

The pet and horticultural trades as introduction and dispersal agents of non-indigenous freshwater molluscs

Zohar Yanai^{1,*}, Tamar Dayan^{1,2}, Henk K. Mienis² and Avital Gasith¹

¹Department of Zoology, George S. Wise Faculty of Life Sciences, Tel Aviv University, Tel Aviv 6997801, Israel

²The Steinhardt Museum of Natural History, Israel National Center for Biodiversity Studies, Tel Aviv University, Tel Aviv 6997801, Israel

Author e-mails: yanai.zohar@gmail.com (ZY), dayant@tauex.tau.ac.il (TD), mienis@netzer.org.il (HKM), avitalg@tauex.tau.ac.il (AG)

*Corresponding author

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Abstract

Understanding the introduction pathways and patterns of distribution of non-indigenous species is essential for minimizing future invasions. In the aquarium and aquatic ornamental plant trades lies the potential for importing freshwater molluscs and dispersing them. We surveyed 37 pet shops and 24 aquatic plant nurseries throughout Israel in search for freshwater molluscs. The survey yielded 29 taxa, of which 15 are offered for sale (deliberate introduction) and 14 are stowaways (accidental introduction). The species offered for sale are alien species not yet established in Israeli natural systems, whereas the stowaways are mainly established species that have already invaded and maintain stable populations in natural habitats. Six species were documented for the first time in Israel. Taxon richness was not correlated with any geographic or socioeconomic variable. We attribute this to the small size of Israel, which enables people from different locations and social classes to travel easily across the country to buy plants or pets. The findings of this study imply that the import of freshwater molluscs deliberately for commerce or on aquatic plants as stowaways is an important mode of introduction for these species. In order to prevent, or at least reduce, the extent of this phenomenon, we recommend establishing more effective restrictions on the import of live material, preventing deliberate import and commerce of freshwater molluscs, and confiscating and eliminating non-indigenous freshwater molluscs once found, before they reach nature.

Key words: aquatic horticulture, freshwater molluscs, introduction pathways, ornamental aquaria, pet industry, water plants

Introduction

Understanding the processes and mechanisms that allow a non-indigenous species to invade novel habitats is likely to assist in early detection of future invasions and efforts to prevent, or at least minimize, their impact (Cowie 1998; Wonham et al. 2001; Mienis 2003). Human-mediated introduction pathways can be a result of accidental introduction when non-indigenous stowaways are transported on goods, vehicles, boats, or passengers (e.g., via ballast water [Hulme 2009]); or of deliberate introduction, as in the cases of species introduced for pest control, food consumption, or research purposes. Deliberate introduction may be illegal (smuggling), a common case in the trade of pets or ornamental plants (e.g., Warchol 2004; Niemiera and von Holle 2009; Phelps and Webb 2015).

Globalization and international free trade markedly facilitate species transition across borders (Jenkins 1996; Ricciardi 2007; Niemiera and von Holle 2009). Species invasion rates are therefore positively influenced by human socioeconomic state, at local (Lin et al. 2007), regional (Vilà and Pujadas 2001) and global (Sharma et al. 2010) levels. A potential introduction pathway is the pet industry, in which billions of animals are exported and sold worldwide every year (Whittington and Chong 2007; Smith et al. 2009) in a market worth US\$159 billion annually (Warchol 2004). Many of these animals may establish invasive populations in their new location (e.g., Cassey et al. 2004; Duggan et al. 2006; Whittington and Chong 2007; Carrete and Tella 2008; Mrugała et al. 2014; Ng et al. 2016). The ornamental aquarium hobby is popular around the world (e.g., Andrews 1990), and involves significant illegal import of

aquatic organisms in response to increasing public demand, thereby enhancing the rate of aquatic introductions (Taylor 2003). Similarly, the horticultural trade also possesses an invasion risk (e.g., Niemiera and von Holle 2009). Aquatic organisms usually reach natural habitats when aquaria and tanks are deliberately disposed of or cleaned in nearby open bodies of water (Duggan 2010; Marr et al. 2010).

Among invasive species, freshwater molluscs are considered to be relatively successful in establishing novel populations worldwide (e.g., Cowie and Robinson 2003; Devin et al. 2005), Israel included (Roll et al. 2009). Their accidental introductions have been relatively well documented but deliberate introductions probably have a more important role in facilitating new introductions than assumed so far (Cowie and Robinson 2003; Ng et al. 2016).

Therefore, we examined the role of pet shops that sell aquarium organisms and of plant nurseries that sell ornamental aquatic plants in the dispersal of freshwater molluscs in Israel. We also examined a possible association between the socioeconomic status of communities in Israel and patterns of mollusc dispersal associated with these businesses.

In order to simplify the discussion and distinguish between three practically distinct groups, we use the following definitions: native species are species indigenous to the local fauna; alien species are non-indigenous species introduced by people and presently restricted to human-dominated habitats such as aquaria and urban horticulture; and established invasive species (hereafter: established) are non-indigenous species that have established sustainable populations in the wild.

Materials and methods

We visited 37 pet shops that provide aquarium animals and 24 plant nurseries that sell ornamental aquatic plants, in various parts of Israel from spring 2012 to winter 2013. The study sites were located in 38 settlements throughout Israel: from the Upper Galilee (Qiryat Shemona) in the north to the Central Negev desert (Midreshet Sedeh Boqer) in the south (Figure 1). The climate along this north-south gradient varies from wet-Mediterranean (mean annual rainfall 768 mm) to arid (mean annual rainfall 93 mm) (IMS 2014). The selected settlements represent a range of demographic and socioeconomic statuses: population size of 200 to *ca.* 800,000 (Noy et al. 2012); national socioeconomic cluster ranking 4 to 9 (following Burck et al. 2006); peripheral cluster ranking 3 to 10 (following Tsibel 2008). The shops and nurseries were selected according to Internet advertising, personal knowledge, recommendations, and/or random

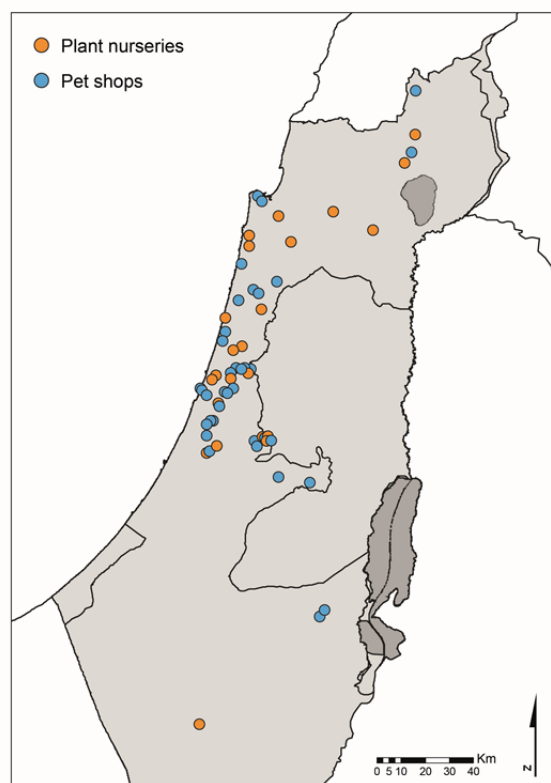


Figure 1. Distribution of pet shops ($n = 37$) and plant nurseries ($n = 24$) that were surveyed for freshwater molluscs.

encounters. Among the nurseries, three were importers, growers, and suppliers of aquatic plants to retailers all over Israel. The remaining nurseries were retailers selling directly to customers.

Most pet shop owners (*ca.* 90%) and all plant nursery owners cooperated with the study and allowed us to search for and collect specimens on site. We received information on the source of the aquarium and horticulture goods from more than 60% of the pet shops and about 90% of the plant nurseries. We ranked the size of pet shops by the number of freshwater aquaria (usually of standard size) and of retailer plant nurseries by the total estimated volume of all containers used for aquatic plants. Aquatic plant diversity was also recorded. In each case, we interviewed the salesperson or owner regarding the presence of freshwater molluscs, and asked for permission to look around and collect molluscs in the ponds, water tanks, or aquaria (hereon, containers). The survey (conducted by two people) included visual search on container walls and floors, plant surfaces, and any other available substrate. The

search always lasted until the site was completely examined and no new taxa were found for 15 additional minutes of search. The molluscs observed (live as well as empty shells) were identified and recorded on site. Several specimens of each taxon were taken (or bought), preserved in 70% ethanol, and brought to the laboratory for taxonomic verification by HKM. The collected material was deposited in the Mollusc Collection of the Steinhardt Museum of Natural History at the Tel Aviv University (SMNH).

The taxa recorded were categorized by their biogeographic origin and by status in Israel, i.e. native, alien and established species. Biogeographic origin was determined according to the known range of native distribution of each species (IUCN 2016; HKM, personal information). One species (*Melanoides tuberculata*) could not be definitely categorized as native or non-indigenous since it is widely distributed in aquatic habitats in Israel (Milstein et al. 2012) but is also found in many other countries (IUCN 2016) that export ornamental water plants globally, including to Israel. Taxa whose biogeographic origin or invasion status was unclear (e.g., due to uncertain identification) were omitted from the relevant analyses.

To determine if the biogeographic and status compositions of pet shop molluscan assemblages differed from the assemblage in nurseries we used both number of species (richness) and a weighted measure that incorporates the rate of occurrence of each taxon in pet shops versus plant nurseries (hereafter: relative occurrence). The latter measure best reflects the weight that a taxon has in the total assemblage (i.e., a dominant and common species will have stronger impact on the results than a rare species that was recorded only once or twice).

To examine possible relationships of mollusc occurrence and socioeconomic status, we obtained data from the Central Bureau of Statistics in Israel regarding population size (log transformed; Noy et al. 2012), socioeconomic status (national cluster on a scale of 1 to 10, poorest to wealthiest, respectively; Burck et al. 2006), and a measure of centrality (peripheral cluster 1 to 10, most isolated to most central settlements, respectively; Tsibel 2008). We conducted a General Linear Model (GLM) analysis to examine relationships between species richness and the above mentioned statistics, using the Backwards Stepwise Model Selection method, followed by calculation of the best fit model that explains most of the variance and uses the fewest possible measures, based on the Akaike Information Criterion (AIC; Gardener 2012). All statistical analyses were conducted with R program (R Core Team 2013), following Gardener (2012).

Results

General findings

Twenty-nine mollusc taxa were recorded in the survey of pet shops and plant nurseries, 22 of which were identified to the species level (Table 1). The recorded taxa included 22 snail species (18 genera, 11 families) and four bivalve species (four genera, two families).

Twenty-five taxa (21 snails and 4 bivalves) were found in pet shops (range 1–10, median 4 per shop) and 11 (all snails) in plant nurseries (range 2–9, median 4; Figure 2). Fifteen taxa were traded in pet shops and a single snail species was sold by a nursery. The remaining taxa were stowaways (pet shops: range 0–6, median 2; plant nurseries: range 2–8, median 4). Six of the taxa were documented for the first time in Israel; these were the snails *Filopaludina martensi martensi*, *Melanoides torulosa*, *Pila ampullacea*, *Pilsbryconcha* sp. and *Thiara cancellata*, and the bivalve *Batissa violacea*. The snails *F. martensi martensi* and *P. ampullacea* were previously intercepted at border checkpoints but had not been found within Israel (Vaisman and Mienis 2011). Five of the newly recorded species were from pet shops, and only *F. martensi martensi* was from a nursery (Table 1).

Average mollusc richness in pet shops did not differ from the average richness in plant nurseries (Mann-Whitney *U*-test, $U = 473$, $n_1 = 37$, $n_2 = 24$, $P = 0.67$). However, stowaway richness was higher in nurseries (Mann-Whitney *U*-test, $U = 149$, $n_1 = 37$, $n_2 = 24$, $P < 0.01$; Figure 2). Mollusc richness did not significantly differ between retail and wholesale nurseries (Mann-Whitney *U*-test, $U = 19.5$, $n_1 = 3$, $n_2 = 21$, $P = 0.3$).

The frequency of occurrence of each mollusc taxon in the pet shops and nurseries is presented in Table 1. The snail *Planorbella duryi* (established) was the only mollusc found in all nurseries, whereas the dominant species in pet shops was *Melanoides tuberculata* (uncertain status; occurrence 80%). The established *Physella acuta* also dominated both nurseries and pet shops (88% and 76%, respectively). Most of the molluscs sold in pet shops (89%) were Ampullariidae (genera *Pomacea* and *Pila*) as was the only case of molluscs sold in a nursery.

Biogeography and invasion status

The biogeographic composition of the mollusc assemblages in pet shops and nurseries was similar (Pearson's χ^2 test, $\chi^2 = 4.875$, $df = 6$, $P = 0.56$). However, Oriental taxa comprise the largest group in pet shops (36% of the species), while in nurseries Oriental and Nearctic taxa were equally represented (27% each; Table 1). Mollusc assemblages of pet shops

Table 1. List of freshwater mollusc taxa (n = 29), invasion status (detailed in text), biogeographic origin and percentage of pet shops and plant nurseries in which they occurred. Species recorded for the first time in Israel are indicated by an asterisk.

Taxon	Invasion status	Biogeographic origin	Pet shop	Plant nursery
Bivalvia				
<i>Batissa violacea</i> *	Alien	Australian	3%	–
Corbiculidae unidentified			3%	–
<i>Pilsbryconcha</i> sp.*	Alien	Oriental	3%	–
Unionidae unidentified			3%	–
Gastropoda				
<i>Marisa cornuarietis</i>	Alien	Neotropical	30%	–
<i>Pila ampullacea</i> *	Alien	Oriental	5%	–
<i>Pomacea diffusa</i>	Alien	Neotropical	16%	–
<i>Pomacea canaliculata</i>	Alien	Neotropical	11%	–
<i>Pomacea maculata</i>	Alien	Neotropical	3%	–
Ampullariidae unidentified	Alien		65%	4%
<i>Bithynia phialensis</i>	Native	Palaeartic	3%	54%
<i>Anentome helena</i>	Alien	Oriental	19%	–
<i>Pseudosuccinea columella</i>	Established	Nearctic	11%	67%
<i>Radix rubiginosa</i>	Alien	Oriental	–	4%
<i>Radix viridis</i>	Alien	Oriental	–	4%
Lymnaeidae unidentified			3%	–
<i>Neritodryas cornea</i>	Alien	Oriental	3%	–
<i>Vittina turrita</i>	Alien	Oriental	5%	–
Neritidae unidentified			19%	–
<i>Tylomelania</i> sp.	Alien	Oriental	16%	–
<i>Physella acuta</i>	Established	Nearctic	76%	88%
<i>Physella gyrina</i>	Established	Nearctic	16%	38%
<i>Ferrissia clessiniana</i>	Established	Ethiopian	–	4%
<i>Planorbella duryi</i>	Established	Neotropical	30%	100%
<i>Melanooides torulosa</i> *	Alien	Oriental	3%	–
<i>Melanooides tuberculata</i>		Old World	81%	38%
<i>Mieniplotia scabra</i>	Established	Oriental	5%	–
<i>Thiara cancellata</i> *	Alien	Oriental	3%	–
<i>Filopaludina martensi</i> *	Alien	Oriental	–	4%
Native = 1				
Alien = 17				
Total taxa			25	11
			Established = 6	
			Unknown = 5	
Taxa recorded in Israel for the first time			5	1

and nurseries did differ when relative occurrence (see Materials and Methods) was considered (Pearson's χ^2 test, $\chi^2 = 37.797$, $df = 6$, $P < 0.01$; Figure 3A). This is attributed mostly to higher occurrence of Oriental taxa in pet shops and of a Palaeartic species (the snail *Bithynia phialensis*) in nurseries.

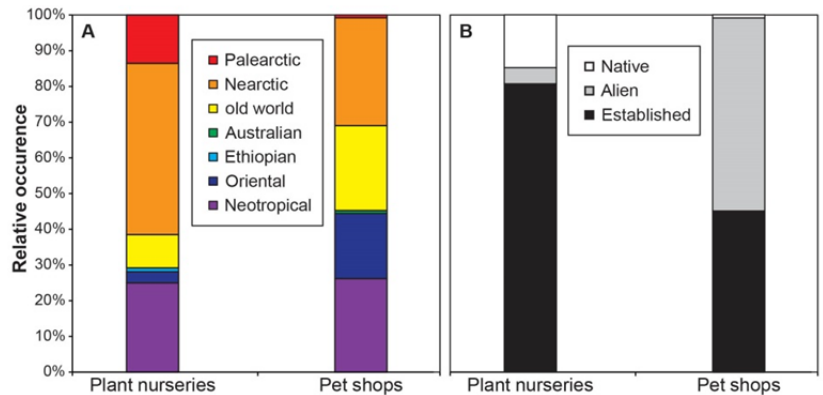
Of all molluscs recorded in pet shops and nurseries, only one (*B. phialensis*) is native to Israel and it is not traded. Most stowaway molluscs found in both pet shops and nurseries are already established invasive taxa. The status of the snail *Melanooides tuberculata* is uncertain (native or non-indigenous), and thus it was omitted from these analyses.

When grouped together by invasion status, pet shops and nurseries showed similar composition of native, alien, and established molluscs (Pearson's χ^2 test, $\chi^2 = 3$, $df = 2$, $P = 0.34$). However, when relative



Figure 2. Mollusc taxon richness in plant nurseries (n = 24) and pet shops (n = 37). Solid line represents median, boxes represent borders of 2nd and 3rd quartiles, whiskers represent borders of 1st and 4th quartiles, and dots represent outliers. **A** total richness, **B** richness of stowaways only. Asterisk indicates significant difference.

Figure 3. Taxa found in pet shops and plant nurseries according to biogeographic origin (A) and invasion status in Israel (B). The figure only includes taxa that could be classified, and it is corrected to the relative rate of occurrence in the survey (see methods for explanation).



occurrence of the molluscs was considered, alien molluscs were more common in pet shops whereas established ones dominated plant nurseries (Figure 3B; Pearson’s χ^2 test, $\chi^2 = 61$, $df = 2$, $P < 0.01$).

Business characteristics

Mollusc species richness was positively correlated with nursery and pet shop sizes (tank volume and number of aquaria, respectively; $r = 0.56$, $n = 20$, $P < 0.01$, Figure 4A; and $r = 0.57$, $n = 24$, $P < 0.01$, Figure 4B, respectively). We found no significant relationship between mollusc richness and aquatic plant richness in nurseries (Spearman’s correlation, $r = 0.38$, $n = 20$, $P = 0.1$; Figure 4C).

Linking taxon richness with geographic, demographic or socioeconomic characteristics yielded no significant relationship (Figure 5). The GLM omitted the less informative variables in a decreasing order, i.e. peripheral cluster, latitude, socioeconomic cluster and population size, but also could not explain mollusc richness (GLM, residual SE = 1.775, $F = 1.76$, $df = 2.57$, $P = 0.18$).

Interviews of owners and workers in pet shops and plant nurseries revealed that aquatic plants and living freshwater organisms are imported into Israel both legally and illegally. About 70% of pet shop employees and over 80% of nursery employees were aware of the existence of “unwanted molluscs” causing damage to aquatic plants in their businesses, particularly alluding to the small “cone snails” (i.e., *Melanoides tuberculata*), revealing lack of knowledge since this species is a detritivore. Most of the employees identified aquatic plants as the major carriers of “unwanted molluscs”. Information about the number and identity of importers and suppliers was more difficult to collect, and we failed to identify the important players in each industry.

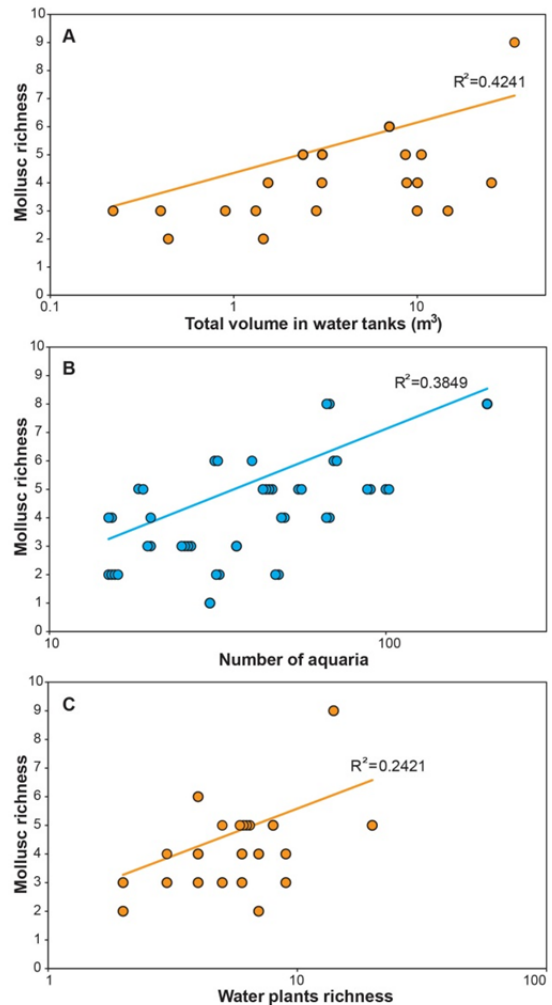


Figure 4. Relationship between mollusc taxon richness and estimated business size: **A** total volume of water tanks in plant nurseries; **B** number of aquaria in pet shops; **C** water plant richness in plant nurseries.

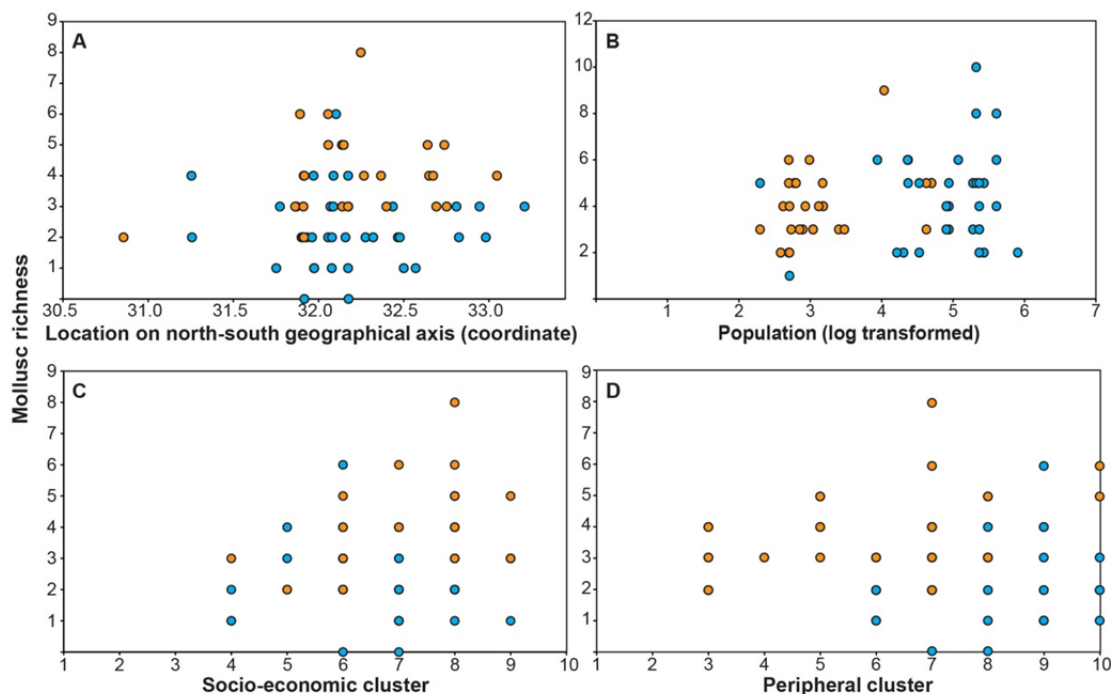


Figure 5. Relationships of mollusc taxon richness in pet shops (blue circles) and plant nurseries (orange circles) with geographical location (A, latitude), settlement population size (B, log transformed), socioeconomic and peripheral clusters (C and D, respectively).

Discussion

The considerable presence of molluscs in both pet shops and nurseries implies that these businesses are potential agents for introducing and dispersing freshwater molluscs in Israel. Pet shop owners reported that most of their aquarium goods arrived from tropical regions (e.g., Thailand, Indonesia, Malaysia, Sri Lanka) where colorful and diverse species of fish, aquatic plants, and other aquatic taxa are abundant; it is therefore of no surprise that tropical freshwater molluscs are common in pet shops in Israel. In contrast, ornamental plants are imported from several areas, and the molluscs found in nurseries are mostly Nearctic species (Figure 3A), mainly because of the high occurrence of the snail *Physella acuta* (Table 1).

Invasion status

Native species. Most of Israel's aquatic malacofauna is of Palearctic origin (ZY, unpublished data). *Bithynia phialensis* (Palearctic) and *Melanoides tuberculata* (Old World) were found in pet shops and nurseries. The global distribution of *B. phialensis* is relatively restricted to the Levant (Milstein et al. 2012) whereas *M. tuberculata* is distributed worldwide (IUCN 2016) and it is a very successful invader

(e.g., Pointier et al. 1992; De Marco 1999; Duggan 2002; Rader et al. 2003). Despite being native to Israel we ignored it in the analyses because the origin of the surveyed populations was not known; molecular analyses may resolve this.

Alien species. Seventeen taxa of alien molluscs (foreign to the region but not yet established in the wild) were recorded in pet shops and nurseries, six of them for the first time in Israel (Table 1), suggesting continuous introduction of non-indigenous mollusc species new to Israel. All alien molluscs found in pet shops ($n = 14$) are traded. To the best of our knowledge none has yet managed to establish populations in the wild in Israel. Given accumulating evidence on introductions elsewhere in the world (e.g., Ampullariidae; Horgan et al. 2014), their presence in pet shops raises concern (Mienis 2011b). Indeed, the European Commission recently (2012) banned all import and trade in species of the genus *Pomacea*. Almost all (>90%) the alien species in Israel are of tropical origin and are possibly restricted in the wild by the relatively low winter temperature (<10 °C). Only four alien snails were found in plant nurseries, of which only one (an unidentified ampullariid) is offered for sale. The alien snail *Filopaludina martensi martensi* is a popular food item in Southeast Asia; it was confiscated a few times in the past by inspectors of the

Plant Protection and Inspection Services, Ministry of Agriculture, from Thai workers arriving in Israel (Mienis 2006a, 2006b). In the present study this species was relatively abundant in a plant nursery where Thai workers are employed. The introduction pathway of the other two alien species (*Radix rubiginosa* and *R. viridis*) to plant nurseries is unclear; they may have entered Israel as stowaways on plants. Since undertaking the survey, “apple snails” (identified as *Pomacea maculata*) have been found at three open sites. All three are horticultural ponds in the central coastal plain of Israel (near Tel Aviv), and in all cases the snails were associated with aquatic horticultural plants planted by the nursery (Mienis et al. 2015a, b) in which we recorded *Pomacea*. As it is not clear that the species is established, we treated it as alien (rather than established) in the analyses. Nonetheless, these findings emphasize the potential risk of alien species invading open systems.

Established species. Six of the snail species recorded in this study have successfully established populations in the wild in Israel; one was found only in pet shops, one only in nurseries and four were recorded both in pet shops and in nurseries (Table 1). The established snail *Planorbella duryi* was the most common mollusc, present in all nurseries but only in 30% of the pet shops. This suggests that its introduction into Israel is mostly with aquatic plants, an assumption supported by the presence of wild populations of this species mostly in man-made aquatic sites (Mienis and Rittner 2012b). Similarly, the established snail *Pseudosuccinea columella* is very common in plant nurseries (ca. 70% occurrence) but rather rare in pet shops (ca. 10%). This species was probably also introduced with aquatic plants (Mienis and Rittner 2012a). A single established species, *Physella acuta*, was similarly abundant in both plant nurseries (90%) and pet shops (>75%). This cosmopolitan, generalist species (Anderson 2003) is the most successful invasive freshwater mollusc in Israel, occurring in more natural freshwater habitats than any other indigenous or non-indigenous species (Roll et al. 2009). The pathway for its introduction could be both pet shops and nurseries. The newly introduced invasive snail *Mieniplotia scabra* was reported in Israel in the wild in the Sea of Galilee (Lake Kinneret) in 2006 (Heller et al. 2013) and in two coastal streams in 2010–2011 (Mienis 2011a). In our survey it was recorded in a few pet shops (<5%) and has not yet been found in plant nurseries. The relatively long distance between the pet shops (in the two adjacent cities Rishon LeZiyyon and Rehovot) and the wild populations is noteworthy (at least 85 km apart), suggesting that there may be other occurrences.

Invasive freshwater molluscs are widely distributed in Israel (Milstein et al. 2012); accordingly, their introduction from the wild into pet shops and plant nurseries cannot a priori be rejected. However, pet shops are usually located in urban environments with no natural water sources nearby. Plant nurseries are usually fenced or surrounded by walls and kept relatively clean, with unwanted material from the surroundings removed regularly. Ditches and canals are lower and downstream relative to the nursery. These conditions make the introduction of established species from the wild into pet shops and nurseries nearly impossible. In contrast, the reverse pathway, from pet shops and nurseries to the wild, is highly likely because customers often transfer aquatic plants and other aquaria material to natural aquatic habitats (e.g., Duggan 2010; Marr et al. 2010).

Established species are the dominant group among the molluscs in plant nurseries, while pet shops hold more alien species (Figure 3B). The latter may easily become established themselves, as reported from other countries (e.g., Burks et al. 2010; Seuffert and Martin 2012). Almost all species in plant nurseries (and a few in pet shops) are stowaways (Figure 2), often considered pests by business owners. The strong link between stowaway freshwater molluscs and successful invasions was demonstrated by Ng et al. (2016) in Singapore. Coping with their invasion is problematic because of their efficient reproduction and dispersal capacities, small size, and already existing populations throughout Israel. Although their eradication is a common interest of ecologists and agronomists, technical barriers render this almost impossible. However, in pet shops most species are pets offered for sale, which sets up two challenges: both sellers and buyers share an interest in having these species, and will object to killing them for the sake of reducing invasion risks; furthermore, consumers naturally look for new, attractive, exotic species with which to decorate their aquaria. Consequently, pet importers and sellers try to import as many new species as possible, legally or illegally. Fish species that are popular among aquarium holders are more likely to invade novel natural environments (Duggan et al. 2006), and the same is true for freshwater crayfish (Chucholl 2013).

Business characteristics

Population size, socioeconomic level, and peripheral cluster may theoretically serve as proxies for consumers' life styles and their abilities to shop frequently and increase the rate of exchange of goods in local businesses. Unlike other studies (Vilà and Pujadas 2001; Lin et al. 2007; Westphal et al. 2008; Sharma

et al. 2010), we did not detect a correlation of mollusc species richness in pet shops or plant nurseries with these variables, nor with latitude. These predictors may not apply to Israel, a very small country (*ca.* 430 km from north to south). As such, people tend not to rely exclusively on stores close to their residence, but also to travel longer distances and shop elsewhere. Direct trade via the Internet may further decrease dependence on local businesses. Moreover, the reasonable price of freshwater molluscs in pet shops (we recorded an average price of 15NIS (~4US\$) per individual, depending on the species) suggests that having aquaria is not an expensive hobby in Israel. Also, the climatic location of the business does not explain its non-indigenous species richness, probably because within the pet shops or nurseries temperature and moisture are continuously regulated, regardless of the season and climate outside.

Our results weakly support the hypothesis that business size may reflect the rate of exchange of goods, and hence the richness of non-indigenous species, with higher mollusc richness found in larger businesses, but only a small portion of the variance was explained (Figures 4A, B). We also tested the potential effect of aquatic vegetation richness in nurseries, since in natural wetlands aquatic plants provide shelter for animals (Orr and Resh 1992) and may affect establishment of related species (Burks et al. 2010), but found no significant correlation between plant and mollusc richness.

General conclusions

Our study reconfirms the important role that pet and horticulture trade can play in the international transfer and spread of various species (Maki and Galatowitsch 2004; Padilla and Williams 2004; Smith et al. 2009; Patoka et al. 2014a, b), aquatic molluscs in particular (Madsen and Frandsen 1989; Ng et al. 2016). As the popularity of pet animals and horticultural plants keeps increasing (Warchol 2004; Alacs and Georges 2008), their introduction into distant countries is a major threat for biodiversity. Freshwater molluscs join other taxa (e.g., Duggan et al. 2006; Mrugała et al. 2014) already proven to efficiently travel around the world via the pet trade. Transfer of stowaway species is very marked in the horticulture trade, in some cases even more than that of target species themselves, thus also facilitating new invasions.

Policy and management recommendations

As species introductions are expected to increase with global trade and transportation, it is necessary to identify the failures in the existing mechanisms

and fix them in order to minimize the possibility of establishing new invasions. The following recommendations, based on scientific literature and the present study, are general and should be implemented for pet and horticulture trade worldwide. We use our findings regarding non-indigenous molluscs in Israel as a case study to demonstrate a potentially effective system that fails for technical reasons.

Legalizing the import of non-indigenous species into countries is recommended to allow the import only of specified species, while forbidding import of any other species (the white list approach). The alternative, of forbidding some species while permitting import of all other species (the black list approach) is much less effective against biological invasions (Hulme et al. 2009; Simberloff 2010; Chucholl 2013). Accurate risk assessment, based on worldwide experience and expert opinion (e.g., Chucholl 2013; Papavlasopolou et al. 2014; Patoka et al. 2014a), is essential for shaping and updating the lists. Monitoring and detection of deliberately imported and stowaway mollusc species in the pet and horticulture trades are important at every stage of the chain, from import, through breeding and to presenting and selling in shops. Tight inspection is required at airports, seaports and land borders, and all imported goods that contain live material, including ornamental water plants and contents of aquaria, should be held in quarantine before release. That way, small propagules such as eggs or very young snails may be easier to detect before the goods are released. Illegal smugglers, for economic profit or for personal use, should be forcefully punished. At any stage, if a mollusc is found it should be confiscated and destroyed. Inspection has to be supported by a trained taxonomist and could also benefit from a DNA barcode library. Maintaining rigorous documentation of the sources of all items will be important in case a new species is discovered and goods from the same shipment need to be located. We also recommend that pet and ornamental plant sellers attend routine education programs, in which they learn about risks and prevention of biological invasions. Customers, as the final checkpoint in the process of invasion, should also be guided never to empty their aquaria or throw their vegetation waste away into or near open, natural water bodies.

The relevant legislation in Israel (Fishery Order 1937, Plant Protection Act 1956) follows the preferred white list approach. However, forbidden species are being imported, bred and sold every day in Israel (Mienis et al. 2016; present study), hence we encourage law enforcement. Absurdly, Israeli law (National Parks and Nature Reserves Act 1998) protects all freshwater molluscs, non-indigenous species included.

Lack of discrimination based on origin can actually be used for coping with invasions, because possessing molluscs in pet shops and plant nurseries, deliberately or accidentally, is illegal and can be used by law enforcers. Non-indigenous molluscs that already entered the country and are present in shops should be detected by trained inspectors, in routine and surprise checks. This practice is almost completely lacking in Israel today. Identifying the molluscs and distinguishing native species, established invaders and new arrivals is performed well only by professional taxonomists. Currently, there are only three people in Israel who are capable of recognizing new mollusc invasions.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

- Alacs E, Georges A (2008) Wildlife across our borders: a review of the illegal trade in Australia. *Australian Journal of Forensic Sciences* 40: 147–160, <https://doi.org/10.1080/00450610802491382>
- Anderson R (2003) *Physella (Costatella) acuta* Draparnaud in Britain and Ireland – its taxonomy, origins and relationships with other introduced Physidae. *Journal of Conchology* 38: 7–22
- Andrews C (1990) The ornamental fish trade and fish conservation. *Journal of Fish Biology* 37: 53–59, <https://doi.org/10.1111/j.1095-8649.1990.tb05020.x>
- Burck L, Tsibel N, Badran Y, Golan (Atias) R, Hamisha Y, Dor I, Bendelac J, Schmeltzer M (2006) Characterization and classification of the local authorities by the socio-economic level of the population. Central Bureau of Statistics, Jerusalem, Israel. http://www.cbs.gov.il/www/publications/local_authorities06/local_authorities_e.htm (accessed 21 March 2017)
- Burks RL, Kyle CH, Trawick MK (2010) Pink eggs and snails: field oviposition patterns of an invasive snail, *Pomacea insularum*, indicate a preference for an invasive macrophyte. *Hydrobiologia* 646: 243–251, <https://doi.org/10.1007/s10750-010-0167-1>
- Carrete M, Tella JL (2008) Wild-bird trade and exotic invasions: a new link of conservation concern? *Frontiers in Ecology and the Environment* 6: 207–211, <https://doi.org/10.1890/070075>
- Cassey P, Blackburn TM, Russell GJ, Jones KE, Lockwood JL (2004) Influences on the transport and establishment of exotic bird species: an analysis of the parrots (Psittaciformes) of the world. *Global Change Biology* 10: 417–426, <https://doi.org/10.1111/j.1529-8817.2003.00748.x>
- Chucholl C (2013) Invaders for sale: trade and determinants of introduction of ornamental freshwater crayfish. *Biological Invasions* 15: 125–141, <https://doi.org/10.1007/s10530-012-0273-2>
- Cowie RH (1998) Patterns of introduction of non-indigenous non-marine snails and slugs in the Hawaiian Islands. *Biodiversity and Conservation* 7: 349–368, <https://doi.org/10.1023/A:1008881712635>
- Cowie RH, Robinson DG (2003) Pathways of introduction of nonindigenous land and freshwater snails and slugs. In: Ruiz GM, Carlton JT (eds), *Invasive species – vectors and management strategies*. Island Press, Washington, USA, pp 93–122
- De Marco P (1999) Invasion by the introduced aquatic snail *Melanoides tuberculata* (Müller, 1774) (Gastropoda: Prosobranchia: Thiariidae) of the Rio Doce State Park, Minas Gerais, Brazil. *Studies on Neotropical Fauna and Environment* 34: 186–189, <https://doi.org/10.1076/snfe.34.3.186.8908>
- Devin S, Bollache L, Noël P-Y, Beisel J-N (2005) Patterns of biological invasions in French freshwater systems by non-indigenous macroinvertebrates. *Hydrobiologia* 551: 137–146, <https://doi.org/10.1007/s10750-005-4456-z>
- Duggan IC (2002) First record of a wild population of the tropical snail *Melanoides tuberculata* in New Zealand natural waters. *New Zealand Journal of Marine and Freshwater Research* 36: 825–829, <https://doi.org/10.1080/00288330.2002.9517135>
- Duggan IC (2010) The freshwater aquarium trade as a vector for incidental invertebrate fauna. *Biological Invasions* 12: 3757–3770, <https://doi.org/10.1007/s10530-010-9768-x>
- Duggan IC, Rixon CAM, MacIsaac HJ (2006) Popularity and propagule pressure: determinants of introduction and establishment of aquarium fish. *Biological Invasions* 8: 377–382, <https://doi.org/10.1007/s10530-004-2310-2>
- European Commission (2012) Commission implementing decision of 8 November 2012 as regards measures to prevent the introduction into and the spread within the Union of the genus *Pomacea* (Perry). *Official Journal of the European Union* L311: 14–17
- Gardener M (2012) *Statistics for Ecologists Using R and Excel® – data collection, exploration, analysis and presentation*. Pelagic Publishing, Exeter, UK, 324 pp
- Heller J, Dolev A, Zohary T, Gal G (2013) Invasion dynamics of the snail *Pseudopotia scabra* in Lake Kinneret. *Biological Invasions* 16: 7–12, <https://doi.org/10.1007/s10530-013-0500-5>
- Horgan FG, Stuart AM, Kudavidanage EP (2014) Impact of invasive apple snails on the functioning and services of natural and managed wetlands. *Acta Oecologica* 54: 90–100, <https://doi.org/10.1016/j.actao.2012.10.002>
- Hulme PE (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalization. *Journal of Applied Ecology* 46: 10–18, <https://doi.org/10.1111/j.1365-2664.2008.01600.x>
- Hulme PE, Pyšek P, Nentwig W, Vilà M (2009) Will threat of biological invasions unite the European Union? *Science* 324: 40–41, <https://doi.org/10.1126/science.1171111>
- IMS (2014) Israel Meteorological Service. <http://www.ims.gov.il/> (accessed 9 November 2014)
- IUCN (2016) The IUCN Red List of Threatened Species. Version 3.1. <http://www.iucnredlist.org/> (accessed 21 March 2016)
- Jenkins PT (1996) Free trade and exotic species introduction. *Conservation Biology* 10: 300–302, <https://doi.org/10.1046/j.1523-1739.1996.10010300.x>
- Lin W, Zhou G, Cheng X, Xu R (2007) Fast economic development accelerates biological invasions in China. *PLoS ONE* 2(11): e1208, 6 pp
- Madsen H, Frandsen F (1989) The spread of freshwater snails including those of medical and veterinary importance. *Acta Tropica* 46: 139–146, [https://doi.org/10.1016/0001-706X\(89\)90030-2](https://doi.org/10.1016/0001-706X(89)90030-2)
- Maki K, Galatowitsch S (2004) Movement of invasive aquatic plants into Minnesota (USA) through horticultural trade. *Biological Conservation* 118: 389–369, <https://doi.org/10.1016/j.biocon.2003.09.015>
- Marr SM, Marchetti MP, Holden JD, García-Berthou E, Morgan DL, Arismendi I, Day JA, Griffiths CL, Skelton PH (2010) Freshwater fish introductions in mediterranean-climate regions: are there commonalities in the conservation problem? *Diversity and Distribution* 16: 606–619, <https://doi.org/10.1111/j.1472-4642.2010.00669.x>
- Mienis HK (2003) Pathways for introductions of foreign freshwater molluscs in Israel and elsewhere. *Ellipsaria* 5(1): 14–15

- Mienis HK (2006a) Aquatic snails intercepted by inspectors of the plant protection and inspection services at Ben-Gurion Airport, Israel. *Ellipsaria* 8(2): 13–14
- Mienis HK (2006b) Failed attempts to smuggle live *Filopaludina martensi* into Israel, but... *Tentacle* 14: 15–16
- Mienis HK (2011a) A further note on the conquest of Israel by the invasive tropical gastropod *Thiara scabra*. *Ellipsaria* 13(2): 29
- Mienis HK (2011b) Will the uncontrolled sale of the snail-eating gastropod *Anentome helena* in aquarium shops in Israel result in another disaster for Israel's native freshwater mollusc fauna? *Ellipsaria* 13(3): 10–11
- Mienis HK, Rittner O (2012a) On the presence of the invasive Mimic lymnaea *Pseudosuccinea columella* in Israel (Gastropoda, Lymnaeidae). *Ellipsaria* 14(2): 17–20
- Mienis HK, Rittner O (2012b) On the presence of the invasive Seminole Rams-horn *Planorbella duryi* in Israel and Palestine (Gastropoda, Planorbidae). *Ellipsaria* 14(3): 16–19
- Mienis HK, Vaisman S, Rittner O (2015a) A first find of the S.E.-Asian *Filopaludina martensi* in a public pond in Kefar-Sava, Israel. *Ellipsaria* 17(1): 25–27
- Mienis HK, Vaisman S, Rittner O (2015b) Three public ponds in Israel have turned out to be infested with the Apple snail *Pomacea maculata* from the same source. *Ellipsaria* 17(3): 14–15
- Mienis HK, Rittner O, Vaisman S (2016) Illegal sale of exotic freshwater molluscs in aquarium shops in Israel. *Ellipsaria* 18(1): 28–30
- Milstein D, Mienis HK, Rittner O (2012) A field guide to molluscs of inland waters of the Land of Israel. Israel Nature and Parks Authority, Israel, 55 pp [in Hebrew]
- Mrugala A, Kozubiková-Balcarová E, Chucholl C, Cabanillas Resino S, Viljamaa-Dirks S, Vukić J, Petrussek A (2014) Trade of ornamental crayfish in Europe as a possible introduction pathway for important crustacean diseases: crayfish plague and white spot syndrome. *Biological Invasions* 17: 1313–1326, <https://doi.org/10.1007/s10530-014-0795-x>
- Ng TH, Tan SK, Wong WH, Meier R, Chan S-Y, Tan HH, Yeo DCJ (2016) Molluscs for sale: assessment of freshwater gastropods and bivalves in the ornamental pet trade. *PLoS ONE* 11: 1–23, <https://doi.org/10.1371/journal.pone.0161130>
- Niemiera AX, von Holle B (2009) Invasive plant species and the ornamental horticulture industry. In: Inderjit (ed), *Management of Invasive Weeds*. Springer Science+Business Media, Netherlands, pp 167–187, https://doi.org/10.1007/978-1-4020-9202-2_9
- Noy E, Aharon A, Bar-Eliezer S, Gidanian Y, Hleihel A, Nathan Y, Paltiel A, Pasternak M, Peleg S, Penso O, Rosenberg B, Tal T (2012) Statistical abstract of Israel 2012 no. 63. Central Bureau of Statistics, Jerusalem, Israel. Online version available at: http://www.cbs.gov.il/reader/shnaton/shnatone_new.htm?CYear=2012&Vol=63&CSubject=30
- Orr BK, Resh VH (1992) Influence of *Myriophyllum aquaticum* cover on *Anopheles* mosquito abundance, oviposition, and larval microhabitat. *Oecologia* 90: 474–482, <https://doi.org/10.1007/BF01875440>
- Padilla DK, Williams SL (2004) Beyond ballast water: aquarium and ornamental trades as sources of invasive species in aquatic ecosystems. *Frontiers in Ecology and the Environment* 2: 131–138, [https://doi.org/10.1890/1540-9295\(2004\)002\[0131:BBWAAO\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2004)002[0131:BBWAAO]2.0.CO;2)
- Papavlasopolou I, Perdikaris C, Vardakas L, Paschos I (2014) Enemy at the gate: introduction of non-indigenous freshwater crayfish in Greece via the aquarium trade. *Central European Journal of Biology* 9: 11–18, <https://doi.org/10.2478/s11535-013-0120-6>
- Patoka J, Kalous L, Kopecký O (2014a) Risk assessment of the crayfish pet trade based on data from the Czech Republic. *Biological Invasions* 16: 2489–2494, <https://doi.org/10.1007/s10530-014-0682-5>
- Patoka J, Petrtyl M, Kalous L (2014b) Garden ponds as potential introduction pathway of ornamental crayfish. *Knowledge and Management of Aquatic Ecosystems* 414(13): 1–8
- Phelps J, Webb EL (2015) “Invisible” wildlife trade: Southeast Asia's undocumented illegal trade in wild ornamental plants. *Biological Conservation* 186: 296–305, <https://doi.org/10.1016/j.biocon.2015.03.030>
- Pointier JP, Delay B, Toffart JL, Lefèvre M, Romero-Alvarez R (1992) Life history traits of three morphs of *Melanoides tuberculata* (Gastropoda: Thiariidae), an invading snail in the French West Indies. *Journal of Molluscan Studies* 58: 415–423, <https://doi.org/10.1093/mollus/58.4.415>
- R Core Team (2013) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org
- Rader RB, Belk MC, Keleher MJ (2003) The introduction of an invasive snail (*Melanoides tuberculata*) to spring ecosystems of the Bonneville Basin, Utah. *Journal of Freshwater Ecology* 18: 647–657, <https://doi.org/10.1080/02705060.2003.9664007>
- Ricciardi A (2007) Are modern biological invasions an unprecedented form of global change? *Conservation Biology* 21(2): 329–336, <https://doi.org/10.1111/j.1523-1739.2006.00615.x>
- Roll U, Dayan T, Simberloff D, Mienis HK (2009) Non-indigenous land and freshwater gastropods in Israel. *Biological Invasions* 11: 1963–1972, <https://doi.org/10.1007/s10530-008-9373-4>
- Seuffert ME, Martín PR (2012) A lentic dweller in lotic habitats: the behavior of the invasive South American apple snail *Pomacea canaliculata* in flowing water. *Aquatic Ecology* 46: 129–142, <https://doi.org/10.1007/s10452-011-9386-4>
- Sharma GP, Esler KJ, Bignaut JN (2010) Determining the relationship between invasive alien species density and a country's socio-economic status. *South African Journal of Science* 106(3/4): article #113, 6 pp
- Simberloff D (2010) Invasive species. In: Sodhi NS, Ehrlich PR (eds), *Conservation biology for all*. Oxford University Press, pp 131–152, <https://doi.org/10.1093/acprof:oso/9780199554232.003.0008>
- Smith KF, Behrens M, Schloegel LM, Marano N, Burgiel S, Daszak P (2009) Reducing the risks of the wildlife trade. *Science* 324: 594–595, <https://doi.org/10.1126/science.1174460>
- Taylor DW (2003) Introduction to Physidae (Gastropoda: Hygrophila). Biogeography, classification, morphology. International Journal of Tropical Biology and Conservation, San José, Costa Rica, 299 pp
- Tsibel N (2008) Press release: Peripherality index of local authorities 2004 – new development. Central Bureau of Statistics, Jerusalem, Israel. Online version available at: http://www.cbs.gov.il/reader/new_hodaot/hodaa_template.html?hodaa=200824160 [in Hebrew]
- Vaisman S, Mienis HK (2011) Molluscs intercepted at the borders of Israel in 2009 and 2010. *Tentacle* 19: 15–18
- Vilá M, Pujadas J (2001) Land-use and socio-economic correlates of plant invasions in European and North African countries. *Biological Conservation* 100: 397–410, [https://doi.org/10.1016/S0006-3207\(01\)00047-7](https://doi.org/10.1016/S0006-3207(01)00047-7)
- Warchol GL (2004) The transnational illegal wildlife trade. *Criminal Justice Studies* 17: 57–73, <https://doi.org/10.1080/08884310420001679334>
- Westphal MI, Browne M, MacKinnon K, Noble I (2008) The link between international trade and global distribution of invasive alien species. *Biological Invasions* 10: 391–398, <https://doi.org/10.1007/s10530-007-9138-5>
- Whittington RJ, Chong R (2007) Global trade in ornamental fish from an Australian perspective: the case of revised import risk analysis and management strategies. *Preventive Veterinary Medicine* 81: 92–116, <https://doi.org/10.1016/j.prevetmed.2007.04.007>
- Wonham MJ, Walton WC, Ruiz GM, Frese AM, Galil BS (2001) Going to the source: role of invasion pathway in determining potential invaders. *Marine Ecology Progress Series* 215: 1–12, <https://doi.org/10.3354/meps215001>