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Alien aquatic plants in wetlands of a large European city (Geneva, Switzerland): from diagnosis to risk assessment

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Abstract
Wetlands often form an important component in the urban matrix, where they are largely disseminated. Despite the abundance of these urban waterbodies, little is known about the spread of alien aquatic plant species in cities. Ponds are frequent in urban parks and domestic gardens where terrestrial alien plant species are common. Therefore, urban ponds are likely to support many aquatic alien species which might disperse to the natural environment. To investigate this potential, we collected data from 178 ponds in a large European city (Geneva, Switzerland), across an urbanization gradient. 17% (23 taxa) of the aquatic flora appears to be non-native, including five species at high risk of invasion. A large proportion of the waterbodies (43%) supported at least one alien taxa. Through the development of a risk assessment tool, the "Geneva-Aquatic Weed Risk Assessment system", a risk map was created which revealed several alien species hotspots situated in the urban environment, but also in rural areas, including in protected wetlands. This risk mapping included the dispersal potential distance of species around these risk hotspots, and showed that most areas of dispersal seem to be relatively small. Ponds are target sites for deliberate introduction but they tend to be hydrologically isolated in the urban matrix, and these 'islands' therefore present a relative low risk of a wider dissemination of alien species. This risk is nevertheless expected to sharply increase in future. Introduction by humans is likely to be the main source of new alien aquatic plants, and so management should primarily aim to prevent the introduction of these species. Sites supporting alien species should also be monitored and, if possible, the species presenting a risk should be eradicated. Sites supporting alien species should also be monitored and, if possible, the species presenting a risk eradicated.

Keywords Invasive alien species · Non-native macrophytes · Urban ponds and lakes · Introduction and dispersal · Risk assessment · Freshwater biodiversity

Introduction

Alien invasive species introductions and their spread to new areas is one of the major causes of biodiversity loss (Gaston and Spicer 2004). In freshwaters, particularly harmful impacts can be caused by invasive alien plant species, including pressure on native biodiversity (Madsen et al. 1991), degradation of water quality (Shillinglaw 1981), reduction of recreational use (Eiswerth et al. 2005), perturbation of water flow and major perturbations of ecosystem functioning (Bunn et al. 1998). Management to control alien aquatic invasive plants once a species is established can also be economically very costly (Hussner et al. 2017).

Humans have greatly facilitated the spread of alien invasive aquatic species through intentional stocking, aquarium releases, canal construction, and international shipping (Rahel 2007; Brunel 2009). Horticultural trade also promotes the movement of invasive aquatic plants (Maki and Galatowitsch 2004), particularly ornamental and aquarium plants (Padilla and Williams 2004), a problem that is today exacerbated by mail-order and e-commerce (Kay and Hoyle 2001). The ornamental trade is considered to be the major pathway of aquatic plant introduction in different continents and climatic regions (Champion et al. 2010; Hussner 2012). For example, 19 of the 27 alien aquatic species that are currently known from German freshwaters are traded in shops as ornamentals for aquaria or garden ponds (Hussner et al. 2014). Several of the most troublesome aquatic weeds in the United

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States are escaped horticultural plants which were cultivated for aquaria and water gardens (Maki and Galatowitsch 2004). In New Zealand, 75% of naturalized alien aquatic plant species have been imported as ornamental plants for aquariums and garden ponds (Champion 1998; Williamson 1999). For terrestrial species, one tenth of introduced species becomes naturalized and about 1% causes degradation. In Central Europe, from 12,000 alien plant species introduced since the Neolithic period, 0.3% are currently invasive (Müller and Sukopp 2016). But this proportion is greater for aquatic plants, with one fourth of all alien aquatic plant species categorized as pest or potentially pest species (Hussner 2012).

The number of alien aquatic plant species is still currently relatively low in European freshwaters. The greatest number has been found in Italy and France (34 species), followed by Germany (27), Belgium and Hungary (26) and the Netherlands (24) (Hussner 2012). But this number is sharply increasing, and has doubled over a nearly 30 year period in Germany (Hussner et al. 2014). In Switzerland, this information is unfortunately currently missing (L. Sager, InfoFlora Switzerland; comm.pers.).

The urban environment is particularly subjected to intentional plant species introduction. Today, the flora of most large cities is reported to include around 30 to 50% alien species (Dunn and Heneghan 2011), and this is illustrated, for example, by the large proportion of exotic seeds species observed in the seed bank (Cilliers and Siebert 2011). Species introduction is also very common in domestic gardens and, for example in Australia, about 80% of 'noxious weeds' come from ornamental plants used in gardening (Virtue et al. 2004). Introduction of aquatic plants in urban areas can be intentional or accidental, and is linked to ornamental gardening activities (e.g. garden ponds) or to aquarium plant trade. It has been estimated that there could be as many as 3.5 million garden ponds in the UK covering up to 349 ha (Davies et al. 2009). This means that there are literally millions of autonomous garden ponds managers and habitat engineers (Hassall et al. 2016). However the diversity, abundance and distribution of aquatic plants in cities are largely unknown. When data does exist, evidence-based information is generally focused on terrestrial plants. In one of the rare comprehensive assessments realised in cities, Kozlowski and Bondallaz (2013) reported only a few alien aquatic macrophyte species (5 out of 69 species) in four Swiss cities. In another study in Portland-Oregon, however, alien species represented more than half of the species from urban wetlands (from a total of 365) (Magee et al. 1999). The invasion risk of alien species is likely to be high in cities, because the urban environment is subjected to a particularly high rate of plant introduction. Furthermore, aquatic freshwater ecosystems are particularly vulnerable to invasions by alien species when compared to terrestrial ecosystems (Lodge et al. 1998; Sala et al. 2000). Many of the questions which have already been investigated for terrestrial plants in cities still remain to be addressed for aquatic plants. For example, does the public have the inclination to introduce alien species? Are alien species also largely present in urban aquatic plant communities, including in urban ponds? And does ponds colonized by alien species in urban area act as a source for dispersal in the wider landscape, within and beyond the edges of cities?

Successful management of alien species includes integrated measures such as accurate risk assessment and prioritization, and early detection and monitoring. The invasive potential of species and their harmful environmental impacts are not necessarily linked (Ricciardi and Cohen 2007), and therefore all species do not present the same risk. Thus, conducting a risk assessment of individual alien aquatic species is one of the first steps to adequately manage these plants. In order to assess the risk of invasion, comprehensive information is required about their biogeography, introduction and establishment history, reproductive biology and ecology. Several countries developed international risk assessment protocols that considerably differ in terms of their scope and completeness (Verbrugge et al. 2010). The absence of a robust, targeted and common risk assessment protocol to predict the invasiveness of species is a major problem. At the European scale, in early 2000, the European and Mediterranean Plant Protection Organisation (EPPO) created a global Pest Risk Analysis (PRA) that applies to a range of non-indigenous organisms (plants, insects, bacteria, virus). The organization recently published a list of pests including seven aquatic plants (Branquart et al. 2016; OEPP/EPPO 2016). The majority of protocols in European countries are generic: they were developed to be applied to all taxonomic groups and ecosystems (e.g. Belgium, Germany, Austria and United Kingdom). The first risk assessment devoted exclusively to plants was developed in Australia (Pheloung et al. 1999). The Australian weed risk assessment ("AWRA") was subsequently modified to reflect local environmental characteristics and now has high accuracy in a range of other regions outside of Australia (Gordon et al. 2008). However this tool weights aquatic plants heavily toward invasiveness (only 5% of the species used in the development of the AWRA were aquatic (Gordon et al. 2012)). The same bias is observed in central Europe with the ranking protocol of Weber and Gut (2004) which proposed a first attempt to evaluate the impact and invasive potential of all introduced plants. A narrower screening process is required to discriminate accurately between invasive and non-invasive alien aquatic plants. Hence, a separate risk assessment tool was built for New Zealand ("NZAqWRA") (Champion and Clayton 2001). This scoring method allows species to be ranked in high, medium of low invasion risk associated with a cut-off threshold. With only small modifications for more accurate implementation in the USA ("USAqWRA"), this tool correctly identified 85% of major-invaders and 98% of non-invaders (Gordon et al. 2012). The USAqWRA is a questionnaire addressing life cycle, ecological requirements, climate tolerance and invasion history. This protocol assesses different types of potential impacts for the purpose of prioritizing management actions against invasive aquatic plants. Effect on biodiversity, ecosystem functioning, economy and human health are included in the questionnaire. Consequently, this tool cannot evaluate species that have become established or included in trade relatively recently (<30 years), for which no impacts have been documented yet. As far as we know, such quantitative risk assessment tool designed for aquatic plants has to date not been tested in Europe.

In the current study, our main objective was to increase our knowledge of aquatic alien plant species in cities. To do this, we investigated the distribution of alien species in 178 ponds in a large European city (Geneva, half a million inhabitants). As ponds tend to be one of the main aquatic habitats where species are introduced in cities (through aquarium releases and ornamental activities), and they are widespread waterbodies in most cities (e.g. in parks and gardens), they constituted the perfect model for studying the establishment and dispersion of aquatic alien species in urban areas. We hypothesized that such ponds support a large number of alien species, especially in the most urbanized areas. Based on the studies in other cities, this number could represent up to 50% of the whole aquatic plant community of Geneva. But as all alien species are not necessarily invasive and so do not present the same risk, we tested the application of a risk assessment to identify problem species and alien invasive plant hotspots. Each alien species recorded in our study was assessed, and this was followed by risk mapping at the city scale, including the potential dispersion areas around each pond. This risk assessment included, for the first time in Europe, testing and implementing of the USAqWRA tool.

Methods

Study sites

A total of 178 ponds were investigated in Geneva and the surrounding urbanized areas (Geneva Canton, Switzerland). Geneva Canton is an administrative area of about 280 km^2 located in the western part of Switzerland. The region has a temperate climate. The Canton of Geneva has a marked gradient of urbanization, from urban (city center) to rural areas (Fig. 1). As a surrogate for this urbanization gradient, we used a definition based on Radford and James (2013): the degree of urbanization of each cell in a 500x500m grid is the proportion of impervious soil in a 2 km range around the center of this cell. A rural area corresponds to less than 15% of impervious soil, peri-urban to 16–30%, sub-urban to 31–40% and urban to more than 40%. The study ponds were distributed in these four areas: 50 in the urban area, 29 in the sub-urban area, 34 in the peri-urban area and 65 in the rural area (Fig. 1).

All ponds were man-made, mostly created for landscape gardening (47% of all ponds) and social well-being (34%), i.e. "garden ponds" or "park ponds". Biodiversity was the management objective for only 18% of these ponds. Other pond uses included education (11%, e.g. in schools) and water storage (6%, e.g. reservoirs for irrigation). Ponds were relatively small in surface area (median area of 200 m^2), often with an artificial substrate, and they had a relatively limited shoreline development generally with little vegetation. The ponds tended to have been created relatively recently (median of 30 years) and half of them supported fish.

Alien aquatic plant taxa

Plant taxa were considered aquatic if they were listed in the highest humidity class (= 5) by Landolt (1977). This included true hydrophytes (submerged or floating-leaved species) and many helophytes (emergent species). To this 'aquatic' species pool, 22 species listed by Landolt (1977) under humidity class 4 as described in Indermuehle et al. (2010) were added.

The native geographical range of a species results from its natural dispersal mechanisms and from biogeographic barriers. Species whose presence in a new area, well outside their native range, is due to intentional or unintentional human involvement are called « alien », « exotic », « introduced », « non-native » or « non-indigenous ». Among alien species, some are considered « invasive » because they persist in their new environment, produce reproductive offsprings, and spread greatly in their distribution (Havel et al. 2015; Pyšek et al. 2014). The above definition of alien invasive species was used in our study.

Species were identified as alien if they fulfilled one of the following five criteria: (i) classified on the Black List or Watch List for Switzerland (Bulholzer et al. 2014), (ii) designated as regional neophytes in the Flora Indicativa (Landolt and Bäumler 2010), (iii) designated as local neophytes on the Geneva Red List (Lambelet-Haueter et al. 2006), (iv) the species can potentially be introduced in Geneva Canton and has already proven to be invasive in other areas, and (v) the species is known as a horticultural variety. In addition, expert advice was provided by the national data and information center for the Swiss flora "InfoFlora" (L. Sager). Species are listed on the Swiss Black List when they have a high potential of expanding their distribution in Switzerland, and if they can potentially cause important and proven negative impacts to the natural environment. They are listed on the SwissWatch List when they have a moderate to high potential for spreading and may provoke moderate to high damage.

The current distribution of alien species in Geneva Canton was assessed from observations collected between 1995 and 2015. About 60% of the data were collected by our own field surveys as part of two large research programs ("MARVILLE", Oertli and Ilg 2014; "URBEXO", Oertli 2017). Ponds were

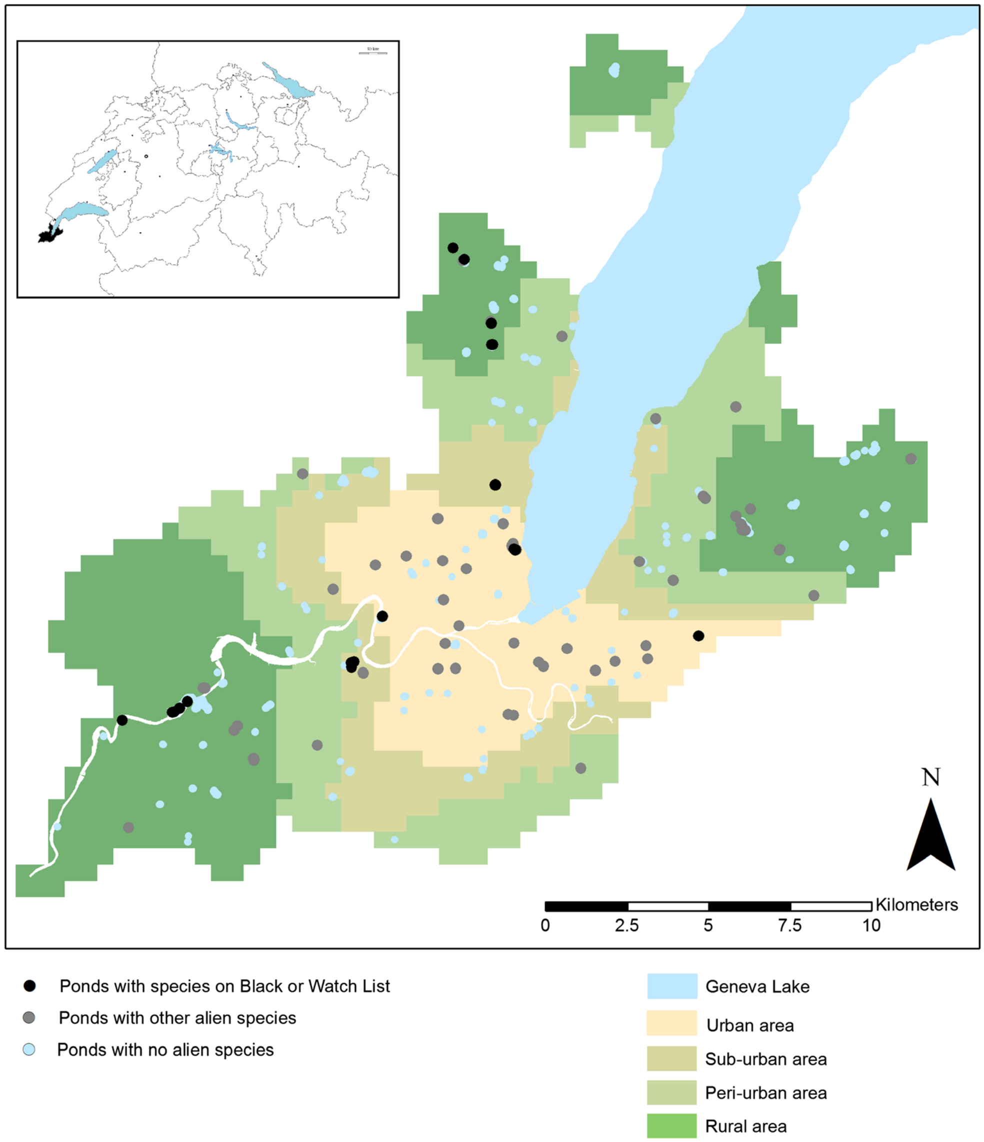

Fig. 1 Study area shown in relation to Switzerland (Canton of Geneva is marked in black in the upper left insert) and distribution of alien aquatic plant taxa recorded in 178 ponds. The urbanization gradient is represented by four classes (shown by different colors)

surveyed in summer (2011 to 2015), and as most were small in surface area, exhaustive inventories were conducted: each site was searched until no new species was recorded. Aquatic species were mostly identified in the field, but some specimens were also collected and confirmed by expert (Patrice Prunier). The other 40% of the data was provided by the national data and information center on Swiss flora "InfoFlora", a center that gather data from various studies (inventories mostly carried out by local botanists between 1995 and 2015).

The relationship between the number of alien species per pond and environmental variables were assessed by mean of generalized linear models (GLMs) with a Poisson distribution. Eight environmental variables were assessed in the models: surface area (log transformed), pond coverage by submerged vegetation (%), pond coverage by helophytes (%), presence of an artificial substrate, the extent of built up area in a 2 km and 50 m buffer around the pond (%) and the extent of woodland in a 0.5 km and 50 m buffer around the pond (%). An iterative stepwise backward selection was used to select the best predictive variables for the model. First, a full model including all predictor variables was built. A model simplification procedure based on Akaike's information criterion (AIC) was then used to remove the less informative parameters included in the initial model, with the model having the lowest AIC value being selected as the best approximating model.

Risk assessment of the alien taxa

Development of the Geneva-aquatic weed risk assessment system

The Weed Risk Assessment system "USAqWRA" developed for aquatic plants in the United States (Gordon et al. 2012) was adapted here for Geneva. The adaptation was necessary because Geneva is in a different biogeographic region. Indeed, the geographic location influences the species traits considered in the index. We named this system "GVAqWRA" for Geneva-Aquatic Weed Risk Assessment.

The "GVAqWRA" is a questionnaire-style risk assessment that includes 39 questions about life history, ecology, climatic tolerance and invasion history of each aquatic plant species (see Data Supplement). Answers to each question are converted into a number, and the total score represents the risk of invasion. Species with high scores are more likely to become invasive and cause important impacts. This tool also includes default responses which can be used to complete the questionnaire in the absence of data. The questionnaire includes three types of criteria:

- Ecological and biological traits, i.e. the intrinsic and undesirable characteristics of the species (habitat versatility, competitive ability, reproductive features, effective dispersal);
- Damage, i.e. the potential negative impacts that can be caused by the species;
- Management, i.e. how difficult the species is to control.

The temperature tolerance question of the USAqWRA is related to a species ability to survive frost. In our study area we believe that temperature range is a more relevant metric to predict the success of invasion. With ongoing climate change, the frost tolerance of species will probably have a weaker influence on invasion success than its ability to survive and reproduce under warmer conditions. Under the relatively optimistic A1B scenario, an increase in air temperature of around 4 °C is expected by the end of the twenty-first century in Switzerland (OFEV 2012). In our study area, the number of frost days did not significantly decrease since 1960 while the number of extremely hot days did increase from 1 to 2 days per decade (Perroud and Bader 2013). Hence the climatic suitability of each species was assessed by two questions:

- temperature range (Q1.1): a −1 score was given to cold stenothermic species, +3 and +2 to eurythermic and warm stenothermic species, respectively.
- frost tolerance (Q1.2): a score of +2 was given to evergreen species (instead of +3 in USAqWRA), 1 if individual plants dies back to underground vegetative parts, 0 if only a viable seed bank remains and −1 if it only overwinters with protection against cold.

We modified USAqWRA in two other ways. Firstly we ignored the question about salinity tolerance (Q1.6) which is not relevant to the study area and replaced it by "eutrophication tolerance": a score of 3 was given to species able to grow in eutrophic to hypereutrophic waters, polluted (human-induced eutrophication), 2 if the species is able to grow in eutrophic but not polluted water (natural eutrophication), and 1 if it is unable to grow in eutrophic waters and is able to grow only in oligo- to mesotrophic conditions.

Secondly, the question 1.4 of USAqWRA put together substrate and water quality properties. As the water quality is already addressed in Q1.6 of GVAqWRA, the question 1.4 was modified to deal with substrate type only: a score "2" was given if tolerant of sandy to muddy (or peaty) substrate, 1 if restricted by either.

Calculation of risk assessment scores

The score representing the risk of invasion were calculated separately for the three types of criteria (traits, impacts, management). Both the traits and damage scores (respectively from −2 to +61 and from 0 to +23) were added to obtain the total score for each species (−2 to 84). The risk assessment score was kept separate from the management required for species control although this additional information is potentially very useful to land managers.

To classify species according to their risk level, each species was positioned on a 2D–plot according to their traits and damages scores (transformed into percentage from 0 to 100% of the maximum score). The damage = traits line with a ± 10% interval was used to define three areas in the diagram, and four types of species were identified from this plot:

- major invasive species ("High risk") which are shown in the top right-hand corner of the diagram;
- moderate invasive species ("Moderate risk") which are closed to the traits = damage score line;
- minor invasive species ("Low risk") which are shown in the bottom left-hand corner;
- species that need further evaluation (for which currently available information is not sufficient to return a score).

Assessed and non-assessed taxa

The risk was assessed for all alien taxa observed in the Geneva Canton (Table 1). Some taxa could not be assessed by the GVAqWRA and this was due to three different reasons. (i) There was insufficient information about the ecology of the species and potential impacts. This was the case for 4 species: *Sagittaria graminea, Phalaris arundinacea var. picta, Nelumbo nucifera, Saracenia purpurea*. (ii) A taxa could not be identified at the species level (e.g. *Mimulus sp.*). (iii) The taxonomic status of a species was unclear. For example horticultural varieties of *Myriophyllum propium* can be sold under an unofficial tradename (pers. Communication from T. van Haaren-Eurofins Omegams and J.L.C.H. van Valkenburg-Nederlandse Voedselen Warenautoriteit). To give a species its proper name without plant examination is risky and unreliable. By default we decided to keep the trade name of *Myriophyllum propium.*

Table 1 Classification of 23 plant taxa non-native in the Geneva Canton: 23 taxa observed in the present study. Status on a regional list is presented for three increasing geographical scales: Geneva (present risk assessment, GVAqWRA), Switzerland (national black and watch lists updated in 2014, Infoflora; the recommendations about the sale of exotic plants provided by the AGIN-Arbeitsgruppe invasive Neobiota 2015) and Europe (EPPO - European and Mediterranean Plant Protection Organization)

		Geneva	Switzerland		Europe
Abbreviation	Latin name	GVAqWRA categories (Table 1)	Black (b)/watch (w) Infoflora lists (2014)	AGIN list (2015)	EPPO lists
accal	*Acorus calamus*	low risk			
lyame	*Lysichiton americanus*	low risk	w	R2	O (A2 in 2005- deleted in 2009)
salat/gra*	*Sagittaria latifolia/graminea*	low risk	w (*S. latifolia*)	R2 (*S. latifolia*)	
cavul	*Carex vulpinoidea*	low risk			
stalo	*Stratiotes aloides*	low risk			
migut	*Mimulus guttatus*	low risk			
pocor/lan*	*Pontederia cordata/lanceolata*	low risk			
elcan	*Elodea canadensis*	moderate risk	b	R1	
sacer	*Saururus cernuus*	moderate risk			
lemin	*Lemna minuta*	moderate risk			
bifron	*Bidens frondosa*	moderate to high risk			O (2012)
elnut	*Elodea nuttallii*	moderate to high risk	b	R3	IAS (2004)
nypel	*Nymphoides peltata*	high risk			
myaqu/prop*	*Myriophyllum aquaticum/propium*	high risk	b (*M. aquaticum*)	R1 (*M. aquaticum*)	IAS (*M. aquaticum*, 2004)
hyran	*Hydrocotyle ranunculoides*	high risk	b	R3	A2 (2005)
pharu.pic**	*Phalaris arundinacea* var. *picta*	need further evaluation			
nenuc**	*Nelumbo nucifera*	need further evaluation			
sapur**	*Sarracenia purpurea*	need further evaluation			
nym.hort**	*Nymphaea* horticultural var.	need further evaluation			
iri.hort**	*Iris* horticultural var.	need further evaluation			
typ.hort**	*Typha* horticultural var.	need further evaluation			

GVAqWRA: * = species for which we used information from another species belonging to the same genera; ** = species for which a simplified evaluation based on questions related to biological traits was made (currently available information is insufficient). EPPO lists: A2 = species highly dangerous and locally present in EPPO region that should be treated as quarantine pests; IAS = Invasive species for which countries should take measures to prevent their introduction and spread or to manage unwanted populations; O = observation list for species having a medium risk or for which the information currently available is not sufficient to make an accurate assessment

We used a different strategy to give a risk score to the taxa listed above. For *Myriophyllum proprium, Mimulus sp.*, *Pontederia lanceolata* and *Sagittaria graminea*, the risk score was based on closely related species (respectively on *Myriophyllum aquaticum, Mimulus guttatus, Pontederia cordata* and *Sagittaria latifolia*). The proper nature of *M. propium* being unknown, the precautionary principle was used and we based its score on those of the major invader *M. aquaticum*. For other species (*Pontederia* sp. and *Sagittaria* sp.), we assumed that the scores would be very similar to close relatives as they share similar growth forms. For the species assessed by GVAqWRA, the scores obtained for each question are presented in Table 3. For the other taxa, since no information was available about impacts in Europe, we used a simplified method including information on reproduction and dispersal, and the single score related to biological traits became the global score (Table 3).

Risk mapping

The risk assessed for each individual taxa was mapped to evaluate the dispersion potential from each pond at the regional scale (the Canton of Geneva). The aim of risk mapping was to provide support for practical management of freshwater biodiversity. Two types of data were used for mapping risk with GIS (ArcGIS): (i) the site-level risk likely from the alien plant community at that pond, and (ii) the resistance of the landscape surrounding the pond to alien species dispersal. The risk for each pond was the sum of the scores "traits and damage" (Table 3) of the alien species found in each pond and reflects the number of alien species as well as their risk scores. The threshold values were therefore defined as follow. "Low risk ponds" (<80) are characterized by the presence of a few alien species classified as being at low risk. "Moderate risk ponds” (>80 and <130) are characterized by the presence of several alien species classified as being at low risk and/ or presence of few species classified as being at moderate risk. The “high-risk ponds” (>130) shelter a large number of alien species, often also including plants considered of being at high risk. The landscape resistance to species dispersal was mapped with the ArcGIS “Cost Distance” tool on the basis of the resistance of the 17 urban matrix patches. We translated the resistance to a mark between 1 (low resistance) and 10 (high resistance), which relates to the ability of propagules to disperse through these types of patches: forest (5), crops (5), orchards or vines (5), sports field (5), urban vegetation (grass, tree, or mixture) (5), open land (5), other green area (5), lake or pond (1), stream (3, or 1 if downstream of a pond), building (10), building surrounding (7), parking (7), railway (5), road (5), aerodrome (7), bare rock or scree (5), other hard surface (5). The data were available from the Geographic Information System Office of the Canton of Geneva (SITG, layer “couche_sol_basse_agglo”). As many aquatic plants are wind dispersed across distances between several tens of meters to several kilometers (Soons 2006), we assumed the maximum dispersal distance of a species to be 2 km.

The map is primarily aimed at site managers and can be used to inform decisions on which management measures to apply to a particular site. For two particularly invasive species, *Elodea canadensis* and *E. nutalii,* managers are unwilling (and also unable) to take management action, and therefore both species were excluded from the mapping. Indeed, both species are already widespread in the region (in a wide range of freshwater habitats including rivers and lake). Furthermore, *Elodea canadensis* (Michx.) can be considered a non-aggressive addition to native flora (Kolada and Kutya 2016).

Results

Alien taxa in pond

A total of 136 aquatic plant taxa were observed in the 178 ponds surveyed (Appendix Table 4), including 23 alien species (Table 1), which represents 17% of all taxa. These 23 alien species were observed in 43% of the Geneva ponds (77 ponds) (Fig. 1). The frequency of alien taxa was higher in urban ponds (54%) than in ponds situated in less densely urbanized areas (between 21% and 37%). The mean species richness in ponds was 7.8 species, with 11% represented by alien species. This proportion was higher in the more urbanized area (15%).

Four species were of particular concern because they are classified on the Swiss Black List: *Elodea canadensis*, *Elodea nuttallii*, *Hydrocotyle ranunculoides* and *Myriophyllum aquaticum*. The two first are present in 15 ponds and are widely distributed in the study area where they have also colonized rivers, streams and Geneva Lake. The two other species are present each in a single pond on the West side of Geneva Lake. One other species, classified on the Swiss Watch List, is of concern: *Lysichiton americanus*. This species was observed in the close vicinity (within less than 60 m) of *Hydrocotyle ranunculoides* and *Myriophyllum aquaticum*. The other 18 alien species were more scattered throughout the Canton of Geneva compared to the five Black or Watch List taxa. The most frequent alien taxa was *Nymphaea* ssp. (horticultural varieties), observed in nearly half of the urban pond. *Pontederia cordata/lanceolata* was also frequently observed (10% of urban ponds).

To test if human pressure was likely to explain the presence of alien species in ponds, we investigated the relationship between the number of alien species and relevant environmental variables. The proportion of built up area in a 50 m buffer around each pond was used as a surrogate of human pressure. The GLM models (Table 2) showed that this variable significantly explained the alien species richness in ponds. Indeed, among the eight predictor variables selected for the GLM models, three variables were kept in the final GLM model: (i) the presence of an artificial substrate, (ii) the proportion of built up area in a 50 m buffer and (iii) the proportion of wooded area in a 0.5 km buffer around the pond. The number of alien species was greater in ponds with an artificial substrate and surrounded by densely built up areas.

Risk assessment

Considering the 17 species assessed through the Geneva-Aquatic Weed Risk Assessment system (GVAqWRA), the total “trait + damage score” allowed their classification between low risk (e.g. 32%; *Lysichiton americanus*) to high risk (e.g. 75%, *Myriophyllum aquaticum/propium*) (Fig. 2, Tables 1 and 3 for detailed scores). The “management score” underlined on one hand species that can potentially be controlled through management measures (e.g. 13%, *Carex vulpinoidea)* and, on the other hand, species which are

Table 2 Modelization (generalized linear models (GLMs) with a Poisson distribution) of the relationship between the number of alien species and the environmental variable in ponds from the Canton of Geneva (Switzerland). Overall, the GLM model explains about 21% of the deviance, and includes three environmental variables: (i) the presence of an artificial substrate, (ii) the proportion of built up area in a 50 m buffer and (iii) the proportion of wooded area in a 0.5 km buffer around the ponds

Environmental variable	Estimates	Sdt. Error	P
Presence of an artificial substrate	0.715	0.326	0.028
Wooded area in a 0,5 km buffer (%)	−2.634	1.380	0.056
Built-up area in a 50 m buffer (%)	1.037	0.507	0.041

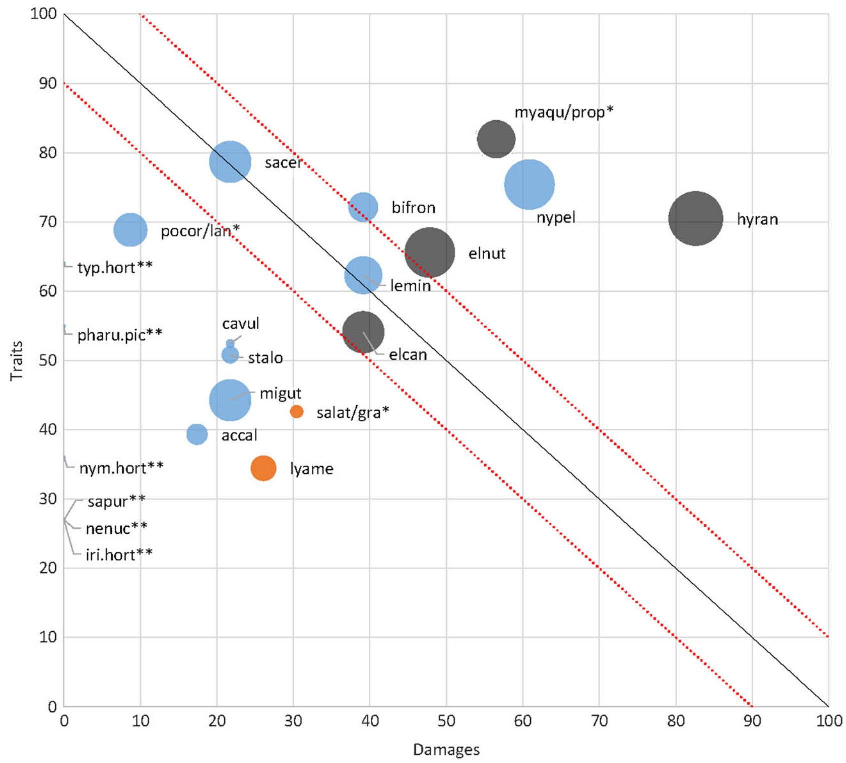

Fig. 2 Risk assessment for 23 alien plants taxa observed in Geneva according to their "biological trait score" and "damage score". The size of the point represents the "management score", with the largest points corresponding to species which are likely to be the most difficult to eradicate. Black-listed and Watch-listed species in Switzerland are respectively in black and orange. The black line is the limit where "biological trait score" =" damage score". Dashed red lines give the interval of ±10% around this limit. * = species for which we used information from a species belonging to the same genera. ** = species for which a simplified evaluation based on questions related to biological traits was made (available information is currently insufficient). For explanation about abbreviations see Table 1

difficult or impossible to control (e.g. 87%, *Hydrocotyle ranunculoides*). Amongst the four black-listed species, two unsurprisingly obtained very high total scores (*Hydrocotyle ranunculoides, 74%; Myriophyllum aquaticum/propium* 75%) and were positioned on the extreme right hand part of the 2d–plot (Fig. 2). The two other black-listed *Elodea canadensis* and *E. nuttallii* obtained lower scores but were still equal or over 50% (respectively 50% and 61%). *Nymphoides peltata* has a very high total score (73%) even though not black-listed. *Bidens frondosa* and *Elodea nuttallii* were both positioned just over the interval line, suggesting that their invasion risk is moderate to high. Three others species were classified inside the interval line and so have moderate invasive risk (*Saururus cernuus, Lemna minuta, Elodea canadensis*). The two species on the watch list, *Sagittaria graminea* and *Lysichiton americanus*, return scores of 39 and 32%, respectively, and are positioned under the lower limit of the interval (minor invasives). *Acorus calamus, Stratiotes aloides, Carex vulpinoidea, Mimulus guttatus* and *Pontederia cordata/lanceolata* are also categorized as minor invasive.

Six species were not assessed through the GVAqWRA, as they are not known to cause damage, hence their scores were not given in details (no damage score, Table 3): *Nelumbo nucifera, Sarracenia purpurea, Phalaris arundinacea* var. *picta*, and horticultural varieties of *Typha*, *Nymphaea* and *Iris*. They are therefore situated directly on the left axes of Fig. 2, but they do need further evaluation.

Dispersion risk mapping

From the 178 ponds surveyed, 77 supported alien species. The risk, already assessed for each alien taxa with the new risk assessment tool (see previous section), was used for assessing the dispersion risk from each pond at the regional scale (Canton of Geneva) and mapped by GIS. The 77 plant communities (excluding *Elodea canadensis* and *E. nutalii*; see Methods section) were classified low to high risk, and were mapped with their dispersion potential in the landscape (Fig. 3). The results show that the 77 ponds are located across the four levels of urbanization. They are however more abundant in the urban area than in less urbanized areas, and this was already highlighted by the species distribution (Fig. 1). Three ponds presented a high dispersion risk: two in the urban area and one in the peri-urban area. One shows a large potential dispersion area (about 1.5 km^2) extending into Geneva Lake, but the other two dispersion areas are less important (0.2 km^2). Eight ponds presented a medium risk, and half of these are located outside the urban area, and have relatively small dispersion area (0.2 to 0.5 km^2). About fifteen ponds with low to medium risk are inside or at the border of designated wetlands.

The dispersion areas represented around each of the 77 ponds mostly appear relatively small (less than 0.5 km^2), especially in the most urbanized areas where the matrix is unfavorable to dispersal processes. Dispersion areas are all slightly larger in less urbanized areas, where the matrix tends to be

Table 3 Risk and management scores obtained using GVAqWRA and simplified questionnaires for the 23 alien aquatic plant taxa

		abbreviation	accal	lyame	migut	salat/gra*	cavul	stalo	elcan	pocor/lan*	lemin	bifron	elnut		
		Latin name	*Acorus calamus*	*Lysichiton americanus*	*Mimulus guttatus*	*Sagittaria latifolia/graminea*	*Carex vulpinoidea*	*Stratiotes aloides*	*Elodea canadensis*	*Pontederia cordata/lanceolata*	*Lemna minuta*	*Bidens frondosa*	*Elodea nuttallii*		
Ecological traits	1.1	Temperature range	2	-1	-1	3	3	3	-1	3	3	2	-1		
	1.2	Frost tolerance	1	2	-1	2	1	2	2	2	1	1	2		
	1.3	Range of habitat	2	1	1	1	1	1	2	1	1	1	2		
	1.4	Substrate type tolerance	2	2	1	1	2	1	2	2	2	2	2		
	1.5	Water clarity tolerance	1	1	1	1	0	0	1	1	1	1	1		
	1.6	Eutrophication tolerance	3	2	3	3	3	1	3	3	3	3	3		
	1.7	pH tolerance	0	1	0	0	1	1	1	1	1	1	1		
	1.8	Water level fluctuation tolerance	2	0	-	0	2	2	3	1	1	3	3		
	2.1	Flowing waters, including their margins	1	1	1	1	1	1	2	3	2	3	3		
	2.2	Standing waters, including their margins	1	1	1	1	1	1	2	3	3	3	3		
	2.3	Wet habitats not covered by 2.1 or 2.2	1	1	1	1	1	0	2	3	0	1	2		
	2.4	Establishment – into existing vegetation	0	-3	-5	0	-5	5	-5	0	-3	-3	-5		
	2.5	Establishment – into disturbed vegetation	0	0	5	0	1	5	1	1	5	5	5		
Biological traits	3.1	Competition – between growth form	0	1	0	0	1	2	1	0	2	0	0		
	4.1	Dispersal by natural agents	0	5	5	3	5	5	5	5	5	5	5		
	4.2	Dispersal by accidental human activity	2	0	3	1	3	1	3	1	3	2	3		
	4.3	Dispersal by deliberate introduction	1	1	0	1	1	1	1	1	0	1	1		
	4.4	Effective spread within waterbody/ landscape	1	0	1	0	-	1	1	1	1	1	1		
	5.1	Generation time	1	2	2	2	2	1	2	2	2	2	2		
	6.1	Seeding quantity	0	2	3	1	2	1	0	2	0	3	0		
	6.2	Seeding viability/persistence	0	1	1	1	1	1	0	1	0	2	5		
	7.1	Vegetative reproduction	3	1	5	3	5	5	5	5	5	5	2		
Damages	8.1	Water use, recreation	1	1	1	1	1	1	1	0	2	1	1		
	8.2	Access	1	1	1	1	1	1	1	0	1	1	2		
	8.3	Water flow, power generation	1	1	1	1	1	1	1	0	1	1	2		
	8.4	Irrigation, flood control	1	1	1	1	1	1	1	1	1	1	0		
	8.5	Visual, olfactory	0	1	0	0	1	0	1	0	1	1	3		
	9.1	Reduces biodiversity	0	0	1	2	0	0	1	1	1	3	1		
	9.2	Impacts water quality	0	0	0	0	0	1	1	0	1	0	0		
	9.3	Negatively affects physical processes	0	0	0	0	0	0	1	0	0	0	0		
	10.1	Human health impairment	0	0	0	0	0	0	1	0	0	0	0		
	10.2	Agricultural weed	0	1	0	1	0	0	0	0	1	1	2		
Management	11.1	Ease of measures implementation	1	0	0	0	1	1	2	0	2	0	1		
	11.2	Recognition of problem	0	0	1	1	0	0	1	0	1	1	1		
	11.3	Scope of control methods	1	1	1	1	0	1	0	2	0	1	1		
	11.4	Control method suitability	0	0	1	0	0	1	1	1	0	0	1		
	11.5	Effectiveness of control measures	0	0	1	0	0	0	1	0	1	0	1		
	11.6	Duration of control	0	1	1	0	0	0	2	0	1	2	2		
	12.1	Problem in other countries	3	4	5	1	1	1	3	5	4	3	5		
														min	max
		Total trait + damages	28	27	32	33	37	36	42	44	47	53	51	-2	84
		Total trait + damages %	*33*	*32*	*38*	*39*	*44*	*43*	*50*	*52*	*56*	*63*	*61*	*0*	*100*
		Management	5	6	10	3	2	4	10	8	9	7	12	0	15
		Management %	*33*	*40*	*67*	*20*	*13*	*27*	*67*	*53*	*60*	*47*	*80*	*0*	*100*

Table 3 (continued)

		abbreviation	sacer	nypel	myaqu/prop*	hyran	pharu.pic**	nenuc**	sapur**	nym.hort**	iri.hort**	typ.hort**
		Latin name	*Saururus cernuus*	*Nymphoides peltata*	*Myriophyllum aquaticum/ propium*	*Hydrocotyle ranunculoides*	*Phalaris arundinacea* var. *picta*	*Nelumbo nucifera*	*Sarracenia purpurea*	*Nymphaea* hort. var.	*Iris* hort. var.	*Typha* hort. var.
Ecological traits	1.1	Temperature range	2	3	2	2	-	-	-	-	-	-
	1.2	Frost tolerance	1	1	2	1	-	-	-	-	-	-
	1.3	Range of habitat	3	2	3	2	-	-	-	-	-	-
	1.4	Substrate type tolerance	2	2	2	1	-	-	-	-	-	-
	1.5	Water clarity tolerance	1	1	1	1	-	-	-	-	-	-
	1.6	Eutrophication tolerance	3	2	3	3	-	-	-	-	-	-
	1.7	pH tolerance	1	0	1	0	-	-	-	-	-	-
	1.8	Water level fluctuation tolerance	3	2	3	3	-	-	-	-	-	-
	2.1	Flowing waters, including their margins	2	3	3	3	-	-	-	-	-	-
	2.2	Standing waters, including their margins	2	3	3	3	-	-	-	-	-	-
	2.3	Wet habitats not covered by 2.1 or 2.2	2	3	3	3	-	-	-	-	-	-
	2.4	Establishment – into existing vegetation	0	0	0	-5	-	-	-	-	-	-
	2.5	Establishment – into disturbed vegetation	5	1	5	5	-	-	-	-	-	-
Biological traits	3.1	Competition – between growth form	2	2	2	2	34	16	16	22	16	39
	4.1	Dispersal by natural agents	5	5	5	5						
	4.2	Dispersal by accidental human activity	1	3	3	3						
	4.3	Dispersal by deliberate introduction	1	1	1	1						
	4.4	Effective spread within waterbody/ landscape	1	1	1	1						
	5.1	Generation time	2	2	2	2						
	6.1	Seeding quantity	3	3	0	1						
	6.2	Seeding viability/persistence	1	1	-	1						
	7.1	Vegetative reproduction	5	5	5	5						
Damages	8.1	Water use, recreation	1	2	2	2	-	-	-	-	-	-
	8.2	Access	1	1	1	2	-	-	-	-	-	-
	8.3	Water flow, power generation	1	1	2	2	-	-	-	-	-	-
	8.4	Irrigation, flood control	1	1	2	2	-	-	-	-	-	-
	8.5	Visual, olfactory	0	1	1	1	-	-	-	-	-	-
	9.1	Reduces biodiversity	1	5	3	5	-	-	-	-	-	-
	9.2	Impacts water quality	0	1	0	3	-	-	-	-	-	-
	9.3	Negatively affects physical processes	0	2	2	2	-	-	-	-	-	-
	10.1	Human health impairment	0	0	0	0	-	-	-	-	-	-
	10.2	Agricultural weed	0	0	0	0	-	-	-	-	-	-
Management	11.1	Ease of measures implementation	1	2	2	2	-	-	-	-	-	-
	11.2	Recognition of problem	1	0	0	1	-	-	-	-	-	-
	11.3	Scope of control methods	1	1	1	1	-	-	-	-	-	-
	11.4	Control method suitability	1	1	1	1	-	-	-	-	-	-
	11.5	Effectiveness of control measures	1	2	1	1	-	-	-	-	-	-
	11.6	Duration of control	1	2	2	2	-	-	-	-	-	-
	12.1	Problem in other countries	4	4	3	5	-	-	-	-	-	-

Table 3 (continued)

											min	max
Total trait + damages	53	60	63	62	34	16	16	22	16	39	-2	84
Total trait + damages %	*63*	*71*	*75*	*74*	*40*	*19*	*19*	*26*	*19*	*46*	*0*	*100*
Management	10	12	10	13	-	-	-	-	-	-	0	15
Management %	*67*	*80*	*67*	*87*	-	-	-	-	-	-	*0*	*100*

*Species for which we used information from the closest evaluated species (same genera)

**Species for which we lack information so a simplified evaluation was made, based on questions related to biological traits (see Method section)

Values in italic are in percentage

min / max = minimum or maximum score that a species can potentially obtain (i.e. 0% - 100%)

For full details about GVAqWRA questionnaire, see the electronic supplementary material

more favorable to species dispersal. Nature reserves partly overlap with some of the dispersion areas for ponds of medium or low risk.

This map can now be used as a tool to prioritize practical management measures and reduce the risk presented by alien invasive plant species. For example management should control or eradicate species in the hotspots at high to moderate risk identified by this method (highlighted with red or orange colors in Fig. 3), particularly those close to nature reserves.

Discussion

Proportion and number of alien taxa in the Geneva territory

The 23 alien aquatic plant taxa identified in the 178 ponds from the Canton of Geneva constitute 17% of the whole aquatic plant species pool observed. This amount is double than the 8% reported in other Swiss cities (Kozlowski and Bondallaz 2013). This remains lower than the figure (50%) reported for Portland (Magee et al. 1999), an urban area that is however four times larger than our study area (the Canton of Geneva) and that obviously suffered from a much longer trade period (aquarium and ornamental trades). The proportion of alien aquatic plant species is likely to vary with the level of urbanization in cities. Indeed this is the case for terrestrial alien plants (Luck and Smallbone 2010), where reported values tend to be mostly around 30 to 50% (Dunn and Heneghan 2011). The proportion of alien invasive species was even reported to reach two third of plant diversity in urban domestic gardens (Thompson et al. 2003). The increasing proportion of alien species with the level of urbanization would still have to be tested for aquatic plants, by investigating additional cities in Switzerland and elsewhere.

The overall number of alien aquatic plant taxa (23 species) can be regarded as low, and is in line with the relative low values of alien aquatic plants reported for other European countries (Hussner 2012). It should however be stressed that we are at the beginning of an emerging problem, as exemplified by the exponential increase in the number of alien aquatic plant species observed in Germany (Hussner et al. 2014). The warming climate will also exacerbate this problem, as most aquarium plants are tropical (e-g. Brunel 2009) and several species are expected to survive in warming cities. The low number presented here also hides a large number of introduction events for native specimens issued from the ornamental trade. For example, the indigenous species *Iris pseudacorus* is present in 50% of the ponds in Geneva. Most specimens of this ornamental species are without doubt from garden centers, where *I. pseudacorus* is among the best sold aquatic species. Another example is the multiple introductions of non-native lineages of *Typha* sp. from plant nurseries (Ciotir and Freeland 2016). This also highlights concerns with genetic diversity because introduced specimens often have non-

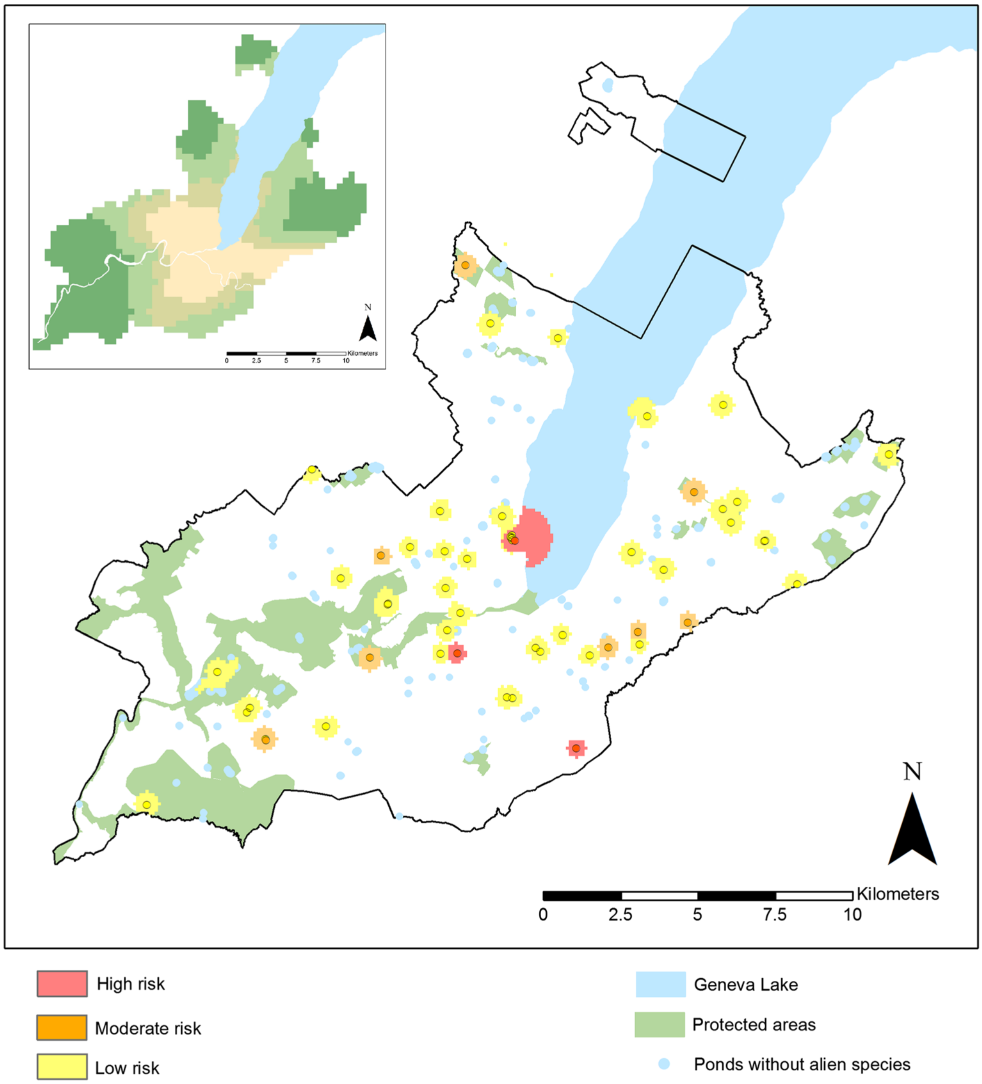

Fig. 3 Distribution of the ponds surveyed in the Canton of Geneva, showing ponds that support alien plant communities presenting a risk (low to high). The dispersion potential of alien taxa into the surrounding landscape depends on the resistance of the landscape, and is represented by the colored areas around the ponds. Protected wetland areas are shown in green. The upper left insert represents the four level of urbanization in the Canton of Geneva (see Fig. 1)

native genotypes and low genetic diversity. Genetic swamping of local genotypes and outbreeding depression has already been reported in terrestrial ecosystems (Hufford and Mazer 2003), and similarly indigenous aquatic plants produced in the horticulture sector may potentially result in the genetic impoverishing of urban aquatic ecosystems. This invisible problem remains to be more thoroughly investigated in future.

Dispersion pattern of alien taxa in the Geneva territory

The 23 alien taxa observed in the Geneva Canton have already spread widely throughout our study area, as 43% of the 178 ponds surveyed supported at least one alien species. Ponds in the urban area are clearly more easily colonized by the alien species than suburban or rural areas, indicating introduction pressure is probably greater in the center of cities. This was also shown by our modelization of the alien species richness in ponds, which was positively linked to the urbanization of the pond environment. Ehrenfeld (2008) also reported a greater invasion rate for aquatic taxa in residential areas than in other types of land-uses, such as industrial area or vegetated uplands. Some ponds in rural areas in the Canton of Geneva were however also colonized by alien species, including several ponds situated in protected nature reserves.

The dispersion pattern in the Geneva territory still remains unclear. Risk mapping (including potential plant dispersion areas) suggested that the risk is not limited to a few locations, but scattered all over the territory, including nature reserves, although there were fewer risk hotspots in those areas. Mapping of the potential dispersion areas from the ponds revealed that these tended to be relatively small, generally less than 0.5 km^2. Indeed, the ponds surveyed were mostly hydrologically isolated from other waterbodies, with no connection to other wetlands. The main pathway of dispersion from the original point of introduction to the wider environment is determined by hydrological connectivity (Lodge et al. 1998; Panov et al. 2009; Rahel and Olden 2008) and is likely to follow streams, rivers and lakes networks, as well as floodplain corridors. Flowing waters are therefore more prone to invasion than isolated ponds. Hydrological connections remains rare for ponds in the urban environments (and this is the case in Geneva), because most are not directly connected to streams, and can be considered water islands in a landuse matrix where there tends to be many obstacles to dispersal processes.

Nevertheless, not all types of aquatic plant rely on direct connections between waterbodies for their dispersal. Helophytes often rely on passive dispersion by wind (anemochory), and may therefore easily cross barriers in the urban matrix (e.g. concrete surface, road, parking). Wind dispersal is one of the major dispersal processes between wetlands not connected by surface water flow (Soons 2006), and so the distance between wetlands is key, with greater distance reducing plant dispersal abilities (Baldwin 2011). Here, a helophyte species identified as presenting a potential risk of spreading, *Bidens frondosa* (Moderate to High risk), disperses through wind, and if this species expand its distribution it may prejudice species eradication measures at the regional scale. Natural dispersion relies also on animals (active dispersion). Birds have been reported to be carriers of propagules (Green 2016), but birds are rare in the smaller waterbodies of urban areas, as garden ponds. They are nevertheless more frequent in larger ponds in parks. Other active dispersal pathways, typical for large waterbodies (such as lakes), are less relevant for ponds: this includes boats and other water sports equipment or fish stocking. Nevertheless private ponds (and garden ponds) are subject of other unique and additional way of dispersion: the exchanges between neighbors or friends. This has often been reported during our field investigations, but is a stochastic process that remains difficult to quantify and to map.

Most urban ponds from the Canton of General appear isolated in this study, a situation that may help reduce the risk of dissemination of alien alien species. So on one hand urban ponds potentially constitute multiple points of plant introduction in a city, and the greater the pond density, the greater the probability of an invasion starting. On the other hand, as demonstrated here, they are isolated, with a dispersal potential narrower than that of ponds in more natural landscapes. Habitat fragmentation (including intentional fragmentation) can help avoid dissemination of unwanted species (Rahel 2013), and this is the situation with isolated ponds. Existing barriers to dispersal have to be maintained, even promoted if a pond constitutes a high risk. Indeed, confining hotspot of alien species is a relevant management strategy (Rahel 2013). Pond isolation is however likely to be more effective as a measure to prevent dissemination of plant propagules for “truly” aquatic species (e.g. *Myriophyllum* sp., *Hydrocotyle* sp., *Elodea* sp., *Nymphoides* sp.) rather than for helophytes, which tend to have seeds dispersed by wind (e.g. *Bidens* sp., *Phalaris* sp., *Typha* sp.).

The future distribution of alien species in a city cannot be predicted, because it relies principally on human behaviour.With increasing human mobility and urbanization, we are playing a greater role in the distribution pattern of plants seen today (Antrop 2004). For aquatic species, deliberate introduction (planting or aquarium release) is without doubts a much more powerful factor in urban environments than natural dispersal (Thiébaut 2007). In the present study, alien species were more frequent in more urbanized areas than in other types of landuses. This pattern is probably related to a higher incidence of introductions where there is a greater population density. Human dispersal is likely to be the major driver for species introduction. Social surveys we conducted in the Canton of Geneva (data not presented here) confirmed this trend, with many pond owners or managers admitting that they themselves had taken part in deliberate alien species introductions at their site. This aspect of alien species management therefore has to be addressed with an awareness raising campaign covering the different stakeholders playing major roles in species introduction (sellers, land managers, private owners, etc.). The legislation over the cross-border movement of species clearly also needs improvements (Havel et al. 2015).

Risk assessment

All alien species do not present the same level of risk, and only one fourth of alien aquatic plant species are categorized as pest or potential pest species (Hussner 2012), a proportion close to our results for Geneva. The use of the USAqWRA risk assessment tool, for the first time in a European city, enabled us to assess the risk level for each of the 23 alien aquatic taxa recorded. This tool proved to be useful for such an assessment, even if it required some adaptation to take into account local conditions, a preliminary step that was realized here through the production of the GVAqWRA (Geneva-Aquatic Weed Risk Assessment). A drawback of such assessment system is that there is a basic need for detailed ecological information on each species which is often lacking. In our study, however, this information was fortunately available for most (78%) of all alien species recorded. The assessment allowed the classification of species along a risk gradient. Of the 17 alien species assessed, one fifth (three taxa) are highlighted here as presenting a “high” risk. Two from these three, *Hydrocotyle ranunculoides* and *Myriophyllum aquaticum/propium*, are already known to be a threat in Switzerland, and are classified on the noxious weed list (“Black list”). But this is not the case of the other high risk species we identified: *Nymphoides peltata*. This shows that noxious weed lists have to be regularly updated when new information becomes available on, for example, species ecology, geographical distribution, and potential impacts, and also on which new species have been introduced and recorded. Indeed, this is already the case in

Switzerland where a revision of the Black list was undertaken in 2014.

The risk assessment developed for individual species was translated into an applied tool for use by site managers. Indeed, the mapping approach took into account the risk from each pond (a pooled score from each individual species risk score), coupled with the dispersal potential of the species through the various elements of the urban matrix. This provided a very clear map for managers, because it allows them to focus on the right geographical place, supports decision-making, and prioritize practical conservation measures. Managers can also take into account their own priorities, for example the presence of nature reserves or ecological corridors, or future urban expansion. The risk map provides an excellent and didactical "science to practice" tool.

Conclusions

A range of aquatic alien plants have colonized the large European city of Geneva, particularly the most urbanized areas where half of the ponds have been colonized. On one hand, ponds constitute target sites for deliberate introductions, and their high density increases the risk of an invasion starting from one of the ponds. On the other hand, most ponds present a relatively low risk for the region, as three quarters of alien species present a low risk of spreading and colonizing new habitats, and so most potential dispersion areas appear to be of relatively small size. Because ponds are mostly hydrologically isolated in the urban matrix, they can be considered islands poorly connected or totally unconnected to each other.

Risk mapping is a useful tool for prioritizing practical conservation measures, such as protecting nature reserve from invasion or eradicating invasive alien species at high risk hotspots. As alien species were more frequent in more urbanized areas, this suggests that human dispersal is likely to be the main driver for species introduction. Management actions should therefore take a more preventative approach and also target social behavior (e.g. trade, sale, purchasing), including awareness raising campaigns and improvements to current legislation.

Compared to the high level of alien terrestrial plants introduced in gardens, the proportion of alien aquatic plants reported by our study in urban ponds is clearly lower, and represents presently still a smaller problem, although further research is needed, including in other cities. Alien aquatic plants are nevertheless a growing problem today, and the frequency of introduction is increasing, bringing species which are currently unknown to the host region. The problem is also likely to be exacerbated by climate change, as more tropical species are able to survive in temperate waterbodies. This underlines also the requirement to take preventive measures, before it turns to a major unsolvable problem.

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Appendix

Table 4 List of the 136 aquatic taxa observed in the 178 ponds investigated in the Geneva Canton

*** *Acorus calamus* L.**	*Glyceria notata* Chevall.	*Polygonum amphibium* L.
Algae	*Gratiola officinalis* L.	*** *Pontederia cordata* L.**
Alisma lanceolatum With.	*Groenlandia densa* (L.) Fourr.	*** *Pontederia lanceolata* Nutt.**
Alisma plantago aquatica L.	*Hippuris vulgaris* L.	*Potamogeton berchtoldii* Fieber
Alnus glutinosa (L.) Gaertn.	*Hydrocharis morsus ranae* L.	*Potamogeton crispus* L.
Alopecurus aequalis Sobol.	*** *Hydrocotyle ranunculoides* L. f.**	*Potamogeton pectinatus* aggr.
Berula erecta (Huds.) Coville	*Iris pseudacorus* L.	*Potamogeton lucens* L.
*** *Bidens frondosa* L.**	*** *Iris* horticultural var.**	*Potamogeton natans* L.
Bidens tripartita L.	*Juncus articulatus* L.	*Potamogeton nodosus* Poir.
*Bolboschoenus maritimus (*L.) Palla	*Juncus conglomeratus* L.	*Potamogeton plantagineus* Roem. & Schult.
Bryophyta	*Juncus effusus* L.	*Potamogeton pusillus* L.
Butomus umbellatus L.	*Juncus inflexus* L.	*Potamogeton trichoides* Cham. & Schltdl.

Table 4 (continued)

* ***Acorus calamus* L.**	*Glyceria notata* Chevall.	*Polygonum amphibium* L.
Callitriche sp.	*Lemna minor* L.	*Potentilla palustris (L.)* Scop.
Caltha palustris L.	* ***Lemna minuta* Humb. & al.**	*Ranunculus circinatus* Sibth.
Carex acutiformis Ehrh.	*Lemna trisulca* L.	*Ranunculus flammula* L.
Carex elata All.	*Ludwigia palustris* (L.) Elliott	*Ranunculus lingua* L.
Carex flava L.	*Lycopus europaeus* L. s.l.	*Ranunculus repens* L.
Carex lasiocarpa Ehrh.	* ***Lysichiton americanus* Hultén & H. St. John**	*Ranunculus reptans* L.
Carex paniculata L.	*Lysimacchia vulgaris* L.	*Ranunculus trichophyllus* Chaix s.l.
Carex pseudocyperus L.	*Lysimachia nummularia L.*	*Rumex hydrolapathum* Huds.
Carex riparia Curtis	*Lysimachia thyrsiflora L.*	* ***Sagittaria graminea* Michx.**
Carex rostrata Stokes	*Mentha aquatica L.*	*Sagittaria sagittifolia* L.
Carex vesicaria L.	*Mentha longifolia (L.) Huds.*	*Salix cinerea* L.
Carex vulpina L.	*Menyanthes trifoliata L.*	* ***Sarracenia purpurea* L.**
* ***Carex vulpinoidea* Michx.**	* ***Mimulus sp.***	* ***Saururus cernuus* L.**
Ceratophyllum demersum L.	*Myosotis cespitosa Schultz*	*Schoenoplectus lacustris* (L.) Palla
Chara aspera Willd.	*Myosotis scorpioides L.*	*Schoenoplectus mucronatus* (L.) Palla
Chara cf. *globularis* Thuill.	* ***Myriophyllum aquaticum (Vell.) Verdc.***	*Schoenoplectus tabernaemontani (*C. C. Gmel.) Palla
Chara contraria Kütz.	* ***Myriophyllum propium***	*Scrophularia umbrosa* Dumort.
Chara strigosa A. Braun	*Myriophyllum spicatum* L.	*Scutellaria galericulata* L.
Chara vulgaris L.	*Myriophyllum verticillatum* L.	*Senecio paludosus* L.
Cicuta virosa L.	*Nasturtium officinale* R. Br.	*Sparganium emersum* Rehmann
Cladium mariscus (L.) Pohl	* ***Nelumbo nucifera* Gaertn.**	*Sparganium erectum* L.
Cyperus longus L.	*Nitella mucronata* (A.Br.) Miquel	*Spirodela polyrhiza* (L.) Schleid.
Eleocharis acicularis (L.) Roem. & Schult.	*Nitella opaca* (Bruzelius) C. Agardh	* ***Stratiotes aloides* L.**
Eleocharis austriaca Hayek	*Nuphar lutea* (L.) Sm.	*Typha angustifolia* L.
Eleocharis palustris aggr.	*Nuphar pumila* (Timm) DC.	* ***Typha* horticultural var.**
Eleocharis mamillata H. Lindb.	*Nymphaea alba* L.	*Typha latifolia* L.
* ***Elodea canadensis* Michx.**	*Nymphaea candida* C. Presl	*Typha minima* Hoppe
* ***Elodea nuttallii* (Planch.) H. St. John**	* ***Nymphaea* horticultural var.**	*Utricularia australis* R. Br.
Equisetum fluviatile L.	* ***Nymphoides peltata (*S. G. Gmel.) Kuntze**	*Veronica anagallis-aquatica* L.
Equisetum palustre L.	*Oenanthe lachenalii* C. C. Gmel.	*Veronica beccabunga* L.
Galium palustre L.	*Phalaris arundinacea* L.	*Veronica catenata* Pennell
Glyceria declinata Bréb.	* ***Phalaris arundinacea* var. picta L.**	*Zannichellia palustris* L.
Glyceria fluitans (L.) R. Br.	*Phragmites australis* (Cav.) Steud.	
Glyceria maxima (Hartm.) Holmb.	*Poa palustris* L.	

The alien taxa are highlighted by bold characters and are preceded by a star (*)

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