, Silva T, Featherstone Z, Crumlish M, MacKenzie S (2016) Thermal preference predicts animal personality in Nile tilapia *Oreochromis niloticus*. Journal of Animal Ecology 85(5): 1389–1400. <https://doi.org/10.1111/1365-2656.12555>
- Christensen EAF, Svendsen MBS, Steffensen JF (2017) Plasma osmolality and oxygen consumption of perch *Perca fluviatilis* in response to different salinities and temperatures. Journal of Fish Biology 90(3): 819–833. <https://doi.org/10.1111/jfb.13200>
- Christensen EAF, Grosell M, Steffensen JF (2019a) Maximum salinity tolerance and osmoregulatory capabilities of European perch *Perca fluviatilis* populations originating from different salinity habitats. Conservation Physiology 7(1): coz004. <https://doi.org/10.1093/conphys/coz004>
- Christensen EAF, Stieglitz JD, Grosell M, Steffensen JF (2019b) Intra-Specific Difference in the Effect of Salinity on Physiological Performance in European Perch (*Perca fluviatilis*) and Its Ecological Importance for Fish in Estuaries. Biology (Basel) 8(4): 89. <https://doi.org/10.3390/biology8040089>
- Corsi SR, Graczyk DJ, Geis SW, Booth NL, Richards KD (2010) A Fresh Look at Road Salt: Aquatic Toxicity and Water-Quality Impacts on Local, Regional, and National Scales. Environmental Science & Technology 44(19): 7376–7382. <https://doi.org/10.1021/es101333u>
- Delcourt J, Ovidio M, Denoël M, Muller M, Pendeville H, Deneubourg J-L, Poncin P (2018) Individual identification and marking techniques for zebrafish. Reviews in Fish Biology and Fisheries 28(4): 839–864. <https://doi.org/10.1007/s11160-018-9537-y>
- Ellis T, Yildiz HY, Lopez-Olmeda J, Spedicato MT, Tort L, Øverli Ø, Martins CI (2012) Cortisol and finfish welfare. Fish Physiology and Biochemistry 38(1): 163–188. <https://doi.org/10.1007/s10695-011-9568-y>
- Ern R, Huang DTT, Cong NV, Bayley M, Wang T (2014) Effect of salinity on oxygen consumption in fishes: A review. Journal of Fish Biology 84(4): 1210–1220. <https://doi.org/10.1111/jfb.12330>
- Fortes Silva R, Heubel K, Simon M-V, Borcherdig J (2019) Have a break or keep going - behavioral and metabolic overwintering strategies of two invasive species of the river Rhine, Germany. Environmental Biology of Fishes 102(8): 1057–1068. <https://doi.org/10.1007/s10641-019-00890-7>
- Green L, Havenhand JN, Kvarnemo C (2020) Evidence of rapid adaptive trait change to local salinity in the sperm of an invasive fish. Evolutionary Applications 13(3): 533–544. <https://doi.org/10.1111/eva.12859>

- Hart BT, Bailey P, Edwards R, Hortle K, James K, McMahon A, Meredith C, Swadling K (1991) A review of the salt sensitivity of the Australian freshwater biota. *Hydrobiologia* 210(1–2): 105–144. <https://doi.org/10.1007/BF00014327>
- Hempel M, Thiel R (2015) Effects of salinity on survival, daily food intake and growth of juvenile round goby *Neogobius melanostomus* (Pallas, 1814) from a brackish water system. *Journal of Applied Ichthyology* 31(2): 370–374. <https://doi.org/10.1111/jai.12696>
- Herbert ER, Boon P, Burgin AJ, Neubauer SC, Franklin RB, Ardón M, Hopfensperger KN, Lamers LPM, Gell P (2015) A global perspective on wetland salinization: Ecological consequences of a growing threat to freshwater wetlands. *Ecosphere* 6(10): art206. <https://doi.org/10.1890/ES14-00534.1>
- Herlevi H, Aarnio K, Puntila-Dodd R, Bonsdorff E (2018) The food web positioning and trophic niche of the non-indigenous round goby: A comparison between two Baltic Sea populations. *Hydrobiologia* 822(1): 111–128. <https://doi.org/10.1007/s10750-018-3667-z>
- Hintz WD, Mattes BM, Schuler MS, Jones DK, Stoler AB, Lind L, Relyea RA (2017) Salinization triggers a trophic cascade in experimental freshwater communities with varying food-chain length. *Ecological Applications* 27(3): 833–844. <https://doi.org/10.1002/eap.1487>
- Hoover Z, Ferrari MCO, Chivers DP (2013) The effects of sub-lethal salinity concentrations on the anti-predator responses of fathead minnows. *Chemosphere* 90(3): 1047–1052. <https://doi.org/10.1016/j.chemosphere.2012.08.051>
- Hudson CM, Brown GP, Shine R (2017) Evolutionary shifts in anti-predator responses of invasive cane toads (*Rhinella marina*). *Behavioral Ecology and Sociobiology* 71(9): 134. <https://doi.org/10.1007/s00265-017-2367-4>
- Hudson CM, Vidal-García M, Murray TG, Shine R (2020) The accelerating anuran: Evolution of locomotor performance in cane toads (*Rhinella marina*, *Bufo* *marina*) at an invasion front. *Proceedings. Biological Sciences* 287(1938): 20201964. <https://doi.org/10.1098/rspb.2020.1964>
- Karsiotis SI, Pierce LR, Brown JE, Stepien CA (2012) Salinity tolerance of the invasive round goby: Experimental implications for seawater ballast exchange and spread to North American estuaries. *Journal of Great Lakes Research* 38(1): 121–128. <https://doi.org/10.1016/j.jglr.2011.12.010>
- Koç C (2008) The environmental effects of salinity load in Great Menderes Basin irrigation schemes. *Environmental Monitoring and Assessment* 146(1–3): 479–489. <https://doi.org/10.1007/s10661-008-0478-0>
- Kosmala GK, Brown GP, Christian KA, Hudson CM, Shine R (2018) The thermal dependency of locomotor performance evolves rapidly within an invasive species. *Ecology and Evolution* 8(9): 4403–4408. <https://doi.org/10.1002/ece3.3996>
- Kosmala GK, Brown GP, Shine R (2020a) Laid-back invaders: Cane toads (*Rhinella marina*) down-regulate their stress responses as they colonize a harsh climate. *Global Ecology and Conservation* 24: e01248. <https://doi.org/10.1016/j.gecco.2020.e01248>
- Kosmala GK, Brown GP, Shine R, Christian K (2020b) Skin resistance to water gain and loss has changed in cane toads (*Rhinella marina*) during their Australian invasion. *Ecology and Evolution* 10(23): 13071–13079. <https://doi.org/10.1002/ece3.6895>

- Lehtonen TK, Svensson PA, Wong BBM (2016) The influence of recent social experience and physical environment on courtship and male aggression. *BMC Evolutionary Biology* 16(1): 18. <https://doi.org/10.1186/s12862-016-0584-5>
- Leite T, Santos JM, Ferreira MT, Canhoto C, Branco P (2019) Does short-term salinization of freshwater alter the behaviour of the Iberian barbel (*Luciobarbus bocagei*, Steindachner 1864)? *The Science of the Total Environment* 651: 648–655. <https://doi.org/10.1016/j.scitotenv.2018.09.191>
- Leuven RSEW, Hendriks AJ, Huijbregts MAJ, Lenders HJR, Matthews J, Velde GVD (2011) Differences in sensitivity of native and exotic fish species to changes in river temperature. *Current Zoology* 57(6): 852–862. <https://doi.org/10.1093/czoolo/57.6.852>
- Lopez LK, Davis AR, Wong MYL (2018) Behavioral interactions under multiple stressors: Temperature and salinity mediate aggression between an invasive and a native fish. *Biological Invasions* 20(2): 487–499. <https://doi.org/10.1007/s10530-017-1552-8>
- Lorenz OT, Riccobono SA, Smith P (2016) Effects of salinity on the survival and aggression of the invasive Rio Grande cichlid (*Herichthys cyanoguttatus*). *Marine and Freshwater Behaviour and Physiology* 49(1): 1–8. <https://doi.org/10.1080/10236244.2015.1103957>
- Magnhagen C (2012) Personalities in a crowd: What shapes the behaviour of Eurasian perch and other shoaling fishes? *Current Zoology* 58(1): 35–44. <https://doi.org/10.1093/czoolo/58.1.35>
- Millot S, Bégout M-L, Chatain B (2009) Exploration behaviour and flight response toward a stimulus in three sea bass strains (*Dicentrarchus labrax* L.). *Applied Animal Behaviour Science* 119(1–2): 108–114. <https://doi.org/10.1016/j.applanim.2009.03.009>
- Murray L, Rennie MD, Svendsen JC, Enders EC (2017) Respirometry increases cortisol levels in rainbow trout *Oncorhynchus mykiss*: Implications for measurements of metabolic rate. *Journal of Fish Biology* 90(5): 2206–2213. <https://doi.org/10.1111/jfb.13292>
- Myles-Gonzalez E, Burness G, Yavno S, Rooke A, Fox MG (2015) To boldly go where no goby has gone before: Boldness, dispersal tendency, and metabolism at the invasion front. *Behavioral Ecology* 26(4): 1083–1090. <https://doi.org/10.1093/beheco/arv050>
- Overton JL, Bayley M, Paulsen H, Wang T (2008) Salinity tolerance of cultured Eurasian perch, *Perca fluviatilis* L.: Effects on growth and on survival as a function of temperature. *Aquaculture (Amsterdam, Netherlands)* 277(3–4): 282–286. <https://doi.org/10.1016/j.aquaculture.2008.02.029>
- Puntila-Dodd R, Bekkevold D, Behrens JW (2021) Estimating salinity stress via hsp70 expression in the invasive round goby (*Neogobius melanostomus*): Implications for further range expansion. *Hydrobiologia* 848(2): 421–429. <https://doi.org/10.1007/s10750-020-04449-x>
- R Core Team (2020) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.
- Richter L, Schwenkmezger L, Becker J, Winkelmann C, Hellmann C, Worischka S (2018) The very hungry amphipod: The invasive *Dikerogammarus villosus* shows high consumption rates for two food sources and independent of predator cues. *Biological Invasions* 20(5): 1321–1335. <https://doi.org/10.1007/s10530-017-1629-4>
- RStudio Team (2019) RStudio: Integrated Development Environment for R. RStudio, Inc., Boston, MA.

- Schulz C-J, Cañedo-Argüelles M (2019) Lost in translation: The German literature on freshwater salinization. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 374(1764): 20180007. <https://doi.org/10.1098/rstb.2018.0007>
- Scott DM, Rabineau J, Wilson RW, Hodgson DJ, Brown JA (2008) Can pikeperch colonise new freshwater systems via estuaries? Evidence from behavioural salinity tests. *Marine and Freshwater Research* 59(8): 694–702. <https://doi.org/10.1071/MF07241>
- Sgarzi S, Brucet S, Bartrons M, Arranz I, Benejam L, Badosa A (2020) Factors Influencing Abundances and Population Size Structure of the Threatened and Endemic Cyprinodont *Aphanius iberus* in Mediterranean Brackish Ponds. *Water (Basel)* 12(11): 3264. <https://doi.org/10.3390/w12113264>
- Thompson GG, Withers PC (2002) Aerial and aquatic respiration of the Australian desert goby, *Chlamydogobius eremius*. *Comparative Biochemistry and Physiology. Part A, Molecular & Integrative Physiology* 131(4): 871–879. [https://doi.org/10.1016/S1095-6433\(02\)00035-1](https://doi.org/10.1016/S1095-6433(02)00035-1)
- Tietze SM, Gerald GW (2016) Trade-offs between salinity preference and antipredator behaviour in the euryhaline sailfin molly *Poecilia latipinna*. *Journal of Fish Biology* 88(5): 1918–1931. <https://doi.org/10.1111/jfb.12955>
- Vander Laan JJ, Hawkins CP, Olson JR, Hill RA (2013) Linking land use, in-stream stressors, and biological condition to infer causes of regional ecological impairment in streams. *Freshwater Science* 32(3): 801–820. <https://doi.org/10.1899/12-186.1>
- White SJ, Kells TJ, Wilson AJ (2016) Metabolism, personality and pace of life in the Trinidadian guppy, *Poecilia reticulata*. *Behaviour* 153(13–14): 1517–1543. <https://doi.org/10.1163/1568539X-00003375>
- Wisotzky F, Cremer N, Lenk S (2018) Hydrogeologisch-wasserwirtschaftliche Verhältnisse im Ruhrgebiet. *Angewandte Grundwasserchemie, Hydrogeologie und hydrogeochemische Modellierung: Grundlagen, Anwendungen und Problemlösungen*. Springer Berlin Heidelberg, Berlin, Heidelberg, 369–384. https://doi.org/10.1007/978-3-662-55558-3_13

From anti-science to environmental nihilism: the Fata Morgana of invasive species denialism

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Abstract

Invasive species denialism (ISD) is a controversial and hitherto underexplored topic, particularly with regard to its potential impacts on stakeholder engagement in support of invasive species management and policy. We examined how ISD is framed within the Great Lakes invasive species community, as well as the impacts of excluding and including those perceived as denialists in engagement efforts. We interviewed key informants in the region to gain an understanding of their framings of ISD, as well as focus groups allowing participants to discuss the impacts of exclusion and inclusion of stakeholders during the engagement process. ISD discussions were organised into three framings: 1) invasive species denialism; 2) invasive species cynicism; 3) invasive species nihilism. Participants raised concerns about outright exclusion of stakeholders and offered recommendations for mitigation of the impacts of inclusion of proponents of ISD in during stakeholder engagement. Our results have shown that a better understanding of the different framings of ISD is crucial to improve communication with stakeholders and to better inform responses and mitigation efforts. The newly defined framings of invasive species cynicism and invasive species nihilism demonstrate that more targeted responses to specific forms of ISD are needed to improve stakeholder engagement outcomes.

Keywords

Communication, cynicism, engagement, framing, management, outreach, stakeholder

Introduction

Science denialism, while not a new concept, is one which has seen heightened focus in recent years in light of worldwide threats such as climate change or the recent SARS-CoV-2 pandemic. Science denialism is described as an “unwillingness to believe in the existing scientific evidence” (Björnberg et al. 2017) and as a form of pseudoscience in opposition to science (Hansson 2017). Some have employed a more goal-oriented meaning, using the term to describe individuals using rhetoric to give the impression that scientific consensus has not been reached on a topic (Diethelm and McKee 2009), for example claiming that the existence of climate change is still ‘up for debate’.

Like climate change and the SARS-CoV-2 pandemic, invasive species are a global threat of great scientific, economic, and social concern and attention. These global threats have also received a lot of attention in the academic literature arising from their mitigation or management efforts further complicated by ‘denialism’ narratives (Brulle 2020; Taylor 2020). Recently, some invasion ecologists have voiced concerns regarding an increase in vocal opposition toward invasive species management and regulation that they refer to as denialism and which they argue is rooted in a “rejection of undisputed scientific facts” (Russell and Blackburn 2017) and the attempt to cast doubt on science through the use of rhetorical tactics—including misrepresenting or ignoring empirical evidence, cherry-picking data, quote mining, and maligning experts with accusations of bias (Ricciardi and Ryan 2018a, b). These concerns, however, are challenged by other researchers who argue that many disagreements in invasion science stem from different values (Frank 2021) and the choice of language and militaristic metaphors used to describe invasive species (Larson 2005; Janovsky and Larson 2019), rather than a rejection of scientific facts, and that the term ‘denialism’ is an inappropriate descriptor, particularly given its historical use as a pejorative with a troubled history (Sagoff 2018). These authors have made arguments based on values, environmental ethics, and metaphors, which interpret the significance and management implications of biological and ecological facts differently. Many of these challenges have been responded to in the literature (Ricciardi and Ryan 2018b).

The existence of these alternative views on the nature of disagreements in invasion science or ISD in general suggests that this term may have alternative framings among invasive species practitioners and stakeholders as well, which warrants further exploration. This understanding that multiple perspectives exist should, however, in no way be understood as an equivocation of these positions, or an endorsement of these alternative views by the authors. The controversies present in the literature are outlined here solely to demonstrate the potential variety of responses that one might expect to receive in response to questions relating to invasive species denialism.

The controversy surrounding invasive species denialism (ISD) is worth considering, particularly in the context of invasive species management and policy. Management of invasive species relies not only on researchers and decision-makers, but also the involvement and cooperation of various stakeholders to ensure success (Shackleton et al. 2019). Regardless of whether any of these groups might consider themselves

to be denialists, the fact remains that at least some researchers, decision-makers, and members of the public have been perceived by prominent invasive species researchers as making denialist claims (Russell and Blackburn 2017; Ricciardi and Ryan 2018a). The ongoing arguments about what constitutes 'invasive species denialism' and the motivations behind it seen in the literature (Ricciardi and Ryan 2018a, 2018b; Sagoff 2018, 2020; Munro et al. 2019) demonstrate that this term is not universally understood or defined and may pose a barrier to cooperation between those labelled versus those doing the labelling.

It is therefore reasonable to question whether people who are critical of invasive species management may have reasons for their positions other than denying scientific claims. If such critics hold different values and preferences of where public funding ought to be spent on issues of environmental protection, their views would not be accurately reflected by being labelled as simply science denialism. Engagement of stakeholder groups, each with their own values and preferences, is an integral part of invasive species management used to spread awareness of invasive species to the public (Carter et al. 2021), improve research outcomes and inform ecological models (Samson et al. 2017), and resolve conflicts arising during management efforts (Crowley et al. 2017). It is therefore also reasonable to question whether misunderstandings or differences in framing (Golebie et al. 2022) perspectives on invasive species may limit stakeholder engagement in invasive species management and policy, in turn contributing to reduced ability to achieve those management goals.

Our study, therefore, asked how perceptions of invasive species denialism affect stakeholder engagement with invasive species management. We considered four questions: 1) How is the concept of ISD framed by researchers, decision-makers, and the public?; 2) What are the impacts of excluding those labelled as ISDs, if any?; 3) What are the impacts of including those labelled as denialists, if any?; and, 4) If there are negative impacts, how might these be mitigated?

By examining the ways in which 'denialism' is described by participants, we will determine whether the meanings are as clear cut as a rejection of undisputed scientific facts, or if this label is applied using other framings. By exploring the impacts of excluding and including individuals or groups labelled as denialists, we will explore some of the hurdles to outreach and engagement that different framings can occasion. Finally, our study will outline the impacts on effective communication and outreach arising from the 'denialism' label itself, regardless of the intended or perceived meaning.

Methods

Data collection

Within the aquatic invasive species community in the Laurentian Great Lakes basin, key informants were identified by the researchers and invited to participate in semi-structured, in-depth interviews [University of Toronto Research Ethics Board Protocol

#40500]. Key informants are those within a particular community who, based on their knowledge, experience, and position in the community, are able and willing to communicate with the researcher about the topic of interest (McKenna and Main 2013). These key informants included individuals with provincial, state, and federal government agencies, those involved in public communication or outreach, and academic researchers. Nine key informants, a sufficient size to reach coding saturation (Hennink and Kaiser 2022), were interviewed between April and August 2021 using the Zoom platform. Each interview took approximately 1–2 hours. Interview participants were asked four questions pertaining to denialism: 1) Does the term ‘invasive species denialism’ mean anything to you, and, if so, what does it mean?; 2) Are there particular ideas or viewpoints that you would characterise as denialist?; 3) Do you believe that individuals or groups are invasive species denialists?; and, 4) Have you ever had trouble working with an individual or group due to believing that they were an invasive species denialist, or because they believed you were an invasive species denialist?

Following the interviews, participants were invited to participate in a focus group to further discuss as a group the perspectives on ISD previously shared individually during the interviews. Five of the interview participants were willing and able to continue participating further in the focus group. The focus groups were conducted using an asynchronous e-Delphi format over the SurveyMonkey (Momentive Inc. 2018) platform. The e-Delphi is an iterative process, whereby topic experts are asked to discuss conflicting perspectives on a topic and come to a consensus over several rounds of group feedback (Cole et al. 2013). The asynchronous e-Delphi format over SurveyMonkey enabled participants to think over the issues discussed and contribute their ideas at their own pace, and over a time frame convenient for them, to alleviate ongoing online fatigue during the COVID-19 pandemic. The focus group lasted five rounds, sufficient to reach coding saturation (Hennink and Kaiser 2022), with each round lasting one week. Participants were asked about the importance of outreach in invasive species management, and to explore the impacts of both exclusion and inclusion of invasive species denialists on that outreach. The group was also asked for recommendations for how to alleviate some of these impacts, based on their own extensive experience in the Great Lakes aquatic invasive species community.

Data analysis

Audio recordings of interviews were transcribed verbatim using Zoom software, and then corrected manually to ensure accuracy. Anonymized interview transcripts were uploaded onto the qualitative data analysis software NVivo, Version 12 (QSR International Pty. Ltd. 2018). Focus group responses each week were summarised by the facilitator and participants were asked to indicate whether they agreed with the summary of the group’s positions, disagreed, or wished to add additional information or context. The anonymised discussion data were then downloaded from the SurveyMonkey platform into Microsoft Excel.

Analysis of the interview and focus group responses involved a reflexive thematic analysis, using an inductive and semantic approach (Braun and Clarke 2006). A reflexive thematic analysis recognises the importance of the researcher themselves as an “analytical resource” by following a six-phase process: 1) familiarising themselves with the data; 2) systematic data coding; 3) using the data to generate themes; 4) reviewing the themes; 5) naming and refining the themes; and, 6) writing the paper (Braun and Clarke 2021). Inductive thematic analysis allows the data to drive framings, rather than solely those within the existing literature. A semantic approach is one in which the data are described based upon what the participants have said, then organised and interpreted by the researcher (Braun and Clarke 2006). We used this approach because it allows for the ways in which participants describe ISD and use those terms to be captured and analysed without presupposing that they will line up with previously published perspectives, or the researchers’ expectations.

From the interviews, three framings of invasive species denialism were extracted during the analysis. These framings are “invasive species denialism”, “invasive species cynicism”, and “invasive species nihilism”. In the focus group that followed, three potential impacts emerged as a result of excluding or including individuals or groups believed to be denialists: 1) impacts relating to the accuracy of information; 2) impacts relating to management decisions, goals, and outcomes; and, 3) impacts regarding representation and perceived legitimacy. Finally, the focus group provided recommendations to mitigate some of the impacts discussed, which were to incorporate facilitators into engagement efforts, providing balanced information, and to know when engagement is no longer worth continuing.

Results

In this section, we begin by describing how interviewees interpreted ISD, which we organised into three framings. Next, we report on the engagement impacts of ISD followed by participant recommendations as they emerged during the focus groups.

Invasive species framings

Three framings of ‘invasive species denialism’ emerged from key interviews (Table 1). These framings do not represent a definitive meaning of ‘ISD’ nor do we propose to set boundaries on its potential meanings and implications. Rather, the emergent framings are intended only to organise the perspectives presented by participants in a way that clarifies different meanings and how they may shape interactions between stakeholder groups.

Invasive species denialism

“Does nuance equal denialism? I don’t believe so, but others might.” (Interview participant, environmental author and journalist)

Table 1. Framings of invasive species denialism from participant interviews, with paraphrased examples.

| Denialism framings | Forms of the framing | Paraphrased examples |
|----------------------------|---|--|
| Invasive species denialism | Lack of understanding of science | Comparison to climate or medical denialism Inability to understand science in general Used to silence critics, frame arguments as non-scientific |
| | Not believing in the existence of invasive species | Invasive species are not real / are not a problem It's just movement from one place to another This is natural / inevitable |
| | Lack of understanding of invasive species science | Nature will solve the problem itself Refusal to believe in one's role in the spread of invasives This species does not require management Not believing that management plans could go awry Unreasonable expectations for management |
| | | Action would be inconvenient |
| Invasive species cynicism | Nothing in it for them /Taking action perceived as costly | |
| | Species-centric values | Species they care about have not been impacted |
| | Inaction perceived as beneficial | This species is providing food for other species |
| Invasive species nihilism | Discussing invasive species is pointless | Who cares? / Why bother? Invasive species don't matter This is not worth talking about / This is a waste of time |
| | Management efforts are futile | This is a waste of money This is a losing proposition / This is futile We shouldn't be doing anything about them |
| | | Optimism is a form of denialism |
| | Uncertainty leading to inaction | The uncertainty paralyzes us |
| | | |

This denialism framing reflects the framing commonly discussed in invasion ecology literature (Table 1), and we therefore labelled it as invasive species denialism. This framing includes the description of the opiner as having a limited understanding of invasive species science. The framing also mimics recent discussions about medical denialism during the COVID-19 pandemic. For example, one participant explained: *“I’ve been saying this, this whole pandemic too. Like not even just in terms of invasive species but like in general. These people. It’s just like people that don’t believe in doctors or vaccines”* (Interview participant, invasive species public outreach). This framing is generally described as lacking any understanding of science in general, and people perceived this denialism as more generalised, rather than referring to specific people or events. This framing was also described the least, with participants often stating that they had not personally had encounters with anyone holding these views and the majority voicing scepticism that such people really existed. One participant voiced concern that this framing of ISD was used both in the literature and the invasive species community to silence or blunt criticism of the status quo. They said *“[l]argely, my experience with that term was seeing it used by members of the academic community to potentially either discredit or silence or blunt the impact of those outside of the academy who were daring to suggest that it wasn’t as black and white as they were suggesting it was”* (Interview participant, environmental author and journalist).

This framing of denialism was also used to describe those who may understand science generally, but who either did not believe in invasive species or did not believe

invasive species were a problem (Table 1). This type of denialism was described far more often by participants, and encounters with individuals expressing these views were often described in terms of frustration or conflict. For example, “*definitely the evolution arguments of, you know, it’s just how things are and this is a natural progression. That to me, that’s a bit of denialism. And others saying that there are no impacts from invasives in general, ‘it’s just another fish’ or ‘it’s just another plant, what’s the big deal?’ I definitely hear that on some occasions, yeah*” (Interview participant, provincial/state government).

This framing also includes those who believed that invasive species were a problem but who lacked an understanding of invasive species science (Table 1). This included people who did not agree that a particular species required management, as well as people who objected to suggestions that they or their industry were responsible for spreading invasive species. For example, “[*The lakera*] will tell you that, and quite rightly so, that they don’t bring [*invasive species*] into the system, because it’s the ocean-going vessels, the salties, that do. Which is true. But then they’ll deny that they really have an effect on it, knowing full well that they’re moving them around the system. There’s no way under the sun that a Zebra Mussel introduced in Lake St Clair would make it to Lake Superior without it being moved by a ship. Internally, they move this stuff around all the time, but they’re in denial about what they should do” (Interview participant, invasive species communicator).

In addition, this framing also included the view of people who supported management action to prevent or control aquatic invasive species, but who did not understand the potential risks or possibility of failure. Many participants expressed frustration when the public expected management efforts to be wholly without risk of environmental harm, or to be 100% effective, despite the fact that that was not typically possible.

Invasive species cynicism

“It’s pooh-poohing something that we know is a problem because you don’t want to be harmed personally” (Interview participant, invasive species communicator)

The second framing identified is characterised by a description of someone with a lack of support for invasive species management but, in contrast to the previous framing, this view is not because the person lacked understanding of the science behind it, but because of cynical motivations (Table 1). The key difference was whether the individual voicing the denialist viewpoint was believed to understand invasive species science. Invasive species cynics are people who are not interested in, or outright resisting invasive species management because of perceived costs or benefits to themselves. Participants describing these perspectives often referred to the impacts that these people were potentially having on the environment and society and stated that those folks appeared not to care. *“It’s a cynical, I’m going to foist my costs off on society’ or ‘I’m going to profit at the expense of others who are going to be harmed by this’. That’s what denialism is all about”* (Interview Participant, invasive species communicator).

Participants also mentioned that some stakeholders were uninterested in invasive species management because the native species they cared about had not been impact-

ed by invasive species, “I think there are some cases where stakeholders do have a single species focus and they are less concerned about the broader benefits of biodiversity and ecosystem function” (Interview participant, federal researcher). Participants also perceived some people as resistant to the idea that species required management because these people had a particular use for them, for example “*you know some of our gardening plants are not native and trying to tell someone that their pretty flower is maybe a problem is actually where I’ve noticed [denialism] the most*” (Interview participant, federal science advisor). In these cases, this framing of denialism again reflected a position of resistance to invasive species management due to the perceived costs of action or benefits of inaction, and so were also grouped into invasive species cynicism.

Invasive species nihilism

“From first-hand experience I would certainly say that there are [denialists] out there. And I think it’s not even limited to non-professional stakeholders. I think it goes really across all members of society, including professionals” (Interview participant, provincial/state government invasive species manager).

The third framing of ISD described a lack of support for invasive species research or management due to the perception that the whole endeavour was ultimately futile (Table 1). This category was described the most often, and descriptions tended to involve first-hand experiences. It included descriptions of denialism that focused on invasive species research, prevention, management, or outreach as ultimately futile, pointless, or without meaning. This was the form of denialism most frequently described by participants, and one that participants most often described having had first-hand, personal experiences of. People with this perspective were described by interview participants as approaching and informing them about the ultimate futility of their management efforts and other invasive species work in a variety of contexts.

Many saw nihilistic denialism posted to them online, saying “*I feel like we get a lot of deniers on social media. Not a ton, but like any time we post things it’s like you get people that just say, ‘oh just eat them’ or ‘who cares?’, or like ‘there are bigger issues out there like water pollution and water quality, why are you wasting your time and money on this?’*” (Interview participant, invasive species outreach). Many participants also described being approached in-person, saying

I’ll be at public events, and you know every once in a while, you’ll have one or two people that are like ‘why are we spending money on this? This is pointless, there’s no point in trying, they’re already here’. And so, it’s not really disagreeing with the definition of invasive, or early detection rapid response, but more so in the spending of dollars, especially public dollars, on those efforts when to them, it seems futile, it seems pointless (Interview participant, invasive species public outreach).

Those people expressing these views were described by participants as being particularly concerned with the waste of financial resources on an endeavour that they did not consider to be worthwhile.

Participants also described experiences with these types of nihilistic framings of their work not just in-person, but in professional settings, and even from colleagues. When asked about ISD, one participant responded, sadly, that they believed others perceived them to be the invasive species denialist because they continued to experience hope related to their own work, rather than believing the endeavour was hopeless. They said:

I suppose my amount of optimism is a form of denial... I've had people approach me being like 'how on earth do you still do this work? Why do you do this? This is ridiculous! It's a waste of your time!'. I've definitely had those people during conferences, and meetings, and presentations confront me about this. And my response is, you know, I'd rather try than not. It's worth the effort. So, I guess I'm sort of a denialist in that way (Interview participant, provincial/state government invasive species management).

This belief that others may experience them as a denialist during the course of their work in invasive species management was not limited to being told one's work was not worthwhile. Others involved in management decision-making also expressed the possibility that their views may be considered denialist by stakeholders because they did not support prioritising the detection of invasive species that were unlikely to be prevented or controlled. For example, one participant stated:

I believe that if we don't have the resources to do anything about an invasive species, or we're not willing to do anything about an invasive species, I don't believe in putting resources into early detection. Like why bother spending resources if we're not going to do anything about it? I know that can rub people the wrong way, and I might get labelled a little bit with denialism (Interview participant, federal government science advisor).

Again, there was a linkage made between a perception of potential waste of resources on management, and denialism. However, when this participant was asked if, resources were unlimited, would they be willing to take action to prevent every invasive species, they said that “[m]aybe if we had all the money in the world, and we knew that it just doesn't make efficient sense, or effective sense, or it's a good use of the taxpayer dollars, we might still not address something, right?” (Interview participant, federal science advisor).

Engagement impacts

Interview participants all agreed that engagement with stakeholders was a priority for invasive species management. Furthermore, they all felt that stakeholder groups should not be excluded on the basis of being perceived to be denialists. However, participants also agreed that inclusion of people with different perceptions or values regarding invasive species management could act as a barrier to communication or action. To address this challenge in more detail, the focus group was asked to discuss these issues as a group. They were asked to describe and come to a consensus regarding some of the impacts of excluding folks believed to be denialists, as well as the impacts of including them in engagement and outreach. They were also asked to come up with some recommendations as a group to prevent or mitigate any of these impacts. The impacts outlined and agreed upon by the focus group can be divided into three

categories: 1) Impacts relating to the accuracy of information; 2) Impacts relating to management decisions, goals, and outcomes; and, 3) Impacts regarding representation and perceived legitimacy.

Impacts relating to the accuracy of information

Decision-makers engage stakeholder groups in invasive species management to inform, as well as gather input about, invasive species occurrences and management practices. Focus group participants raised concerns about excluding stakeholder groups for two main reasons: that engagement might be biased and therefore lead to less effective outcomes; and second, that unique and important knowledge may be missed if some stakeholder groups are excluded. Focus group participants were particularly concerned that “*exclusion of different stakeholder groups may lead to a biased or limited representation of different values and perceptions*” in the data they gather during engagement efforts for use by decision-makers, making it less accurate and therefore less useful for effective management.

The inclusion of more diverse perspectives was conversely seen as potentially allowing for improvement in the overall information available to researchers and managers. For example, it was noted that some people seen as denialists may still have information on novel invasion pathways that could be of value to managers. Furthermore, engagement with as many people as possible was described as providing greater leverage to promote changes in behaviour and practices.

Impacts relating to management decisions, goals, and outcomes

Participants often described outreach as potentially the only way to convince those who were opposed to management efforts of its value. Exclusion of individuals or groups without at least an initial attempt at outreach was therefore seen as generally undesirable as it could undermine the ability to meet engagement and management goals. As noted by one participant, “*[e]xcluding engagement is a problem because politicians are not going to regulate a major industry without some justification, and if the industry is not engaged with those working in [aquatic invasive species] policies, they have no incentive at all to cooperate and seek mutually agreeable solutions*”.

The primary concern of people in the focus group regarding inclusion of perceived denialists in engagement efforts was that it could lead to delays in decision-making, particularly when urgent decisions and actions are necessary. There were concerns that such inclusion “*may make the process more difficult or lead to decisions that are not supported by some decision-makers*”. Their inclusion was also believed to require increased time and effort as “*repeated conversations and outreach will need to take place along with the understanding that some stakeholders will never support the project*”.

Impacts regarding representation and perceived legitimacy

Including diverse stakeholders was repeatedly emphasised as a priority, and any exclusion was seen as a potential detriment to that. Exclusion of individuals or groups

believed to be denialists was also described as “*risking public outcry and loss of faith in the process*” of engagement. This was described not as necessarily harmful to a current management project, but potentially harmful for future attempts at engagement if it was perceived that only agreeable perspectives were included.

Because inclusion and representation of diverse stakeholders and values was seen as a priority, the inclusion of denialists was seen as an inherently positive choice, despite the aforementioned drawbacks. Some also noted the ethical importance of including all those who had been, or may be, harmed by the invader to give them the chance to learn more and prevent future harms.

Participant recommendations

The focus group consensus was that inclusion of diverse perspectives, values, and stakeholders was a priority to them, even if those were believed to be denialists who may impede ongoing management goals. Therefore, the recommendations they provided regarding how to best proceed to mitigate potential impacts focused on those impacts resulting from the denialists’ inclusion. Exclusion, at least directly from the outset, was not presented as a viable option.

Include people trained to engage with stakeholders to facilitate engagement

This guidance was described as being important when engagement may become counterproductive, either because participants are not actually interested in invasive species management, or they are against management entirely. It was emphasised that “*mitigating this type of issue can be helped with a strong chairperson during the engagement process overall. Having participant guiding principles, similar to the Canadian Science Advisory Secretariat, helps the chair point to unproductive conversations*”. The use of a facilitator could also potentially ease the emotional burdens placed on the practitioners facing nihilistic comments regarding their careers or values by having a third party take on that responsibility.

Provide clear, balanced information

This was viewed as particularly important for those considered denialists due to their disbelief in the existence of invasive species, or invasive species science. A scepticism toward invasive species science or researchers was described as stemming from hearing ‘one-sided’ information from science communicators. As explained by one participant

The best way to engage individuals who do not tend to agree with prevention or other management of aquatic invasive species [AIS] is to show examples of situations where AIS have led to important (i.e., damaging) ecological or social outcomes. To ensure credibility and avoid the ‘sky is falling’ mentality, these should also be countered with situations where AIS have not led to extreme impacts, which ensures that objectivity is retained.

This was seen as improving credibility of the communicator, and potentially allowing sceptical participants to be convinced.

In addition, this guidance was also viewed as important for those who lacked an understanding of invasive species science, or management limitations or costs. Rather than asking those who may not be informed on this topic, participants noted that “*effective engagement needs to be done with a series of structured management options that clearly lay out potential management targets, their costs (ecological and economic), and related uncertainties, which is a very large undertaking*”. This was described as useful for allowing stakeholders to understand the goals and limitations of management, and to make choices that are possible to implement. They also emphasised that communicators “*should also ensure that balanced information makes it clear that invasive species management may fail (i.e., management success is not a certain outcome, and we have to be cognizant of this possibility when committing resources and seeking stakeholder support)*”. Ensuring that participants are aware that success is not guaranteed also enables them to be better informed and make realistic decisions.

Know when to move on

It was noted that breakdowns in communication can occur for a variety of reasons, including resistance due to holding denialist positions. It was therefore noted that “*there are times when you need to accept that, for whatever reason, the stakeholders aren't ready to hear what you have to say or to move forward on a project. Best to reduce engagement and, perhaps, bring in others to try a different strategy*”, and that “*the manager might have to accept that he/she can never ‘adjust’ all stakeholder expectations.*” Focus group participants noted that they had an ethical responsibility to represent all members of the community they were serving, and that if the majority of folks were wishing to proceed with urgent management action, it would not be ethical to prevent that through continued engagement with folks who would not be convinced. Rather, it was recommended to move on without the denialists in the interim and try to reach out to them again at a later date, when urgent action was no longer required.

Discussion

This study has explored the meanings of ISD and its implications for invasive species engagement and management. ISD has been shown to have a greater variety of meanings and implications than previously explored in the literature. While the research literature has previously discussed the framing of ISD as being a lack of understanding of invasive species science, invasive species cynicism and invasive species nihilism are arguably the most important for practitioners to understand. The latter were reported far more often than views perceived as simply anti-scientific and with more potentially complex impacts on engagement effectiveness and management outcomes. An understanding of these ISD framings, particularly of the importance of cynicism and nihilism in an ISD context, are therefore integral to stakeholder communication and engagement efforts.

Why is it important how invasive species denialism is framed?

The invasive species literature has mostly focused on discussing the existence and implications of invasive species denialism as a form of science denialism. Our results suggest that this view is an oversimplification with potential negative impacts on stakeholder engagement and invasive species management communication.

General descriptions of denialists as anti-science do not address those people who question invasive species based on public spending or on the likelihood of success/failure of attempts to manage invasive species. All too often, academic technical experts interpret invasive species management as the operationalization of a scientific understanding of the risks and solutions to invasive species. Our results suggest that other views about invasive species are tied to questioning societal prioritisation of environmental protection, spending of public funds, and perceptions of the overall effectiveness of management practices. Such views cannot simply be described as “science denialist” as their objections are not solely about the science of invasive species. Rather, often these views are concerned with policy implications and socio-economic impacts, constituting societal domains of concern which are legitimate grounds for questioning.

Generalisations appear to serve a rhetorical purpose of dismissal of contrarian views, something which was of some concern to at least one interview participant. This dismissal has the potential for biasing engagement efforts, or of omitting important input from the engagement process and resulting decision-making. It is notable that when exploring their understanding of ISD, participant descriptions of a person who lacks understanding of science were generalised and hypothetical, rather than an actual experience. Conversely, discussions of ISD that fit within the cynicism or nihilism frameworks were often of specific people or groups, rooted in first-hand experience. This suggests two things: the idea of the contrarian science denialist appears more widespread than the denialists themselves; and, denialism rooted in cynicism and nihilism appears to be a more immediate concern, particularly given participants’ concerns with potential impacts on those forms of ISD for future management and outreach efforts. In both cases, a more nuanced view enables decision-makers and science communicators to better hone their communication strategies and engagement processes.

While the first framing described as invasive species denialism reflects the viewpoints commonly described in the invasion ecology literature of individuals or groups who do not accept invasive species science, the existence of other framings, i.e., cynicism and nihilism in ISD, is an important finding. Previous published work regarding ISD has often framed it as rejecting invasive species science for contrarian reasons (Russell and Blackburn 2017; Ricciardi and Ryan 2018a, 2018b). We have teased apart these as different aspects of ISD to show that these facets are not always seen together, or in every case. Individuals who were described as not believing in invasive species, or believing that we should not intervene because invasive species are natural, were not described in the same way as individuals who did not care about their local ecosystem, or who were perceived to be foisting their costs onto others. Our results also explored a form of ISD rooted in perceptions of futility not captured in descriptions of those who are denialists

to be cynical or contrarian. We have increased the resolution at which we can examine ISD, as described by those involved in invasive species management and engagement.

This will better enable both researchers and practitioners to better understand the potential meanings that these terms may hold to those they communicate with, as well as to consider how the impacts of ISD on their work may differ depending on the framing being employed. For example, outreach devoted to public education must take time to determine precisely whether the community is open to education, and what exactly they need to be educated about. For example, education devoted to defining invasive species will not be as useful for convincing a laker stakeholder who already knows what invasive species are that lakers are partly responsible for the transport and spread of invasive species.

‘Opening up’ and ‘closing down’: potential responses to cynicism

Cynicism is a broader societal problem and invasive species management must give careful thought on how to handle this issue. On the one hand, there is a need to ‘open up’ engagement to diverse views, including cynics, because it enables us to produce more accurate science that is seen as legitimate, accountable, and allowing for social empowerment (Stirling 2008). On the other hand, there is a need to ‘close-down’ engagement with cynics once the basis for their views is understood, discussed, and considered within an expansive view of the values and priorities held by others.

Cynicism or apathy in climate denialism has been previously described not as linked to a lack of scientific understanding, but to a culture of denialism where those who benefit ignore the problem because “we don’t really want to know” (Norgaard 2006). Participants in this study also differentiated between those expressing cynicism toward management and those who did not understand or believe the science. Much of invasion science practices and recommendations are rooted not in objective data, but in subjective, normative values (Munro et al. 2019; Latombe et al. 2022). The fact that one’s values may lead one to ignore the problem of invasive species for cynical gain means that conventional outreach and engagement, which tend to focus on education about invasive species science, may not be sufficient to change behaviours. Rather, if encountering invasive species cynicism, outreach may need to pivot to focus on the way that invasive species may impact particular values. However, if indeed some people ‘don’t really want to know’, it may be best to ‘move on’ as recommended by the focus group participants.

The Janus face of nihilism

Nihilism can lead to reflexivity and empathy for views that question the feasibility of effectively controlling invasive species. Take the example of Sea Lamprey. Management of Sea Lamprey has been touted as “a remarkable success” and “tremendously successful” (GLFC 2014; DFO 2018), yet at the same time eliminating Sea Lamprey is described as “impossible” to the extent that management cannot be relaxed for “even a short time” in the same publications. There is reason to question our ability to fully prevent new invasive species, and what resistance to management really means, not because of a lack of science, but because of limited resources and different perceptions and evaluations of risks and impacts.

On the other hand, nihilism can become debilitating for action when action is needed, feasible and desired. It can also impact managers' ability to do their work. Invasive species nihilism should be particularly concerning to those involved in invasive species work in that it was experienced by participants in their workplaces and was expressed toward them not only from the public, but also from colleagues. Research into workplace wellbeing has shown a connection between perceptions of one's work as meaningless with experiences of alienation, emotional exhaustion, and burnout (Bailey and Madden 2019). While research has been conducted on the impacts of emotional exhaustion in fields such as health care (Meltzer and Huckabay 2004), the emotional labour cost of those in the invasive species community confronted with nihilistic comments on a regular basis about their work remains unexplored. More research is needed to fully measure and comprehend the impacts of invasive species nihilism on invasive species practitioners and their work. This research is needed due to the prevalence of this form of ISD being experienced by participants during the course of their work, and the potential for the impacts of emotional exhaustion or burnout affecting practitioners' ability to manage invasive species or engage with stakeholders.

Nihilism is often expressed as something being a waste; a waste of resources, a waste of effort, a waste of time. Some of our participants expressed that, even were resources unlimited, they would still not support management of every invasive species in the region. This suggests that it is not solely the limited nature of what is being wasted, which is the underpinning concern for this form of denialism, but rather the concept of waste itself; the perception that the effort of management is, at least in some cases, itself wasteful and therefore not worth doing, even if what is being wasted were unlimited. This idea of invasive species research and management being perceived as a type of inherent waste should be examined further, particularly as it may relate to inaction or resistance to other types of environmental research and management.

Strengths and limitations

This research has delved deeper into the growing and controversial topic of invasive species denialism. To our knowledge, this is the first study to include Great Lakes community members to determine what the term "invasive species denialism" means to them, and how it is being used by decision-makers or practitioners in the field. Our results have shown that ISD is a term with different meanings with different connotations. As a result, we have also shown that the implications of different types of ISD, and the appropriate responses to each, differ as well. This research will contribute to growing efforts to better understand the topic of ISD and provide solid strategies to outreach and engagement professionals encountering different framings of ISD during their work. More in-depth research is needed into how each of these different framings specifically impact management, engagement, and policy in order to craft more finely tuned recommendations for specific situations. We hope that our research has contributed to those future efforts by enabling the identification of these different framings and providing general strategies to build upon.

This research was conducted amongst members of the aquatic invasive species community of the Great Lakes basin. Therefore, it is unclear whether the framings of

ISD employed by participants are due to a unique perspective of people in this region, or whether they can be generalised to the overall invasive species community. More research should be conducted specifically exploring the ways that other communities describe the phenomena of ISD and its impacts to determine how widespread are these framings, particularly that of invasive species nihilism, due to its novelty.

Conclusions

Familiarity with the framings of ISD are important both to understand the values and motivations that drive those who espouse views perceived as denialist, as well as to clarify how these individuals are either understood or dismissed in the environmental decision-making process. An understanding of these framings is also vital to respond to instances of ISD appropriately. Whether we are being confronted with anti-science contrarianism, environmental cynicism, or outbursts of nihilism, should rightly inform our responses and our strategies to counter these positions.

Future research should examine the topic of invasive species nihilism in greater detail. It is currently unknown how pervasive this phenomenon is in the broader invasive species community and among the public. It is also currently unknown what the impacts of exposure to these nihilistic framings of their work may be on those involved in invasive species research and management. An awareness of those impacts will help us to better understand the role of ISD in invasive species communication and engagement.

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References

- Bailey C, Madden A (2019) “We’re not scum, we’re human”: Agential responses in the face of meaningless work. *Scandinavian Journal of Management* 35(4): e101064. <https://doi.org/10.1016/j.scaman.2019.101064>
- Björnberg KE, Karlsson M, Gilek M, Hansson SO (2017) Climate and environmental science denial: A review of the scientific literature published in 1990–2015. *Journal of Cleaner Production* 167: 229–241. <https://doi.org/10.1016/j.jclepro.2017.08.066>

- Braun V, Clarke V (2006) Using thematic analysis in psychology. *Qualitative Research in Psychology* 3(2): 77–101. <https://doi.org/10.1191/1478088706qp063oa>
- Braun V, Clarke V (2021) One size fits all? What counts as quality practice in (reflexive) thematic analysis? *Qualitative Research in Psychology* 18(3): 328–352. <https://doi.org/10.1080/14780887.2020.1769238>
- Brulle RJ (2020) Denialism: organized opposition to climate change action in the United States. In: Konisky M (Ed.) *Handbook of US Environmental Policy*. Edward Elgar Publishing, Cheltenham, 328–341. <https://doi.org/10.4337/9781788972840.00033>
- Carter L, Mankad A, Zhang A, Curnock MI, Pollard CR (2021) A multidimensional framework to inform stakeholder engagement in the science and management of invasive and pest animal species. *Biological Invasions* 23(2): 625–640. <https://doi.org/10.1007/s10530-020-02391-6>
- Cole ZD, Donohoe HM, Stelfox ML (2013) Internet-based Delphi research: Case based discussion. *Environmental Management* 51(3): 511–523. <https://doi.org/10.1007/s00267-012-0005-5>
- Crowley SL, Hinchliffe S, McDonald RA (2017) Conflict in invasive species management. *Frontiers in Ecology and the Environment* 15(3): 133–141. <https://doi.org/10.1002/fee.1471>
- Diethelm P, McKee M (2009) Denialism: What is it and how should scientists respond? *European Journal of Public Health* 19(1): 2–4. <https://doi.org/10.1093/eurpub/ckn139>
- DFO [Fisheries and Oceans Canada] (2018) Sea Lamprey: The battle continues to protect our Great Lakes fishery. <https://www.dfo-mpo.gc.ca/species-especes/publications/ais-eae/lamprey-lamproie/index-eng.html>
- Frank DM (2021) Disagreement or denialism? “Invasive species denialism” and ethical disagreement in science. *Synthese* 198(S25): 6085–6113. <https://doi.org/10.1007/s11229-019-02259-w>
- Golebie EJ, van Riper CJ, Arlinghaus R, Gaddy M, Jang S, Kochalski S, Lu Y, Olden JD, Stedman R, Suski C (2022) Words matter: A systematic review of communication in non-native aquatic species literature. *NeoBiota* 74: 1–28. <https://doi.org/10.3897/neobiota.74.79942>
- GLFC [Great Lakes Fisheries Commission] (2014) Sea Lamprey control in the Great Lakes: A remarkable success!. http://www.glfc.org/pubs/factsheets/FACT%205_all.pdf
- Hansson SO (2017) Science denial as a form of pseudoscience. *Studies in History and Philosophy of Science* 63: 39–47. <https://doi.org/10.1016/j.shpsa.2017.05.002>
- Hennink M, Kaiser BN (2022) Sample sizes for saturation in qualitative research: A systematic review of empirical tests. *Social Science & Medicine* 292: 114523. <https://doi.org/10.1016/j.socscimed.2021.114523>
- Janovsky RM, Larson ER (2019) Does invasive species research use more militaristic language than other ecology and conservation biology literature? *NeoBiota* 44: 27–38. <https://doi.org/10.3897/neobiota.44.32925>
- Larson BM (2005) The war of the roses: Demilitarizing invasion biology. *Frontiers in Ecology and the Environment* 3(9): 495–500. [https://doi.org/10.1890/1540-9295\(2005\)003\[0495:TWOTRD\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2005)003[0495:TWOTRD]2.0.CO;2)
- Latombe G, Lenzner B, Schertler A, Dullinger S, Glaser M, Jarić I, Pauchard A, Wilson JR, Essl F (2022) What is valued in conservation? A framework to compare ethical perspectives. *NeoBiota* 72: 45–80. <https://doi.org/10.3897/neobiota.72.79070>

- McKenna SA, Main DS (2013) The role and influence of key informants in community-engaged research: A critical perspective. *Action Research* 11(2): 113–124. <https://doi.org/10.1177/1476750312473342>
- Meltzer LS, Huckabay LM (2004) Critical care nurses' perceptions of futile care and its effect on burnout. *American Journal of Critical Care* 13(3): 202–208. <https://doi.org/10.4037/ajcc2004.13.3.202>
- Momentive Inc (2018) SurveyMonkey. Mome-ntive Inc., San Mateo, California, USA. <https://www.momentive.ai>
- Munro D, Steer J, Linklater W (2019) On allegations of invasive species denialism. *Conservation Biology* 33(4): 797–802. <https://doi.org/10.1111/cobi.13278>
- Norgaard KM (2006) “We don't really want to know” environmental justice and socially organized denial of global warming in Norway. *Organization & Environment* 19(3): 347–370. <https://doi.org/10.1177/1086026606292571>
- QSR International Pty Ltd (2018) NVivo (Version 12). <https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home>
- Ricciardi A, Ryan R (2018a) The exponential growth of invasive species denialism. *Biological Invasions* 20(3): 549–553. <https://doi.org/10.1007/s10530-017-1561-7>
- Ricciardi A, Ryan R (2018b) Invasive species denialism revisited: Response to Sagoff. *Biological Invasions* 20(10): 2731–2738. <https://doi.org/10.1007/s10530-018-1753-9>
- Russell JC, Blackburn TM (2017) The rise of invasive species denialism. *Trends in Ecology & Evolution* 32(1): 3–6. <https://doi.org/10.1016/j.tree.2016.10.012>
- Sagoff M (2018) Invasive species denialism: A reply to Ricciardi and Ryan. *Biological Invasions* 20(10): 2723–2729. <https://doi.org/10.1007/s10530-018-1752-x>
- Sagoff M (2020) Fact and value in invasion biology. *Conservation Biology* 34(3): 581–588. <https://doi.org/10.1111/cobi.13440>
- Samson E, Hirsch PE, Palmer SC, Behrens JW, Brodin T, Travis JM (2017) Early engagement of stakeholders with individual-based modelling can inform research for improving invasive species management: The round goby as a case study. *Frontiers in Ecology and Evolution* 5: 149. <https://doi.org/10.3389/fevo.2017.00149>
- Shackleton RT, Adriaens T, Brundu G, Dehnen-Schmutz K, Estévez RA, Fried J, Larson BMH, Liu S, Marchante E, Marchante H, Moshobane MC, Novoa A, Reed M, Richardson DM (2019) Stakeholder engagement in the study and management of invasive alien species. *Journal of Environmental Management* 229: 88–101. <https://doi.org/10.1016/j.jenvman.2018.04.044>
- Stirling A (2008) “Opening up” and “closing down” power, participation, and pluralism in the social appraisal of technology. *Science, Technology, & Human Values* 33(2): 262–294. <https://doi.org/10.1177/0162243907311265>
- Taylor L (2020) Covid-19: How denialism led Mexico's disastrous pandemic control effort. *BMJ (Clinical Research Ed.)* 371: m4952. <https://doi.org/10.1136/bmj.m4952>

Forty years of invasion research: more papers, more collaboration...bigger impact?

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Abstract

Scientific research has become increasingly collaborative. We systematically reviewed invasion science literature published between 1980 and 2020 and catalogued in Clarivate Analytics Web of Science to examine patterns of authorship and the relationship between co-authorship and annual citation rates. This study analysed 27,234 publications across 1,218 journals and demonstrated that, as the number of publications in invasion science has exponentially increased, the number of authors publishing per year and the average number of authors per paper have also increased. The rising number of authors per paper coincides with a marked decline of single-authored publications; approximately 92% of publications in this dataset were multi-authored, with single-authored papers comprising less than 4% of all papers published in 2020. The increase in multi-authored papers is likely driven by multiple factors, including the widespread perception that collaboration increases scientific quality. The number of authors is positively correlated with perceived research impact; papers with two or more authors produce research that is more frequently cited compared to single-authored papers, and papers with five or more authors have annual citation rates almost double that of single-authored papers. The complexity, context-dependence and urgency of biological invasions contributed to the rise of the highly collaborative field of modern invasion science.

Keywords

Bibliometrics, biological invasions, citations, coauthorship, collaboration, scientific publication

Introduction

Charles Elton's 1958 monograph, "The Ecology of Invasions by Animals and Plants", documented the breakdown of Wallace's biogeographic realms and discussed the biology and impacts of invasive species on native communities, constituting one of the first works calling scientific attention to biological invasions. This monograph resulted in some, albeit insignificant, initial interest in biological invasions (Simberloff 2011a) but has since become the single most cited source in the field of invasion science (Richardson and Pyšek 2008) with > 8500 citations (via Google Scholar) at the time of writing. Invasion science encompasses research in multiple disciplines examining facets of the causes, consequences and management of non-native species (Richardson et al. 2011; Richardson and Ricciardi 2011). Though Elton (1958) is often cited as the foundation of invasion science as a distinct discipline, the field was catapulted into mainstream ecology in the 1980s (Simberloff 2011a, 2011b) after the Scientific Committee on Problems of the Environment (SCOPE) programme on biological invasions generated research on the causes, impacts and management of invasive species (Mooney and Drake 1986; Drake et al. 1989). Research on biological invasions subsequently grew at an exponential pace, beginning in the 1990s (Richardson and Pyšek 2008; Davis 2009; Simberloff 2011a), reflecting the need to address the management of the rapidly increasing number of non-native species spreading globally. The initiation of several journals solely dedicated to research on biological invasions (e.g. "Biological Invasions" in 1999 and "NeoBiota" in 2011) and journals relaunching with substantial focus on invasions (e.g. "Diversity and Distributions" in 1999) demonstrate the increased scientific interest in understanding and managing invasive species.

Price (1963) is often cited as the foundational paper predicting the demise of single-authored publications by 1980 after observing an increasing trend in multiple authorship in chemical science. Many studies have duplicated Price's observation of the rise of multi-authored publications in a wide variety of disciplines, including, but not limited to, economics (e.g. Hudson 1996; Kuld and O'Hagan 2017), the social sciences and humanities (e.g. Ossenblok et al. 2014; Henriksen 2016; Verleysen and Ossenblok 2017), medical sciences (e.g. Khan et al. 1999; King 2000) and natural sciences (e.g. Regalado 1995; Nabout et al. 2015). However, the decline in single authorship and rise of multiple authorship has not been consistent across fields. While social sciences manifested declines in single authorship of 72% to 38%, pharmacology manifested declines from 13% to 4% (Gorham and Kelly 2014). Research in the fields of ecology and environmental sciences shows a similar overall trend in the rise of multiple authorship (e.g. Weltzin et al. 2006; Gorham and Kelly 2014; Barlow et al. 2018), with a decline in single authorship from 35% to 5% between 1981 and 2012 (Gorham and Kelly 2014). Qiu and Chen (2009) examined some authorship patterns in the field of invasion science; however, their temporal scope was limited to research published between 1991 and 2007 and, although they calculated the average number of authors per publication for each year, they did not examine the proportions of single- and multi-authored papers. In light of the necessity of a transdisciplinary approach

to and the complexity and the global nature of biological invasions (Diagne et al. 2020), the field of invasion science as a distinct field selects for multi-authored papers.

The declining trend in the proportion of single-authored papers is probably driven by a complex interplay of multiple factors. Collaboration is likely, in part, a byproduct of advances in transportation (i.e. deregulation of the airline industry reducing travel costs) and technology (e.g. fax, long-distance phone calls, email, the internet, videoconferencing) that facilitate communication amongst collaborators (Rosenblat and Mobius 2004; Hamermesh 2013). The decline of single-authored papers also likely reflects the increasingly collaborative and interdisciplinary nature of science. This trend is often encouraged by funding sources (e.g. National Science Foundation, European Research Council) and promoted by working groups and institutions (e.g. National Center for Ecological Analysis and Synthesis, German Center for Integrative Biology Research) in the field of ecology (Weltzin et al. 2006; Barlow et al. 2018). Interdisciplinary teams with a wide range of skills (e.g. taxonomists, statisticians, ecological modellers, field assistants, technicians) are often required to conduct ecological studies. Additionally, the increased number of co-authors may also be driven by changes in the criteria for authorship. Technicians, data collectors, field assistants or research students who, in the past, may have been included in the acknowledgements, are now often co-authors (Weltzin et al. 2006; Gorham and Kelly 2014; Barlow et al. 2018). Moreover, the notion of 'publish or perish' and publications as a currency for productivity in science may play a large role in increasing collaboration (Nabout et al. 2015). Multiple authorship allows for a division of labour and costs, effectively decreasing the amount of time and funding each individual author contributes in comparison to a single-authored publication (Leimu and Koricheva 2005a), which may increase overall perceived productivity. Furthermore, funding, hiring and promotion decisions are all often influenced by collaborations (Katz and Martin 1997), and this fact may increase the participation of scientists in multi-authored papers. No single factor drives the decline of single-authored papers, but multiple factors act together to promote the rise of multi-authored papers.

Collaboration is often assumed to result in higher quality research and impact (Katz and Martin 1997; Franceschet and Costantini 2010). However, the evidence for this presumption is not always clear. Scholars have examined the impact of collaboration on the quality and impact of research by relating the number of authors to citations or citation rate. Citations are used as a proxy for scientific success, academic impact and the relative importance of a publication and/or its author (Hamilton 1990) despite studies (e.g. Leimu and Koricheva 2005b; Borsuk et al. 2009) demonstrating bias and influence by other unrelated factors. Some disciplines show a negative or no relationship between citations or citation rate and number of authors (e.g. Smart and Bayer 1986; Rousseau 2001; Leimu and Koricheva 2005a; Bornmann et al. 2012), while others show a positive relationship (e.g. Smart and Bayer 1986; Rousseau 2001; Hudson 2007), including the field of ecology (e.g. Leimu and Koricheva 2005a; Borsuk et al. 2009; Fox et al. 2016; Barlow et al. 2018). In the field of invasion science, Qiu and Chen (2009) examined patterns in citations per publication by journal, country,

institution and amongst the top ten most productive authors, while Pyšek et al. (2006) evaluated the most-cited publications for changes in citations over time, which journals published highly-cited papers and citation performance for specific sub-fields of study. To our knowledge, no work has examined the relationship between citation rate and number of authors in invasion science.

While some studies (e.g. Pyšek et al. 2006; Qiu and Chen 2009) have addressed authorship patterns and the impacts of collaboration on citation rate in invasion science, no systematic review to date covers publications published from the rise of modern invasion science (i.e. 1980s) to the present. Here, we systematically review literature in the field of invasion science published between 1980 and 2020 to determine how trends in co-authorship have changed over time and how patterns of authorship relate to citation rate. We expected that the mean number of authors and proportion of multi-authored publications will have increased over time and that there will be a positive relationship between the number of authors and citation rate.

Methods

We queried Clarivate Analytics Web of Science Core Collections topics, which examines the title, abstract, author keywords and keywords plus for all records in the database, between May and October 2021 for the following search terms: (“non-native” OR “nonnative” OR “exotic speci*” OR “alien” OR “invas* speci*” OR “biolog* invas*”). The results of this search (N = 76,239*) were further refined by publication year (1980–2020, inclusive) to coincide with the rise of modern invasion science and to exclude irrelevant Web of Science categories (e.g. ‘Dermatology’; see Suppl. material 1: Appendix S1 for complete search query). We defined an invasion as a species introduced, deliberately or accidentally, to geographic areas outside of their historical native range (Simberloff 2011c). We systematically screened the remaining results (N = 42,695*) following a co-developed set of rules. A publication was retained if it discussed an invasion, range-expanding natives (Simberloff 2011c) while addressing the issue of analogy to an invasion and potential impacts, documented new records while discussing possible route of invasion and/or potential impacts, had a clear objective of quantifying the proportion of non-native species in an area, documented the spread of an established non-native species, examined the biology of a non-native species in its native or non-native range and clearly linked the reported biology to the invasion or managing it and/or was related to the management of non-native species. A publication was excluded if it contained species occurrences for an area and mentioned only that a species was introduced without further discussion regarding the invasion, examined the biology

* Clarivate Analytics Web of Science continually updates the database such that content is added or purged from the system and/or KeyWords Plus are recalculated which generates new sets of terms. These features resulted in minor fluctuations in the number of records produced by the query over the course of this systematic review as the most relevant results were continuously updated.

of a non-native species in its native or non-native range without discussion of how the biology related to the invasion or managing it, mentioned that the study organism was non-native in the study area and that the research could be used for management without any detail or obvious linkages between the research and management, indicated a new record of a non-native species without further discussion regarding potential route of invasion, impacts or control and any biocontrol publications that focused on non-invasion related aspects (e.g. treatment of the biocontrol agent during importation).

A total of 27,535 publications met the criteria for inclusion. These publications included three papers that have been retracted, 297 early view papers published in a volume in 2021 and one early view paper published in a volume in 2022, which were all excluded from further analyses. Bibliographic information for each publication was exported via Web of Science Fast 5K, including the name(s) of the author(s), publication type, publication title, journal or source title, total times cited, publication date, volume, issue, page number(s), early access date, digital object identifier and accession number (a unique Web of Science identification number) when available and where applicable.

For each record, we tallied the total number of authors to calculate the mean number of authors, maximum number of authors and the proportion of single-author publications each year from 1980 to 2020. We excluded a single outlier published in 2020 with 642 authors from mean and maximum calculations, as well as the analysis examining citations. We also summed the total number of papers each author co-authored. We assumed that papers with an anonymous author ($N = 56$) were single-authored and that authors with the same last name and first initial(s) were the same author. We searched each record via Google Scholar and matched institutional affiliations to the best of our ability in cases where multiple authors had the same last name and first initial(s). Annual citation rates for individual publications were calculated as the number of citations divided by the number of years since publication (sensu Leimu and Koricheva 2005b). We calculated mean annual citation rates as the sum of all citation rates across publications in a year divided by the number of publications published in that year. To explore how the number of authors is related to citation rate, we completed a generalised linear mixed model (GLMM) with the annual citation rate (plus one) log-transformed as a response variable, number of authors (one, two, three, four or more than four) as a fixed effect and age calculated as number of years since publication as a random effect. We also examined the relationship between the number of authors and the rate of self-citation. We randomly sampled 100 papers authored by one, two, three, four, five, six to ten and eleven or more authors, respectively. We accessed the entry for each randomly sampled paper on Web of Science, recorded the total number of citations up to 20 June 2022 and recorded the number of citations excluding papers authored by authors of the randomly sampled paper (i.e. we excluded self-citations). All analyses were completed in R statistical software, version 4.0.5 (R Core Team 2021) using the *dplyr* (Wickham et al. 2021), *emmeans* (Lenth 2021), *ggplot2* (Wickham 2016), *ggpubr* (Kassambara 2020), *lme4* (Bates et al. 2015) and *MuMIn* (Bartoń 2020) packages.

Results

The total number of publications related to invasion science published each year and registered in Clarivate Analytics Web of Science Core Collections has exponentially increased (Fig. 1) from three publications in 1980 to 2,535 publications in 2020, with an average of 680.9 publications per year. The number of source titles (e.g. journals) publishing papers each year has also increased exponentially from three source titles in 1980 to 495 source titles in 2020 (Fig. 2). A total of 1,218 source titles have published invasion science literature between 1980 and 2020. The top five journals publishing papers in invasion science during this period were “Biological Invasions” (N = 2653), “PLoS ONE” (N = 723), “Diversity and Distributions” (N = 547), “Hydrobiologia” (N = 432) and “Aquatic Invasions” (N = 397) (Table 1). Approximately 29.5% of source titles have contributed only one publication between 1980 and 2020.

Patterns in authorship also changed over this period (Figs 3 and 4). A total of 53,685 authors contributed to 27,234 publications. Of these, 36,232 (67.5%) authors contributed a single paper, 14,293 (26.6%) contributed between 2 and 5 papers, 1,833 (3.4%) contributed between 6 and 9 papers and 1,327 (2.5%) contributed 10 or more papers. Amongst authors who have published a paper in any given year, the proportion of those who have published a single paper versus those who have published two or

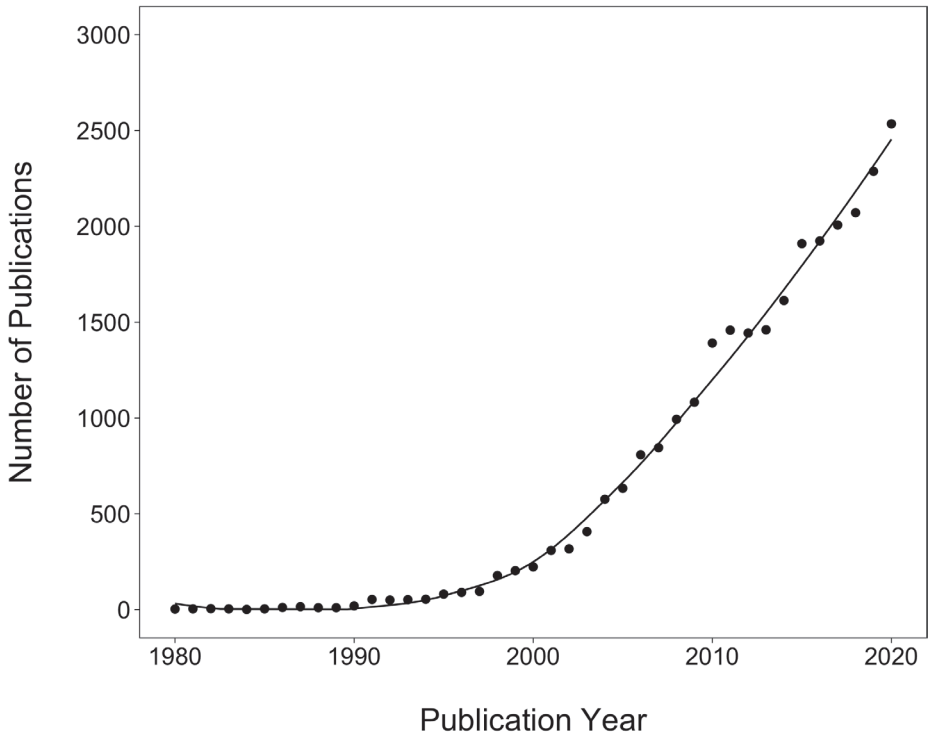


Figure 1. Total number of publications (N = 27,234) in invasion science published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria).

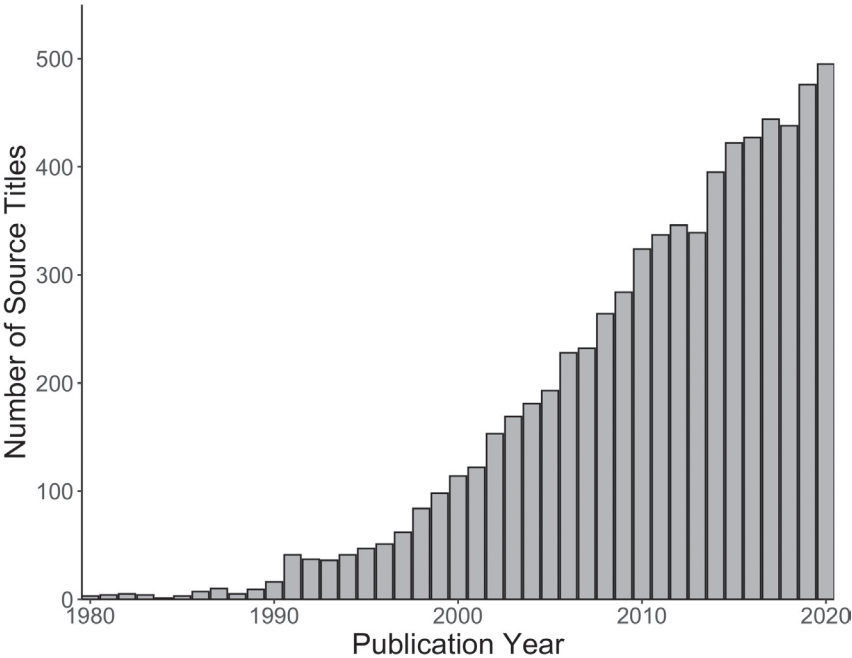


Figure 2. The total number of source titles (e.g. journals, N = 1,218) that have published at least one publication in invasion science literature (N = 27,234) between 1980 and 2020 that were also registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria).

Table 1. The number of papers published by the 20 most productive source titles (e.g. journals) in invasion science literature published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria).

| Journal | Number of Publications | | | | Total |
|---------------------------------------|------------------------|-----------|-----------|-----------|-------|
| | 1980–1990 | 1991–2000 | 2001–2010 | 2011–2020 | |
| Biological Invasions | 0 | 0 | 757 | 1896 | 2653 |
| PLoS ONE | 0 | 0 | 33 | 690 | 723 |
| Diversity and Distributions | 0 | 0 | 255 | 292 | 547 |
| Hydrobiologia | 0 | 23 | 104 | 305 | 432 |
| Aquatic Invasions | 0 | 0 | 66 | 331 | 397 |
| Biological Conservation | 7 | 43 | 164 | 181 | 395 |
| Ecology | 3 | 35 | 144 | 181 | 363 |
| Oecologia | 3 | 29 | 123 | 180 | 335 |
| Journal of Applied Ecology | 2 | 17 | 109 | 194 | 322 |
| Ecological Applications | 0 | 30 | 149 | 138 | 317 |
| Ecology and Evolution | 0 | 0 | 0 | 313 | 313 |
| Forest Ecology and Management | 0 | 7 | 81 | 205 | 293 |
| Invasive Plant Science and Management | 0 | 0 | 64 | 202 | 266 |
| Plant Ecology | 0 | 8 | 94 | 160 | 262 |
| Conservation Biology | 3 | 47 | 126 | 84 | 260 |
| Freshwater Biology | 0 | 9 | 82 | 164 | 255 |
| Marine Ecology Progress Series | 0 | 5 | 102 | 128 | 235 |
| Scientific Reports | 0 | 0 | 0 | 231 | 231 |
| Management of Biological Invasions | 0 | 0 | 0 | 229 | 229 |
| Journal of Ecology | 0 | 8 | 79 | 139 | 226 |

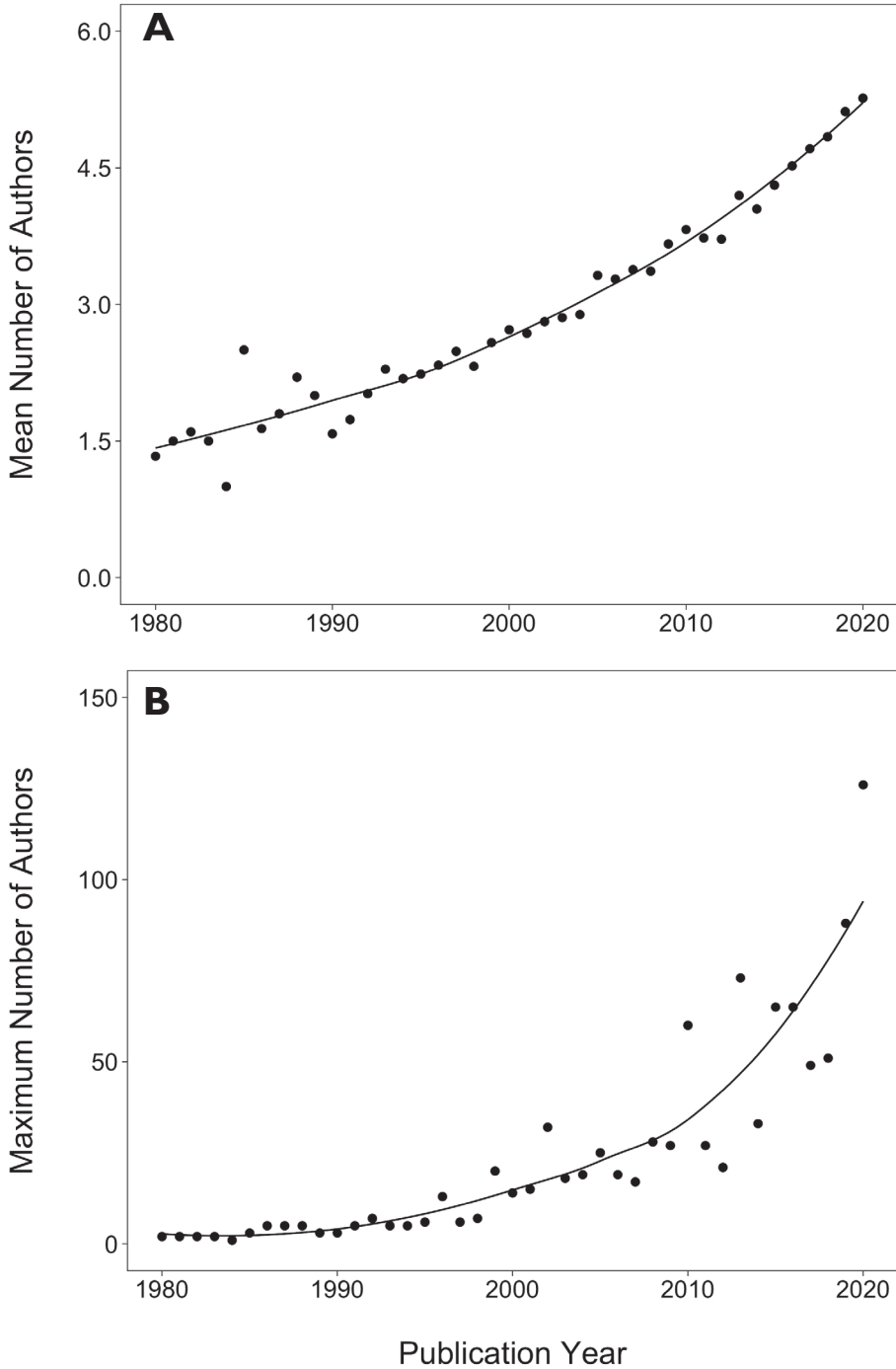


Figure 3. The mean (A) and maximum (B) number of authors on publications in invasion science (N = 27,233) published between 1980 and 2020. A single outlier (with 642 authors) published in 2020 was removed.

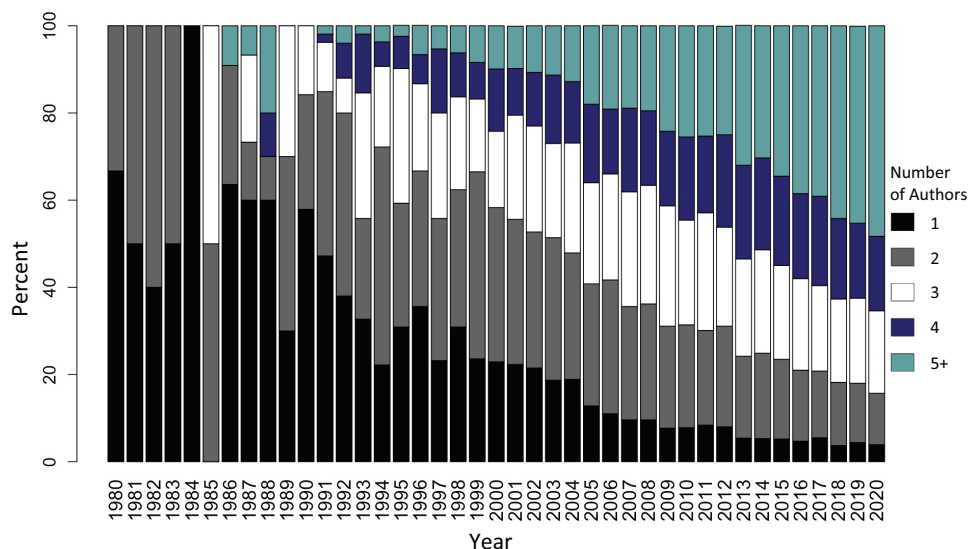


Figure 4. The proportions of single- and multi-authored publications ($N = 27,234$) in invasion science published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria).

more papers between 1980 and 2020 has remained relatively stable (Fig. 5). The mean number of authors has steadily increased between 1980 and 2020 from ~ 1.3 to ~ 5.3 . Likewise, the maximum number of authors has increased from 2 in 1980 to 126 in 2020, not counting the outlier. Approximately 92.0% of publications ($N = 25,045$), published in the invasion science literature between 1980 and 2020 were multi-authored (Fig. 4; Table 2). The proportion of single-authored publications has decreased from $\sim 66.7\%$ in 1980 to $\sim 3.9\%$ in 2020 and has fluctuated around 5% or less since 2013 (Fig. 4; Table 2). Conversely, the proportion of publications with five or more authors has increased from 0% in 1980 to 48.3% in 2020 (Fig. 4; Table 2).

The mean annual citation rate across publications has increased from ~ 0.6 citations per year in 1980 to ~ 3.6 citations per year in 2020 (Fig. 6). Approximately 28.7% of publications accounted for 80% of total citations; these publications had a mean of 4.2 authors, while the remaining 71.3% of publications had a mean of 4.1 authors. A positive relationship exists between annual citation rates and number of authors. While the number of authors predicted the annual citation rate ($p < 0.001$), the marginal coefficient of determination (i.e. considering only fixed effects) was 0.04, indicating high variability in the data and a low fraction of variation explained by number of authors alone. Examining the influence of number of authors on annual citation rate, we found that multi-authored papers had significantly higher citation rates than did single-authored papers ($p < 0.0001$; Fig. 7). Papers with four or more authors had significantly higher citation rates than did papers with one, two, or three authors ($p < 0.0001$; Fig. 7); however, no significant differences existed in citation rates between papers with two authors

Table 2. The proportion of single- and multi- authored publications (N = 27,234) in invasion science published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria).

| Year | Percentage of publications by number of authors | | | | |
|------|---|------|------|------|------|
| | 1 | 2 | 3 | 4 | 5+ |
| 1980 | 66.7 | 33.3 | 0 | 0 | 0 |
| 1981 | 50.0 | 50.0 | 0 | 0 | 0 |
| 1982 | 40.0 | 60.0 | 0 | 0 | 0 |
| 1983 | 50.0 | 50.0 | 0 | 0 | 0 |
| 1984 | 100.0 | 0 | 0 | 0 | 0 |
| 1985 | 0 | 50.0 | 50.0 | 0 | 0 |
| 1986 | 63.6 | 27.3 | 0 | 0 | 9.1 |
| 1987 | 60.0 | 13.3 | 20.0 | 0 | 6.7 |
| 1988 | 60.0 | 10.0 | 0 | 10.0 | 20.0 |
| 1989 | 30.0 | 40.0 | 30.0 | 0 | 0 |
| 1990 | 57.9 | 26.3 | 15.8 | 0 | 0 |
| 1991 | 47.2 | 37.7 | 11.3 | 1.9 | 1.9 |
| 1992 | 38.0 | 42.0 | 8.0 | 8.0 | 4.0 |
| 1993 | 32.7 | 23.1 | 28.8 | 13.5 | 1.9 |
| 1994 | 22.2 | 50.0 | 18.5 | 5.6 | 3.7 |
| 1995 | 30.9 | 28.4 | 30.9 | 7.4 | 2.5 |
| 1996 | 35.6 | 31.1 | 20.0 | 6.7 | 6.7 |
| 1997 | 23.2 | 32.6 | 24.2 | 14.7 | 5.3 |
| 1998 | 30.9 | 31.5 | 21.3 | 10.1 | 6.2 |
| 1999 | 23.6 | 42.9 | 16.7 | 8.4 | 8.4 |
| 2000 | 22.9 | 35.4 | 17.5 | 14.3 | 9.9 |
| 2001 | 22.3 | 33.3 | 23.9 | 10.7 | 9.7 |
| 2002 | 21.5 | 31.2 | 24.3 | 12.3 | 10.7 |
| 2003 | 18.7 | 32.7 | 21.6 | 15.7 | 11.3 |
| 2004 | 18.9 | 29.0 | 25.2 | 14.1 | 12.8 |
| 2005 | 12.8 | 28.0 | 23.2 | 18.0 | 18.0 |
| 2006 | 11.0 | 30.7 | 24.3 | 14.9 | 19.2 |
| 2007 | 9.6 | 26.0 | 26.3 | 19.2 | 18.9 |
| 2008 | 9.6 | 26.6 | 27.2 | 17.1 | 19.5 |
| 2009 | 7.7 | 23.4 | 27.6 | 17.1 | 24.2 |
| 2010 | 7.8 | 23.6 | 24.0 | 19.1 | 25.5 |
| 2011 | 8.4 | 21.7 | 27.0 | 17.6 | 25.3 |
| 2012 | 8.0 | 23.1 | 22.7 | 21.2 | 24.9 |
| 2013 | 5.4 | 18.8 | 22.3 | 21.5 | 32.1 |
| 2014 | 5.3 | 19.6 | 23.7 | 21.1 | 30.3 |
| 2015 | 5.2 | 18.3 | 21.5 | 20.5 | 34.5 |
| 2016 | 4.7 | 16.3 | 21.0 | 19.5 | 38.5 |
| 2017 | 5.5 | 15.3 | 19.6 | 20.5 | 39.1 |
| 2018 | 3.7 | 14.5 | 19.1 | 18.5 | 44.2 |
| 2019 | 4.4 | 13.6 | 19.5 | 17.2 | 45.2 |
| 2020 | 3.9 | 11.8 | 18.9 | 17.1 | 48.3 |

and papers with three authors ($p = 0.1078$; Fig. 7). The average rate of self-citation across all randomly sampled papers was 15.9% and was positively correlated with the number of authors (Table 3). Papers with three or more authors had self-citation rates three to four times higher than single-authored papers (Table 3) and papers with eleven or more authors had the highest self-citation rate at 23.7%.

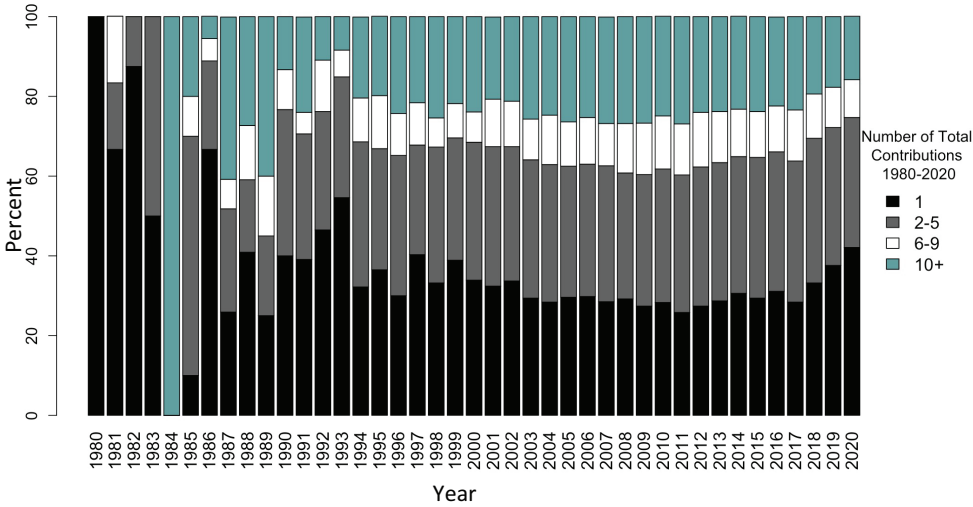


Figure 5. The proportions of authors publishing a paper in invasion science each year who have contributed one, two to five, six to nine or ten or more papers between 1980–2020.

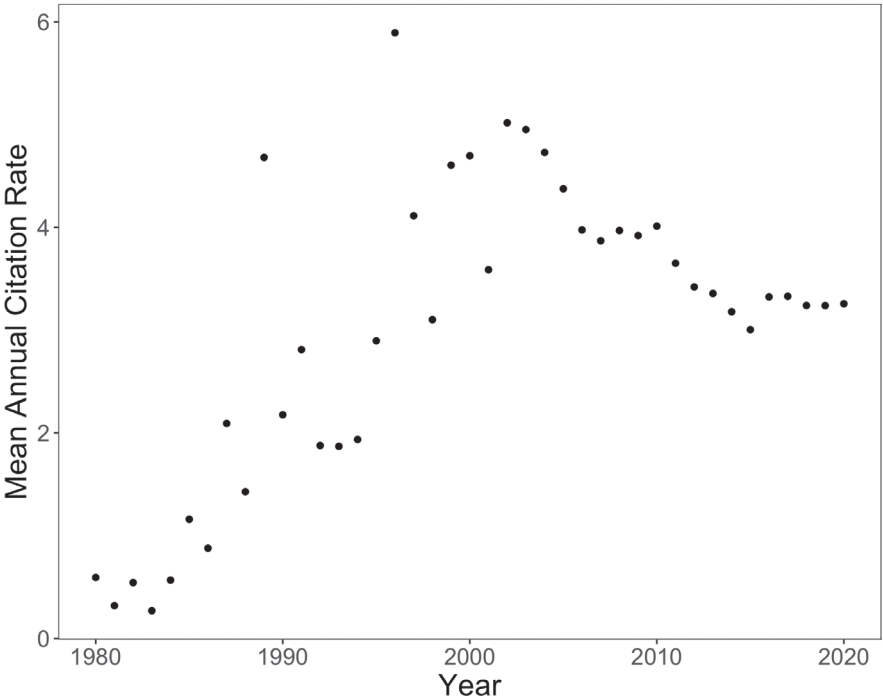


Figure 6. The mean annual citation rate for publications (27,225) in invasion science published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria). Mean annual citation rate was calculated as the sum of citation rates across publications published in a year divided by the number of papers published that year. Outliers for number of authors ($N = 1$; 642 authors) and number of citations ($N = 8$; > 1900 citations) were excluded.

Table 3. The percentage of total citations that are self-citations for randomly sampled papers authored by one, two, three, four, five, six to ten and eleven or more authors, respectively, in invasion science literature published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections. A total of 700 papers were randomly sampled evenly across author number groups.

| Number of Authors | Total Number of Citations | Number of Citations Excluding Self-Citations | Percentage of Total Citations that are Self-Citations | Average Age of Sampled Papers (Years) |
|-------------------|---------------------------|--|---|---------------------------------------|
| One | 5029 | 4763 | 5.3 | 13.4 |
| Two | 3862 | 3512 | 9.1 | 11.4 |
| Three | 2237 | 1775 | 20.7 | 10.4 |
| Four | 2931 | 2489 | 15.1 | 8.8 |
| Five | 3052 | 2359 | 22.7 | 8.2 |
| Six to Ten | 2595 | 2040 | 21.4 | 6.5 |
| Eleven or More | 4658 | 3552 | 23.7 | 5.6 |

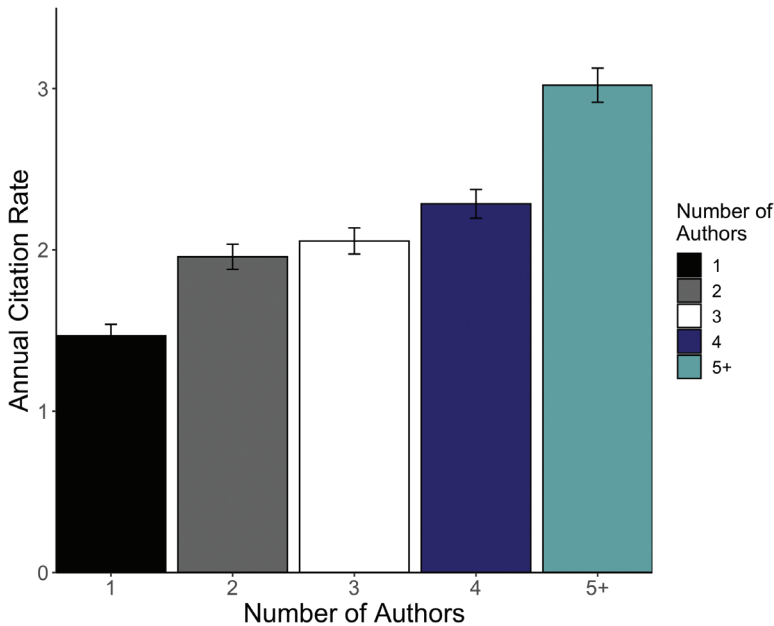


Figure 7. The back-transformed least square mean annual citation rate and standard error for publications (N = 27,225) with one (N = 2,188), two (N = 5,523), three (N = 6,032), four (N = 4,949) and five or more (N = 8,533) authors in invasion science published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria). Annual citation rate was calculated as the number of citations divided by the number of years since initial publication. Outliers for number of authors (N = 1; 642 authors) and number of citations (N = 8; > 1900 citations) were excluded.

Discussion

This study examined patterns of authorship and how these relate to citations in the field of invasion science. Our analysis indicates research activity has exponentially increased since the rise of modern invasion science in the 1980s and the rate of increase

in the number of papers published is almost 50 times higher than that recorded for the biological sciences between 1990 and 2016 (Boltovskoy et al. 2018). Invasion science is highly collaborative, with a very small proportion of single-authored publications and two-thirds of authors publishing only a single paper between 1980 and 2020. The proportion of multi-authored papers surpassed that of single-authored papers in the early 1990s, coinciding with a sharply increased rate of publication. The steady increase in the mean number of authors could signal the maturation (Clarke 1964) of the field of invasion science, which is also supported by the growth of journals publishing invasion science literature. Collaboration has a positive relationship with research impact as measured by annual citation rate. Publications with four or more authors have a significantly higher citation rates than those with one, two or three authors. The higher citation rates amongst multi-authored papers in comparison to single-authored papers may reflect benefits and higher quality of collaborative research, increased visibility owing to a larger network for dissemination or other factors.

Invasion science has become increasingly collaborative over the past 40 years. The number of publications has exponentially increased and the increase in the mean number of authors per publication indicates the growth of the number of scientists working in the field. Over 53,000 authors have contributed at least one publication in invasion science, with only one-third contributing multiple publications between 1980 and 2020. Although Qiu and Chen (2009) documented an average of 3.2 authors per publication between 1991 and 2007, the fact that our data for the same time period show a lower number is likely due to the increased scope of this analysis with additional search terms, temporal breadth and, thus, sample size. Regardless, the increase in the number of authors reveals the theoretical, analytical, temporal, spatial and financial scale of biological invasions that requires multiple skillsets, expertise and division of labour or cost. Similarly, as data on biological invasions have accumulated globally, collaborative authors benefit from sharing data. Although it is nearly impossible to parse out the frequency of data-sharing in collaborative papers, the increase in data publications may provide some indication of this collaborative benefit. Our dataset included 27 publications categorised as data papers that were published between 2016 and 2020 (see Suppl. material 1: Appendix S2) with an average of 14.6 authors, while only two were single-authored. Two of these publications accounted for the highest number of authors in our dataset, with 126 and 642 authors. Sharing data, amongst other factors, has likely played an important role in the rise of multi-authored papers.

Collaboration plays an important role in the invasion science literature. Fewer than 10% of publications published between 1980 and 2020 were single-authored, a trend comparable to patterns of multiple authorship in the biological sciences generally (Franceschet and Costantini 2010) and the field of ecology (Paine 2005; Gorham and Kelly 2014; Barlow et al. 2018). The frequency of multi-authored publications increased rapidly, with the first publication containing five or more authors appearing in 1986, indicating the early contribution of multiple authorship to the rise of the field. By 1991, publications with two or more authors exceeded the proportion of single-authored publications and, in 2020, close to half of all publications had five or more

authors. The proportion of publications with two authors has decreased since 2007, with three authors has decreased since 2012, with four authors has decreased since 2015 and with five or more authors has steadily increased. This pattern may reflect the widespread notion that collaborative research results in higher quality science, particularly in light of the finding that manuscripts with four or more authors were more likely to be accepted for publication (Tregenza 2002; Barlow et al. 2018).

The increasing complexity in the challenges and types of questions studied in invasion science, ecology and science in general, increasingly requires synthesis of information. The rise of synthesis in ecology is demonstrated by the establishment of synthesis centres around the world beginning in the 1990s (Lynch et al. 2015) where researchers assemble in working groups for intensive, collaborative research on a key topic or question in the field. These groups often include individuals at different career stages with different specialities, expertise, and skills (Baron et al. 2017). Although examining the proportion of publications produced by working groups was outside the scope of our analysis, working groups have, nonetheless, played an important role in research on biological invasions, with SCOPE working groups initiating the rise of the field. Collaboration on SCOPE projects set an early precedent for synthesis and the necessity of biologists, statisticians, modellers and managers to work together to address the growing concern regarding biological invasions and their management (Simberloff 2011b). This rise in synthesis is further demonstrated by the establishment of institutions like the Centre for Invasion Biology in South Africa, which has produced 1,745 peer-reviewed publications between 2004 and 2018; this work involved 4,237 authors from 110 countries across 1,729 of these publications (Richardson et al. 2020). Working groups and institutions will likely continue to contribute to an ongoing decline in the proportion of publications that are single-authored; examples in invasion science include, but are not limited to, the European Information and Research Network on Aquatic Invasive Species (ERNAIS), Global Invader Impact Network (GIIN), Global Invasions Research Coordination Network, Global Naturalized Alien Flora database (GloNAF), Mountain Invasive Research Network (MIREN), Phragmites Network (PhragNet), Pacific Invasives Partnership and Southern Hemisphere Network on Conifer Invasions.

The increase in the number of source titles publishing invasion science literature signals the growth of the discipline. During the rise of modern invasion science, general journals like “Ecology” published increasing numbers of papers on invasions and the specialised journal “Biological Invasions” began in 1999. Another specialised journal, “NeoBiota”, began in 2002 as conference proceedings and became a standard journal in 2011. Although “NeoBiota” ranks below the top 20 journals publishing invasion science literature, this is likely an artifact of the scope of Clarivate Analytics Web of Science, as the earliest record in our dataset was published in 2015; similarly, the first volume of “Biological Invasions” is also absent on Web of Science. Pyšek (1995) found that nine journals published 28% of plant invasion literature and 20 journals accounted for almost 50% of plant invasion literature between 1974 and 1993. Although our study examines literature across taxa from 1980 to 2020, we similarly found that the top nine journals accounted for 22.6% of invasion science literature. However, the top

20 journals published only 33.2% of papers and this pattern, coupled with the large number of journals contributing only one paper to invasion science literature, indicates the growth of the field beyond popular generalised journals like “Ecology”, as well as specialised journals like “Biological Invasions” or “NeoBiota”. Qiu and Chen (2009) examined the journals publishing invasion research from 1991 to 2007 and our analysis documented more than twice the number of source titles. The ten most productive journals identified by Qiu and Chen (2009) were similar to the top ten in our study and all were amongst the top twenty source titles identified by our analysis. The slight departure in our analysis compared to Qiu and Chen (2009) probably stems from increased search terms, a longer time series, the growth of the discipline and the launch of new scientific journals. Despite the challenges associated with records registered in Web of Science, the sheer number of journals publishing invasion science literature in 2020 indicates the impact biological invasions have across ecosystems, taxa and sub-fields of study globally.

Analysis of citations and citation rates reveals important information on the maturity of the field, citation density and the potential role of collaboration in the impact of research. Here, we have shown that the mean annual citation rate steadily increased as the field has matured, a pattern Pyšek et al. (2006) also noted amongst highly-cited publications in invasion ecology. As the number of publications and scientists working in the field has increased, the body of work available for citation has also grown. Garfield (2006) termed a pattern of 20% of articles accounting for 80% of publications the “80/20 phenomenon,” with the majority of publications receiving few or no citations. We found that approximately 28.7% of publications accounted for 80% of total citations in the field between 1980 and 2020. The number of highly-cited papers depends on the size of the field, and the relative youth of modern invasion science as a distinct discipline may explain the slight departure of our results from the 80/20 indicator. We also found a positive relationship between collaboration and impact as measured by annual citation rates. Previous research on the ecological literature has demonstrated that publications with four or more authors (Leimu and Koricheva 2005b; Barlow et al. 2018) were cited more and our analysis found multi-authored publications have a higher annual citation rate than do single-authored publications. The positive association between collaboration and annual citation rate could indicate a net benefit of collaboration on the quality of a publication or, alternatively, researchers may perceive greater merit or credibility in multi-authored publications and are more likely to cite them rather than a single-authored paper.

Multiple factors could account for a positive relationship between citations and number of authors. Characteristics of the author(s) could influence the number of citations a publication accumulates. Rather than a reflection of collaborative benefits, multi-authored publications may accumulate more citations via self-citation (Herbertz 1995; Aksnes 2003; Leimu and Koricheva 2005a; Glänzel et al. 2006), even if self-citations do not solely account for the positive relationship between citations and the number of authors (Larivière et al. 2015). Previous work has shown that citations by others increases in parallel with self-citations (Leimu and Koricheva 2005a), and our analysis of randomly sampled papers also demonstrates a positive relationship between the number of authors and rate of self-citations. A potentially important factor might

be citations by colleagues of authors who may be more familiar with the work; an increased number of authors equates to a larger network and, potentially, citations by that network. The positive relationship between citations and number of authors could also reflect the common scientific practice of citing recent publications, which are more likely to be multi-authored as the proportion of single-authored publications declines. Citation rates may not necessarily always reflect research quality or real impact (American Society for Cell Biology 2012; Pulverer 2015; Schmid 2017).

The positive association between annual citation rate and number of authors may also be a by-product of technological advancements facilitating collaboration of scientists amongst different countries and institutions, both of which have been shown to be associated with increased citation rates (Narin et al. 1991; Katz and Hicks 1997; Goldfinch et al. 2003; Leimu and Koricheva 2005a). Larger collaborative teams could also promote the visibility of research, thus increasing citations; as the number of authors increases, the number of research networks and individual researchers introduced to the publication also increases (Franceschet and Costantini 2010). The emergence of ‘citation farms,’ whereby groups of scientists preferentially cite one another’s work (Van Noorden and Chawla 2019), may also play a role in the relationship between collaboration, number of authors and citation rates. Although there have been calls for increasing interdisciplinarity in invasion science to advance the field (e.g. Vaz et al. 2017; Heger et al. 2021), socio-ecological research began in the 1990s and early 2000s (Vaz et al. 2017), and some advances in interdisciplinary collaboration have occurred in research on historical, economic and management aspects of biological invasions. As interdisciplinary collaboration has been associated with increased citation rates in some instances in ecology (Leimu and Koricheva 2005a), such a relationship could also play a role in the effect of number of authors on citation rates in invasion science. Despite the potential role other factors – including, but not limited to, authors’ stages of career, previous contributions to the field, open access status and type of contribution (e.g. primary research, review, data paper) – may play in the annual citation rate of a publication, we have demonstrated here a positive association with number of authors.

Conclusions

Price (1963) predicted the extinction of single-authored publications by 1980 and, although this prediction coincided with the beginning of modern invasion science, the field, nonetheless, shifted towards increasing multiple authorship almost immediately. The field of modern invasion science responded to the complexity, idiosyncrasy and urgency of biological invasions through increased collaborative research. The rise of multiple authorship likely reflects a combination of multiple factors including perceived scientific quality, division of labour and costs, technological advances in communication and transportation and increasingly interdisciplinary teams. Collaboration has a positive impact on the accumulation of citations, effectively conferring a higher likelihood of increased research impact as measured by annual citation rates.

References

- Aksnes DW (2003) A macro study of self-citation. *Scientometrics* 56(2): 235–246. <https://doi.org/10.1023/A:1021919228368>
- American Society for Cell Biology (2012) San Francisco declaration on research assessment (DORA).
- Barlow J, Stephens PA, Bode M, Cadotte MW, Lucas K, Newton E, Nuñez MA, Pettoirelli N (2018) On the extinction of the single-authored paper: The causes and consequences of increasingly collaborative applied ecological research. *Journal of Applied Ecology* 55(1): 1–4. <https://doi.org/10.1111/1365-2664.13040>
- Baron JS, Specht A, Garnier E, Bishop P, Campbell CA, Davis FD, Fady B, Field D, Gross LJ, Guru SM, Halpern BS, Hampton SE, Leavitt PR, Meagher TR, Ometto J, Parker JN, Price R, Rawson CH, Rodrigo A, Sheble LA, Winter M (2017) Synthesis centers as critical research infrastructure. *Bioscience* 67(8): 750–759. <https://doi.org/10.1093/biosci/bix053>
- Bartoń K (2020) MuMIn: Multi-model inference. R package version 1.43.17.
- Bates D, Maechler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. R package version 1.1-26. *Journal of Statistical Software* 67: 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Boltovskoy D, Sylvester F, Paolucci EM (2018) Invasive species denialism: Sorting out facts, beliefs, and definitions. *Ecology and Evolution* 8(22): 11190–11198. <https://doi.org/10.1002/ece3.4588>
- Bornmann L, Schier H, Marx W, Daniel H-D (2012) What factors determine citation counts of publications in chemistry besides their quality? *Journal of Informetrics* 6(1): 11–18. <https://doi.org/10.1016/j.joi.2011.08.004>
- Borsuk RM, Budden AE, Leimu R, Aarssen LW, Lortie CJ (2009) The influence of author gender, national language and number of authors on citation rate in ecology. *The Open Ecology Journal* 2(1): 25–28. <https://doi.org/10.2174/1874213000902010025>
- Clarke BL (1964) Multiple authorship trends in scientific papers. *Science* 143(3608): 322–324. <https://doi.org/10.1126/science.143.3608.822>
- Davis MA (2009) *Invasion biology*. Oxford University Press Inc., New York.
- Diagne C, Catford JA, Essl F, Nuñez MA, Courchamp F (2020) What are the economic costs of biological invasions? A complex topic requiring international and interdisciplinary expertise. *NeoBiota* 63: 25–37. <https://doi.org/10.3897/neobiota.63.55260>
- Drake JA, Mooney HA, diCasti F, Groves RH, Kruger FJ, Rejmánek M, Williamson M (1989) *Biological invasions: A global perspective*. Wiley, Chichester.
- Elton CS (1958) *The ecology of invasions by animals and plants*. Methuen, London. <https://doi.org/10.1007/978-1-4899-7214-9>
- Fox CW, Paine CET, Sauterey B (2016) Citations increase with manuscript length, author number, and references cited in ecology journals. *Ecology and Evolution* 6(21): 7717–7726. <https://doi.org/10.1002/ece3.2505>
- Franceschet M, Costantini A (2010) The effect of scholar collaboration on impact and quality of academic papers. *Journal of Informetrics* 4(4): 540–553. <https://doi.org/10.1016/j.joi.2010.06.003>

- Garfield E (2006) The history and meaning of the journal impact factor. *Journal of the American Medical Association* 295(1): 90–93. <https://doi.org/10.1001/jama.295.1.90>
- Glänzel W, Debackere K, Thijs B, Schubert A (2006) A concise review of the role of author self-citations in information science, bibliometrics, and science policy. *Scientometrics* 67(2): 263–277. <https://doi.org/10.1007/s11192-006-0098-9>
- Goldfinch S, Dale T, DeRouen Jr K (2003) Science from the periphery: Collaboration, networks, and ‘periphery effects’ in the citation of New Zealand Crown Research Institutes articles, 1995–2000. *Scientometrics* 57(3): 321–337. <https://doi.org/10.1023/A:1025048516769>
- Gorham E, Kelly J (2014) Multiauthorship, an indicator of the trend toward team research in ecology. *Bulletin of the Ecological Society of America* 95(3): 243–249. <https://doi.org/10.1890/0012-9623-95.3.243>
- Hamermesh DS (2013) Six decades of top economics publishing: Who and how? *Journal of Economic Literature* 51(1): 162–172. <https://doi.org/10.1257/jel.51.1.162>
- Hamilton DP (1990) Publishing by – and for? – the numbers. *Science* 250(4986): 1331–1332. <https://doi.org/10.1126/science.2255902>
- Heger T, Jeschke JM, Kollmann J (2021) Some reflections on current invasion science and perspectives for an exciting future. *NeoBiota* 68: 79–100. <https://doi.org/10.3897/neobiota.68.68997>
- Henriksen D (2016) The rise in co-authorship in the social sciences (1980–2013). *Scientometrics* 107(2): 455–476. <https://doi.org/10.1007/s11192-016-1849-x>
- Herbertz H (1995) Does it pay to cooperate? A bibliometric case study in molecular biology. *Scientometrics* 33(1): 117–122. <https://doi.org/10.1007/BF02020777>
- Hudson J (1996) Trends in multi-authored papers in economics. *The Journal of Economic Perspectives* 10(3): 153–158. <https://doi.org/10.1257/jep.10.3.153>
- Hudson J (2007) Be known by the company you keep: Citations – quality or chance? *Scientometrics* 71(2): 231–238. <https://doi.org/10.1007/s11192-007-1671-6>
- Kassambara A (2020) ggpubr: ‘ggplot2’ based publication ready plots. R package version 0.4.0.
- Katz JS, Hicks D (1997) How much is a collaboration worth? A calibrated bibliometric model. *Scientometrics* 40(3): 541–554. <https://doi.org/10.1007/BF02459299>
- Katz JS, Martin BR (1997) What is research collaboration? *Research Policy* 26(1): 1–18. [https://doi.org/10.1016/S0048-7333\(96\)00917-1](https://doi.org/10.1016/S0048-7333(96)00917-1)
- Khan KS, Nwosu CR, Khan SF, Dwarakanath LS, Chien PFW (1999) A controlled analysis of authorship trends over two decades. *American Journal of Obstetrics and Gynecology* 181(2): 503–507. [https://doi.org/10.1016/S0002-9378\(99\)70585-5](https://doi.org/10.1016/S0002-9378(99)70585-5)
- King Jr JT (2000) How many neurosurgeons does it take to write a research article? Authorship proliferation in neurosurgical research. *Neurosurgery* 47(2): 435–440. <https://doi.org/10.1097/00006123-200008000-00032>
- Kuld L, O’Hagan J (2017) Rise of multi-authored papers in economics: Demise of the ‘lone star’ and why? *Scientometrics* 114(3): 1207–1225. <https://doi.org/10.1007/s11192-017-2588-3>
- Larivière V, Gingras Y, Sugimoto CR, Tsou A (2015) Team size matters: Collaboration and scientific impact since 1900. *Journal of the Association for Information Science and Technology* 66(7): 1323–1332. <https://doi.org/10.1002/asi.23266>

- Leimu R, Koricheva J (2005a) Does scientific collaboration increase the impact of ecological articles? *Bioscience* 55(5): 438–444. [https://doi.org/10.1641/0006-3568\(2005\)055\[0438:DS CITI\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2005)055[0438:DS CITI]2.0.CO;2)
- Leimu R, Koricheva J (2005b) What determines the citation frequency of ecological papers? *Trends in Ecology & Evolution* 20(1): 28–32. <https://doi.org/10.1016/j.tree.2004.10.010>
- Lenth RV (2021) emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.6.0.
- Lynch AJJ, Thackway R, Specht A, Beggs PJ, Brisbane S, Burns EL, Byrne M, Capon SJ, Casanova MT, Clarke PA, Davies JM, Dovers S, Dwyer RG, Ens E, Fisher DO, Flanigan M, Garnier E, Guru SM, Kilminster K, Locke J, Mac Nally R, McMahon KM, Mitchell PJ, Pierson JC, Rodgers EM, Russell-Smith J, Udy J, Waycott M (2015) Transdisciplinary synthesis for ecosystem science, policy, and management: The Australian experience. *The Science of the Total Environment* 534: 173–184. <https://doi.org/10.1016/j.scitotenv.2015.04.100>
- Mooney HA, Drake JA (1986) Ecology of biological invasions of North America and Hawaii. *Ecological Studies* 58. Springer, New York. <https://doi.org/10.1007/978-1-4612-4988-7>
- Nabout JC, Parreira MR, Teresa FB, Carneiro FM, da Cunha HF, de Souza Ondeí L, Carmori SS, Soares TN (2015) Publish (in a group) or perish (alone): The trend from single- to multi-authorship in biological papers. *Scientometrics* 102(1): 357–364. <https://doi.org/10.1007/s11192-014-1385-5>
- Narin F, Stevens K, Witlow ES (1991) Scientific co-operation in Europe and the citation of multinationally authored papers. *Scientometrics* 21(3): 313–323. <https://doi.org/10.1007/BF02093973>
- Ossenblok TLB, Verleysen FT, Engels TCE (2014) Coauthorship of journal articles and book chapters in the social sciences and humanities (2000–2010). *Journal of the Association for Information Science and Technology* 65(5): 882–897. <https://doi.org/10.1002/asi.23015>
- Paine RT (2005) Cross environment talk in ecology: Fact or fantasy? *Marine Ecology Progress Series* 304: 280–283. <https://www.jstor.org/stable/24869862>
- Price DJS (1963) Little science, big science...and beyond. Columbia University Press, New York. <https://doi.org/10.7312/pric91844>
- Pulverer B (2015) Dora the brave. *The EMBO Journal* 34(12): 1601–1602. <https://doi.org/10.15252/embj.201570010>
- Pyšek P (1995) Recent trends in studies on plant invasions (1974–1993). In: Pyšek P, Prach K, Rejmánek M, Wade M (Eds) *Plant invasions – general aspects and special problems*. SPB Academic Publishing, Amsterdam, 223–236.
- Pyšek P, Richardson DM, Jarošek V (2006) Who cites who in the invasion zoo: Insights from an analysis of the most highly cited papers in invasion ecology. *Preslia* 78: 437–468.
- Qiu H, Chen Y-F (2009) Bibliometric analysis of biological invasions research during the period of 1991 to 2007. *Scientometrics* 81(3): 601–610. <https://doi.org/10.1007/s11192-008-2207-4>
- R Core Team (2021) R: A language an environment for statistical computing. R Foundation for Statistical Computing, Vienna.

- Regalado A (1995) Multiauthor papers on the rise. *Science* 268(5207): 25–25. <https://doi.org/10.1126/science.7701334>
- Richardson DM, Pyšek P (2008) Fifty years of invasion ecology—the legacy of Charles Elton. *Diversity & Distributions* 14(2): 161–168. <https://doi.org/10.1111/j.1472-4642.2007.00464.x>
- Richardson DM, Ricciardi A (2011) Misleading criticisms of invasion science: A field guide. *Diversity & Distributions* 19(12): 1461–1467. <https://doi.org/10.1111/ddi.12150>
- Richardson DM, Pyšek P, Carlton JT (2011) A compendium of essential concepts and terminology in invasion ecology. In: Richardson DM (Ed.) *Fifty years of invasion ecology. The legacy of Charles Elton*. Wiley-Blackwell, Oxford, 409–420. <https://doi.org/10.1002/9781444329988.ch30>
- Richardson DM, Abrahams B, Boshoff N, Davies SJ, Measey J, van Wilgen BW (2020) South Africa's Centre for Invasion Biology: an experiment in invasion science for society. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (Eds) *Biological invasions in South Africa*. Springer, Cham, 879–914. https://doi.org/10.1007/978-3-030-32394-3_30
- Rosenblat TS, Mobius MM (2004) Getting closer or drifting apart? *The Quarterly Journal of Economics* 119(3): 971–1009. <https://doi.org/10.1162/0033553041502199>
- Rousseau R (2001) Are multi-authored articles cited more than single-authored ones? Are collaborations with authors from other countries more cited than collaborations within the country? A case study. *Proceedings of the Second Berlin Workshop on Scientometrics and Informetrics, Collaboration in Science and Technology*. Gesellschaft fuer Wissenschaftsforschung, Berlin, 173–176.
- Schmid SL (2017) Five years post-DORA: Promoting best practices for research assessment. *Molecular Biology of the Cell* 28(22): 2941–2944. <https://doi.org/10.1091/mbc.e17-08-0534>
- Simberloff D (2011a) Charles Elton: Neither founder nor siren, but prophet. In: Richardson DM (Ed.) *Fifty years of invasion ecology: The legacy of Charles Elton*. Blackwell Publishing, West Sussex, 11–24. <https://doi.org/10.1002/9781444329988.ch2>
- Simberloff D (2011b) SCOPE project. In: Simberloff D, Rejmánek M (Eds) *Encyclopedia of biological invasions*. University of California Press, Berkeley and Los Angeles, 617–619. <https://doi.org/10.1525/9780520948433-138>
- Simberloff D (2011c) Native Invaders. In: Simberloff D, Rejmánek M (Eds) *Encyclopedia of biological invasions*. University of California Press, Berkeley and Los Angeles, 472–475. <https://doi.org/10.1525/9780520948433-106>
- Smart J, Bayer A (1986) Author collaboration and impact: A note on citation rates of single and multiple authored articles. *Scientometrics* 10(5–6): 297–305. <https://doi.org/10.1007/BF02016776>
- Tregenza T (2002) Gender bias in the refereeing process? *Trends in Ecology & Evolution* 17(8): 349–350. [https://doi.org/10.1016/S0169-5347\(02\)02545-4](https://doi.org/10.1016/S0169-5347(02)02545-4)
- Van Noorden R, Chawla DS (2019) Hundreds of extreme self-citing scientists revealed in new database. *Nature* 572(7771): 578–580. <https://doi.org/10.1038/d41586-019-02479-7>
- Vaz AS, Kueffer C, Kull CA, Richardson DM, Schindler S, Muñoz-Pajares AJ, Vicente JR, Martins J, Hui C, Kühn I, Honrado JP (2017) The progress of interdisciplinarity in invasion science. *Ambio* 46(4): 428–442. <https://doi.org/10.1007/s13280-017-0897-7>

- Verleysen FT, Ossenblok TLB (2017) Profiles of monograph authors in the social sciences and humanities: An analysis of productivity, career stage, co-authorship, disciplinary affiliation and gender, based on a regional bibliographic database. *Scientometrics* 111(3): 1673–1686. <https://doi.org/10.1007/s11192-017-2312-3>
- Weltzin JF, Belote RT, Williams LT, Keller JK, Engel EC (2006) Authorship in ecology: Attribution, accountability, and responsibility. *Frontiers in Ecology and the Environment* 4(8): 435–441. [https://doi.org/10.1890/1540-9295\(2006\)4\[435:AIEAAA\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2006)4[435:AIEAAA]2.0.CO;2)
- Wickham H (2016) *ggplot2: elegant graphics for data analysis*. R package version 3.3.5. Springer-Verlag, New York.
- Wickham H, François R, Henry L, Müller K (2021) *dplyr: a grammar of data manipulation*. R package version 1.0.5.

Supplementary material I

Appendices S1, S2

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Data type: Search Query (docx. file)

Explanation note: Appendix S1. Clarivate analytics Web of Science core collections topics search query. Appendix S2. List of publications published in invasion science between 1980 and 2020, registered in Clarivate Web of Science Core Collections, and categorized as data papers.

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The authors misarranged the order of the figures in Sirbu et al. (2022). The correct order of the figures is reproduced below.

The correct Fig. 4 is reproduced below.

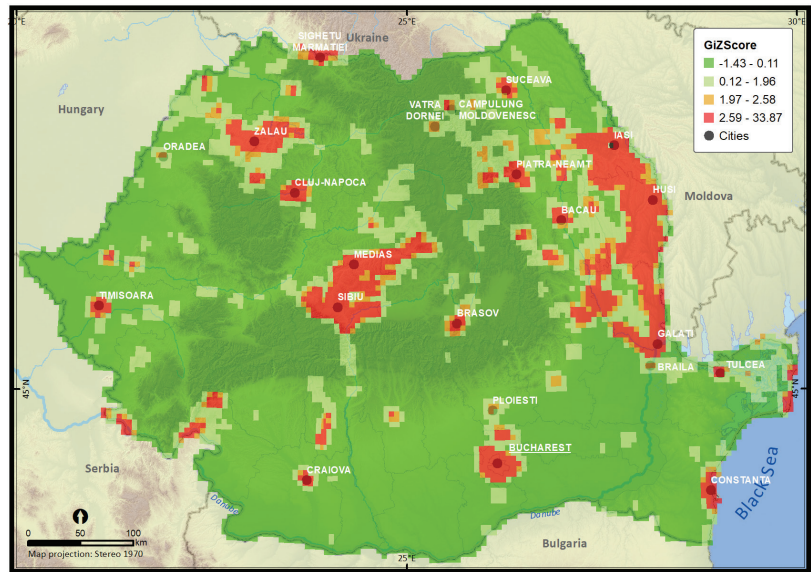


Figure 4. Hotspots of invasive and potentially invasive alien plant species sampling in Romania (in red). The p-value was < 0.05 when Z scores took values between 1.96 and 33.87, suggesting a highly clustered pattern in the number of IAP species occurrences per UTM 5 × 5 km grid cell.

The correct Fig. 5 is reproduced below.

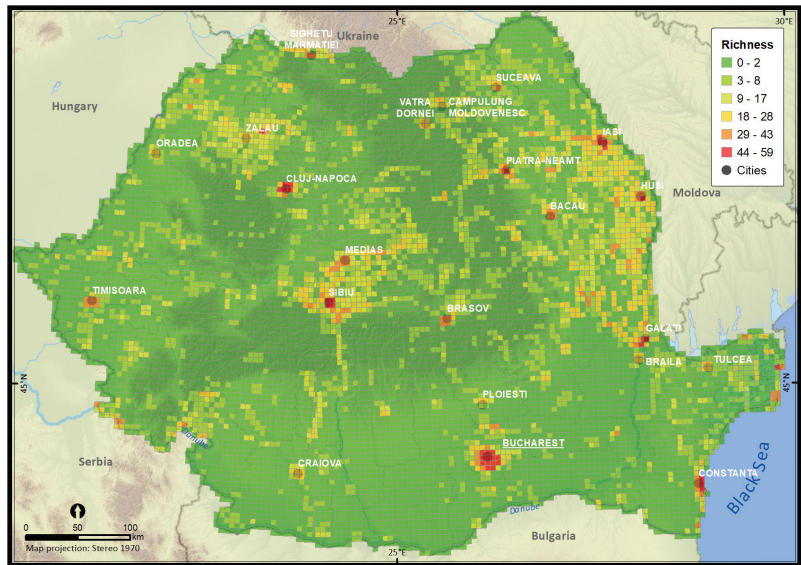


Figure 5. Invasive and potentially invasive alien plant species richness in Romania (5 × 5 km grid resolution).

The correct Fig. 6 is reproduced below.

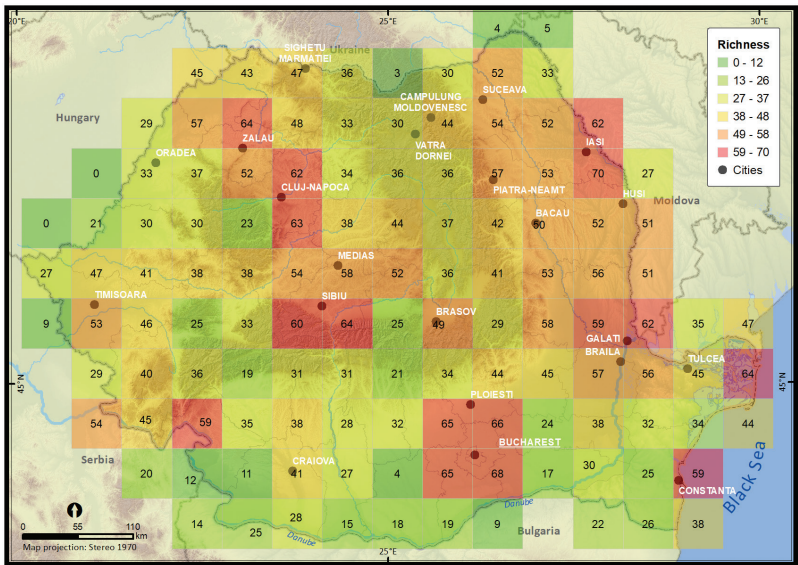


Figure 6. Invasive and potentially invasive alien plant species richness in Romania (50 × 50 km grid resolution).

The correct Fig. 7 is reproduced below.

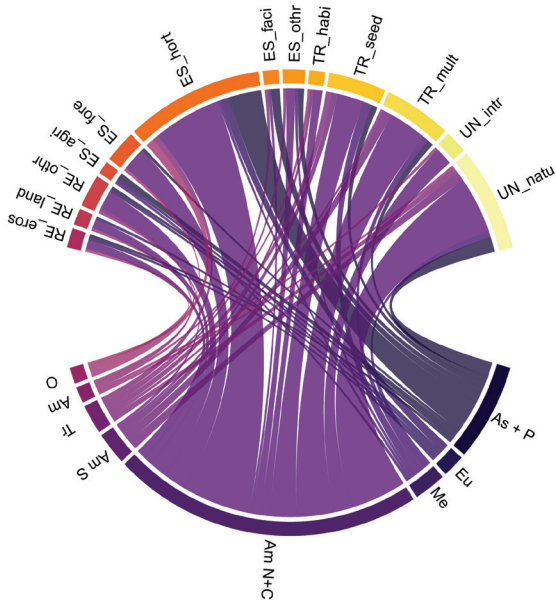


Figure 7. Proportion of invasive and potentially invasive alien plant species' introductions by pathway and geographic origins (see Table 1 for abbreviations).

The correction does not alter the conclusions of Sirbu et al. (2022).

References

Sirbu C, Miu IV, Gavriliadis AA, Gradinaru SR, Niculae IM, Preda C, Oprea A, Urziceanu M, Camen-Comanescu P, Nagoda E, Sirbu IM, Memedemin D, Anastasiu P (2022) Distribution and pathways of introduction of invasive alien plant species in Romania. *NeoBiota* 75: 1–21. <https://doi.org/10.3897/neobiota.75.84684>