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Research Article

First record of *Pontederia cordata* L. (Pontederiaceae) in southern Spain and risk assessment for Europe

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Abstract

Pontederia cordata L. (Pontederiaceae) is an emerging aquatic plant native to the American continent that has been introduced to various continents through long-distance commerce as an ornamental plant. Individuals growing in the wild belonging to *Pontederia* L. genus where found in South Spain. The analysis of diagnostic characters of the collected specimens and their comparison to those represented in herbarium vouchers allowed us to distinguish them from its closest relative, *P. sagittata* C. Presl and to assign all the specimens found at the locality to *P. cordata* L. This is the southernmost European record of the species. It was clear that the origin of the introduction was the use as ornamental aquatic plant in the area. Its invasion risk was assessed for Europe, firstly, by analysing the suitability of European climate for the species, secondly, by assessing the potential impact. Results showed that from 92.5 to 92.9% of the meteorological stations analysed showed climate conditions that were compatible with the species' climatic requirements. The ecological characteristics of the species and the climatic features of the area analysed suggest a great risk of invasion that could lead to the species' spread in Europe. These findings suggest that *P. cordata* could threaten European wetlands.

Key words: plant invasion, aquatic plant, climate, Köppen-Geiger, Climatch, European Union

Introduction

Pontederia L. is a small genus with three to six species, depending on species delimitation (e.g. Novelo and Lot 1994), all native to the American continent. Based on recent molecular studies, however, some authors have proposed to transfer the related genera, *Monochoria* C. Presl and *Eichhornia* Kunth to *Pontederia* (Pellegrini et al. 2018), thus increasing the number of species to 26, mostly distributed in the Neo- and Paleotropics. Several representatives of *Pontederia* s. str., *Monochoria*, *Eichhornia* and *Heteranthera* Ruiz & Pav., are reputed environmental or agricultural weeds (Randall 2017). Some of them, e.g. *Pontederia crassipes* Mart., belong to the most invasive species worldwide (Villamagna and Murphy 2010).

Pontederia cordata L. (pickerelweed), is an emerging invasive alien aquatic plant. Flowers are generally blue or blueish (rarely white), disposed in racemose groups 50–150 mm long at the extreme end of each stem (Schultz 1942; Lowden 1973; Novelo and Ramos 1998; Gettys and Wofford 2007; Lusweti et al. 2011). It is a diploid (2n = 16), erect (up to 1.5 m high), emergent, herbaceous, long-lived and rhizomatous perennial plant, that can grow either rooted on pond margins or free-floating with emerging, branched stems above water surface, forming dense mats (Heisey and Damman 1982). *Pontederia cordata* is native to the American continent but it has been introduced into various countries as an ornamental species. It colonises marshes, streams with standing waters, ponds and shallow lakes (Gettys and Wofford 2007) and is a weed of rice fields in South America (Barrett 1978; Gomes and Magalhães Jr. 2004; Lallana 2005) and has been recorded as an emerging weed in South Africa (Hill and Coetzee 2017). The plant mainly disperses by seeds and fragmented rhizomes and, once arrived at a new appropriate site, colonisation usually takes place through rapid vegetative propagation (Lowden 1973).

Here, a second record for *P. cordata* in Spain is provided. Further, the invasion risk and potential impact linked to this species in the European continent (eastwards up to the European Union's external borders) was assessed. As the protocol used for this risk assessment includes a question on the species' climatic matching between the native and alien range, a specific analysis was conducted.

Materials and methods

Site characteristics, species identification and distribution

The species was detected by chance in June 2019, in Arroyo Hornillos, a freshwater stream (arroyo Hornillo, 20 m.a.s.l., water conductivity = 925–1058 μS cm^{-1}) near the city of Dos Hermanas (Seville, southern Spain). The whole stream (7.1 km) was explored on foot along the shore in search of *P. cordata*. The climate of the area shows a wet season from October to April and a dry season from May to September; mean temperature and rainfall values in Seville meteorological station (located 21 km from the area of study) are 19.2 °C and 539 mm, respectively (AEMET 2020). The climate type corresponds to "Csa" in the Köppen-Geiger system, i.e. "warm temperate with dry and hot summer" (Kottek et al. 2006, updated by Beck et al. 2018). The vegetation of the site is composed of *Populus nigra* L., *P. alba* L., *Olea europaea* L., *Typha domingensis* Pers., *Mentha suaveolens* Ehrh., *Phragmites australis* (Cav.) Trin. ex Steud., *Iris pseudacorus* L. and *Persicaria decipiens* (R. Br.) K.L. Wilson, with presence of invasive alien species such as *Arundo donax* L. and *Colocasia esculenta* (L.) Schott (García-de-Lomas et al. 2012; Dana et al. 2017).

Herbarium specimens were prepared and deposited in the herbarium of the University of Seville (Spain, herbarium code: SEV288881). The species was identified based on morphological characters such as petiole length, size and colour of flowers, perianth features, length of larger filaments, utricules size and seeds shape (Novelo and Lot 1994). *Pontederia cordata* is a quite distinct, readily recognizable species that can hardly be confused with other aquatic herbs. However, its closest relative, *P. sagittata* C. Presl, is morphologically very similar and distinguishing characters proposed to separate these two species are often contradictory (compare Novelo and Lot 1994 and Pellegrini et al. 2018). Comparison of herbarium specimens of these two species in the herbarium of Meise Botanic Garden (BR), demonstrated that *P. cordata* may be distinguished based on its serrate-edged fruits as compared to the smooth-edged fruits of *P. sagittata*. The plants found in the new Spanish locality here reported clearly belong to *P. cordata*.

Risk assessment and modelling strategy

The species' invasion risk was assessed following two different methods: the one provided by Pheloung et al. (1999) and Harmonia⁺ with the default configuration (D'hondt et al. 2015). The methodology and principles used are quite different in each of them (e.g., they differ in questionnaires and score calculation methods).

The procedure designed by Pheloung et al. (1999) was initially developed to screen the risk of weeds in Australia based on questions dealing with the target species' distribution, eco-physiological characters and undesirable attributes (hereinafter called Weed Risk Assessment, WRA). The method was shown to be also applicable in other parts of the world (e.g. Andreu and Vilà 2010; Gassó et al. 2010; Verloove et al. 2018; Dana et al. 2017, 2021). Gordon et al. (2010) subsequently improved the definition of the criteria used to answer the questions. The resulting scores place a species in one out of three categories: accept, i.e., low invasion risk (score < 6), further information needed (score = 6) or reject, i.e., high invasion risk (score > 6). The WRA system takes into account not only biological, ecological or historical aspects but also the features of the species in the native areas (such as its presence or absence across a variety of climate types) and the climatic matching between the native and alien range area, among others (Gordon et al. 2010). It is generally accepted that a greater similarity results in minimising the restrictive effect of potential climate filters (e.g. Beans et al. 2012).

The Harmonia⁺ protocol differs from Pheloung's system in questions, procedure for obtaining scores and user's choices (D'hondt et al. 2015). However, it also analyses climate resemblance as a key set of variables. In Harmonia⁺ the overall score obtained for a species and area under analysis ranges from 0 to 1, with a score of 0.5 being the threshold between low and high risk of invasion.

Both assessment methods require an objective analysis of climate match between the species' climate range in its native area and the area under study (Gordon et al. 2010; D'hondt et al. 2015). Hence, a matrix (which proceeds from 146 databases including herbaria, published records and observations, $n = 8{,}045$) with georeferenced records (geographical coordinates) corresponding to the species' distribution in its native and alien area was built and used for climate match analyses. Records were extracted from Global Biodiversity Information Facility Database (www.gbif.org). Only records indicating geographical coordinates matching the locality provided in the original labels were used. Two independent procedures were followed for climate match analysis. With the first procedure the association of each record in the original matrix to Köppen-Geiger's climate types according to the World Map of the Köppen-Geiger climate classification (Kottek et al. 2006, updated by Beck et al. 2018, with spatial resolution = 0.5 degree) was analysed. The resulting map allowed the identification of those climatic types that are suitable for the species. The second procedure used the Climatch software (Australian Bureau of Rural Science, available at https://climatch.cp1.agriculture.gov.au/climatch.jsp). The programme algorithms produce a classification of localities based on the similarity level shown by climatic features between the meteorological station nearest to a native or invaded locality ("input" sites) and the localities of the area under assessment, the "target" area or sites (Crombie et al. 2008). This allowed to inspect for critical climate matches between the species' distribution and the study area (European countries and member-countries of the European Union). Due to limitations in software processing capability with such a high amount of records, a subset database was built by randomly selecting 2,000 records (24.8% of the initial matrix) by using the random selection function provided by Excel software.

Due to the growth rate reported for *P. cordata* (Xin et al. 2020) and the dormancy of its seeds (Whigham and Simpson 1982; Gettys and Dumroese 2009), average quarterly values of climatic variables were employed instead of average month values. Thus, average temperature and rainfall of the coldest, warmest, wettest and driest quarter were used. Climatic data of 1,157 meteorological stations covering an area of ca. 5,337,142 km^2 in the native and alien ranges were compared to data gathered in 1,248 stations located across Europe (with an estimated covered area of ca. 4,943,225 km^2, Figure 1). Up to ten stations located within the nearest 50 km from each record were selected for each pair of comparisons. Using real meteorological data instead of projected data allowed to include in the analysis some of the biggest islands belonging to the European Union (e.g. Malta, Balearic Isles, Ultra peripheral regions of Azores and Canary Islands, etc.).

In order to assess the consistency of the results obtained, two different classification algorithms were used: the "Euclidean" algorithm (hereafter "model 1") and the "Closest standard score" (hereafter "model 2"). The

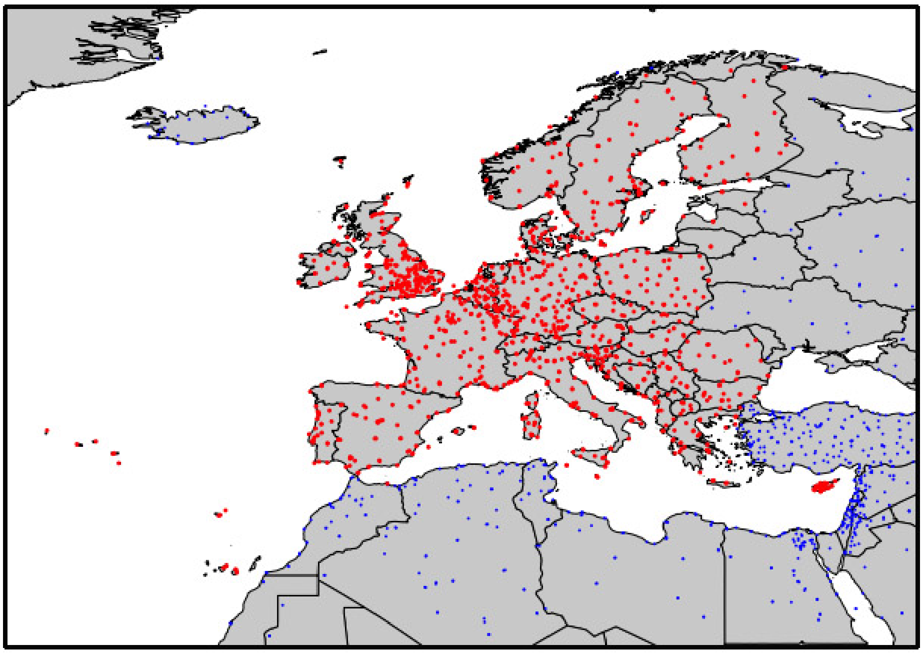

Figure 1. Target area under analysis (European Union and adjacent countries). Red dots indicate the meteorological stations used, whereas blue dots refer to other meteorological stations outside the assessed area.

model 1 calculated the "climate distance" between the input sites and each target site across the climate variables used in the analysis, while model 2 was based on the maximum Euclidean distance of each climate variable, considered individually, between the source sites and each target site (see Crombie et al. 2008 for details). Both algorithms produced a range of score categories from 0 (complete climatic dissimilarity) to 10 (complete similarity and hence absence of climatic filters). Areas with a score ≥ 7 were considered as suitable, while areas with a score = 6 were considered within the threshold of suitability, i.e., near-suitable (Koutsikos et al. 2018).

Results

Distribution and habitat invaded

The species covered an area of 100 m^2 (37.240787°N; 5.978206°W). The population included flowering and fruiting individuals, up to ca. 90 cm tall (Figure 2) forming dense thickets.

Climate match

Known records of *P. cordata* outside the American continent are concentrated in western Europe, with secondary clusters in southern and eastern Africa, Australia and New Zealand (Figure 3). The analysis of Köppen-Geiger's climate types revealed that *P. cordata* is distributed across regions with very different climatic features, both in its native and alien distribution range (Table 1). Overall, records of *P. cordata* could be linked to 15 climate types, i.e. 50% of all types considered, which clearly indicates the high climatic amplitude of the species. Therefore, the vast majority of

Figure 2. Pictures of *Pontederia cordata* in southern Spain: view of the naturalised population (a), flowering sprouts; (b-c), inflorescence; (d), leaves; (e), utricules; (f) removed plant showing its size. Photos by Juan García-de-Lomas.

freshwater bodies throughout European countries show climatic conditions that are potentially suitable for the species.

Analyses with Climatch 1.0 showed similar results, with 92.9 % vs. 92.5 % of European stations being found suitable for the species, regardless of the classification algorithm used (Table 2). This allowed to conclude that European climate types can be considered suitable to *P. cordata* (Figure 4).

Risk assessment

Based on the WRA (Supplementary material Table S1), *P. cordata* scored 25 points, indicating a high risk of invasion for European wetlands and

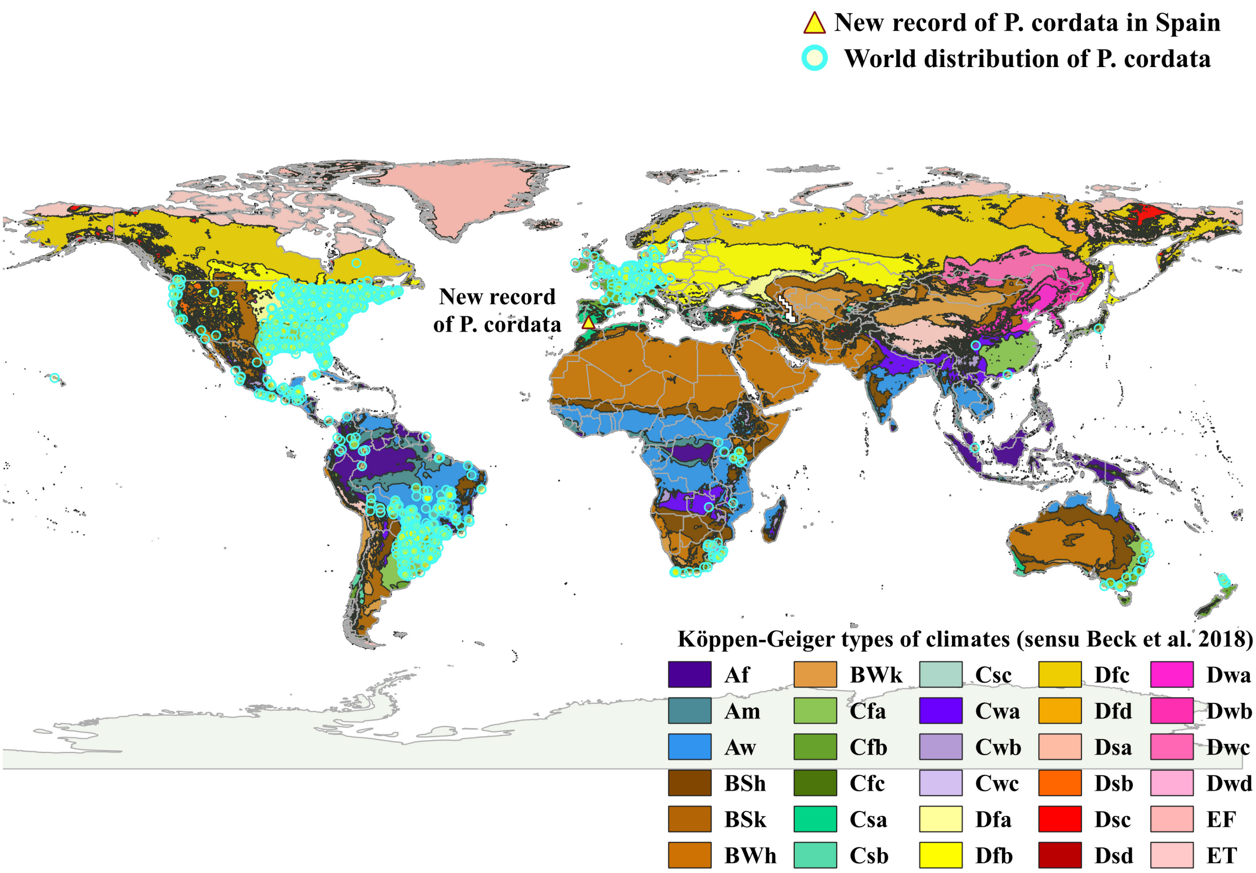

Figure 3. Köppen-Geiger climate types (sensu Beck et al. 2018) and world distribution of *P. cordata* (light-blue circles), native as well as introduced.

Table 1. Frequency of Köppen-Geiger's climate types associated to geographical records of *P. cordata* (based on Beck et al. 2018). In this system, the first letter describes the main climate classes, namely tropical (A), arid (B), warm-temperate (C), cold-temperate (D) and cold climates (E). The second letter accounts for precipitation regimes: hot (h) and cool (k). The third letter refers to the temperature class: hot summer (a), warm summer (b), dry, short summer (c) and very cold winter (d).

Geographical area	Frequency of climate type recorded (n = 8,045 records)	
	≥ 90 %	≤ 10 %
N America	Dfb, Dfa, Cfa	Cfb, Csb, Bwh
C and S America	Cfa, Cfb, Aw	Af, Am, Bsh, Bwh, Cwa, Cwb, Cwc
Europe	Cfb	Bsk, Csa, Csb, Dfb
Africa	Cfa, Cfb, Csb, Cwb	Af, Aw, Bsh, Cwa
Oceania	Cfa, Cfb	Aw (Hawaii)
Asia	Af, Cfa, Cwa	–

Table 2. Number and percentage of climatic suitability and near-suitability areas obtained with climate match analysis.

	Model 1	Model 2
Percentage and number [n] of suitable areas [score ≥ 7]	92.9 [1160]	92.5 [1155]
Percentage and number [n] of near-suitable areas [score = 6]	4.3 [54]	4.5 [56]

watercourses (see Supplementary material for details). This score was obtained by the contributions of biogeography (14 pt.) and biological/ ecological features (11 pt.). Moreover, the species achieved high scores for agricultural (14 pt.) and environmental impacts (21 pt.).

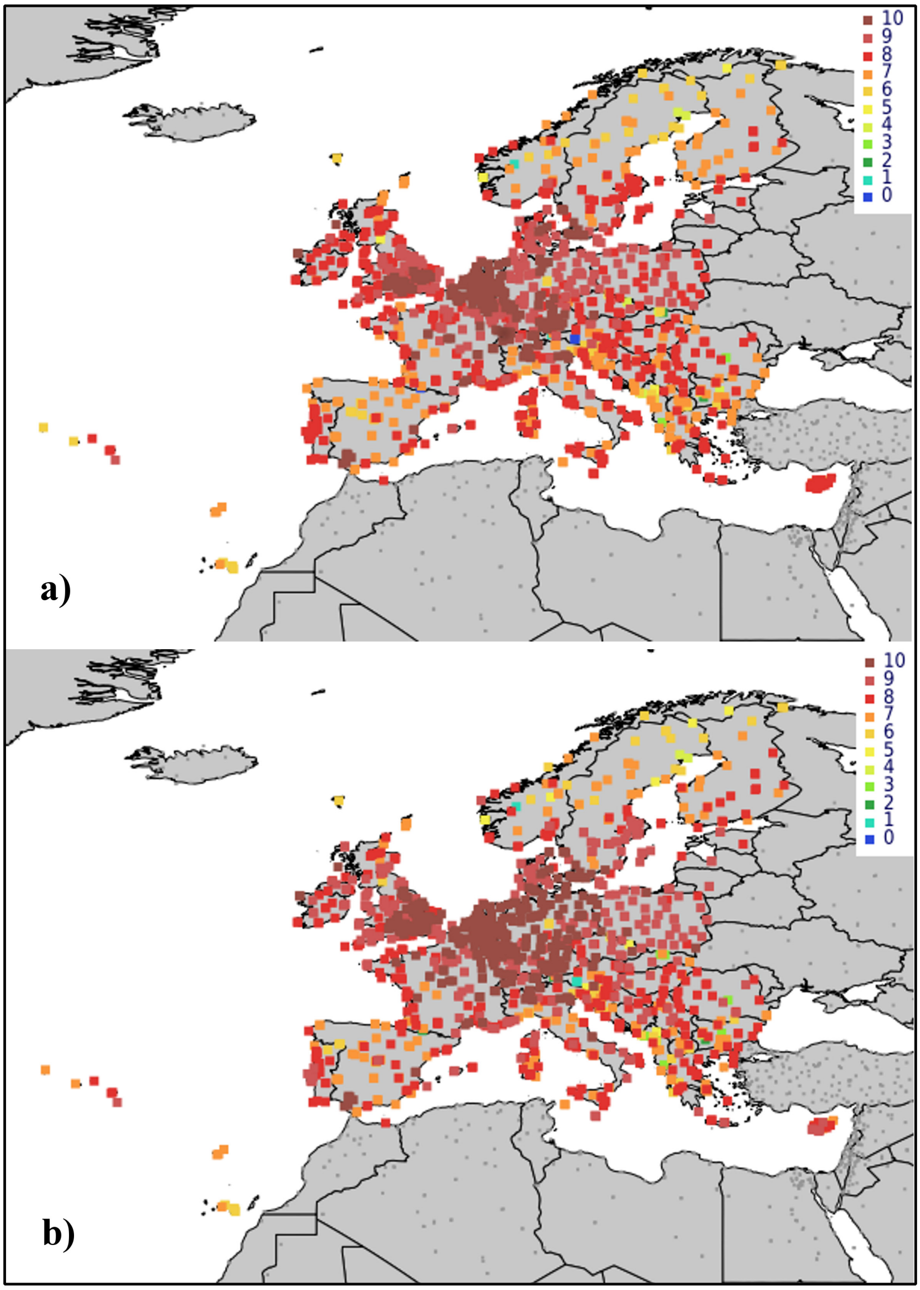

Figure 4. Climate match map showing the suitability of analysed regions for the establishment of *P. cordata* for model 1, obtained with Euclidean algorithm (a) and model 2, obtained with Closest standard score algorithm (b). Areas with a score ≥ 7 are considered suitable. Areas with a score = 6 are considered to be near-suitable.

Discussion

There are very few previous published records of *P. cordata* in the Iberian Peninsula. Apparently, none at all in Portugal (Almeida and Freitas 2006, 2012; Almeida 2018) while in Spain, it was previously recorded as casual escape in northeastern Spain (Romo et al. 2002; then confirmed as casual by Royo Pla 2006). Therefore, the record provided in the present study is the southernmost record in Spain.

Overall, records of *P. cordata* could be linked to 15 climate types, i.e. 50% of all types considered by Beck et al. (2018), which clearly indicates the high climatic amplitude of the species. Therefore, the vast majority of freshwater bodies throughout European countries show climatic conditions that are potentially suitable for the species. The percentage of potentially suitable areas is really high (92.5 to 92.9), and in correspondence with the distribution pattern in the species native area (from North to South America). These results corroborate with the species' records in most countries of continental Europe and with the results obtained by the Köppen-Geiger climate type analysis. Furthermore, both the Köppen-Geiger analysis and the one carried out with Climatch revealed that, despite the fact that most of the citations are located in northern Europe, the countries of the Mediterranean area present climate types that suit the species particularly well. Of special interest is the case of countries such as Portugal and Spain, in which the species' presence is still, comparatively, testimonial, despite the fact that the models showed a high climatic-coincidence with the species' requirements.

The high score (25 points) obtained in the risk assessment was caused by the presence of a high number of characteristics critically related to invasion process and impact. Some outstanding aspects related to previous records of the species or congeneric species as an invader contributed to the score. Climate similarity between native and potentially alien range, weedy behaviour of the species in agricultural and natural sites (Barrett 1978; Brandão et al. 1989; Gomes and Magalhães Jr. 2004; Lallana 2005; Randall 2017; Rolon et al. 2018), its repeated history of introductions in freshwater lakes, reservoirs, artificial dams and ponds in numerous warm and temperate areas of the world and the existence of important co-generic weeds (Lusweti et al. 2011; Randall 2017; Pellegrini et al. 2018). Other important traits also contributed to the final score. Some of these traits were related to the easy propagation, explicitly, its production of viable seed and self-fertilization (USDA NRCS Northeast Plant Materials Program 2002; Scribailo and Barrett 1994), its vegetative propagation and rapid generative time (Otis 1914; USDA NRCS Northeast Plant Materials Program 2002; Gettys 2005). Effective dispersal mechanisms were also responsible for the high score of the species. Propagules could be dispersed either intentionally (due to its attractive flowers and leaves) or unintentionally. The latter may include a broad range of dispersal mechanisms such as seed contaminant of rice paddy fields (Barrett 1978; Brandão et al. 1989; Gomes and Magalhães Jr. 2004; Lallana 2005; Randall 2017; Rolon et al. 2018), water currents due to their capability for floating dispersal (Schultz 1942; Croat 1978, and references therein, Garbisch and McIninch 1992; Gettys and Dumroese 2009) or zoochory (Croat 1978).

The species causes impacts where introduced. Extracts derived from the rhizome inhibit the growth of the algal species *Microcystis aeruginosa* (Kütz.) Kütz. and *Scenedesmus obliquus* (Turpin) Kütz. (Qian et al. 2017, 2019), although the existence of allelopathic interactions as an ecological mechanism in the wild has not been confirmed yet. Other important traits related to invasiveness are a high seed production (Gettys and Dumroese 2009; Whigham and Simpson 1982), and the rapid formation of dense thickets. These thickets alter the vegetation composition, structure and dynamics as well as provoke navigation and fishing nuisances that justified the prohibition of this species in South Africa (Department of Environmental Affairs 2004). It is also important to note the effect on evapotranspiration dynamics provoked by the species as another important source of impact. Otis (1914) demonstrated that total water pond evaporation due to the presence of *P. cordata* patches was on average 1.98–2.08 fold the values recorded in ponds with free water surface. These values are even greater than the rates found by Rao (1988) for other common invasive aquatic species such as *P. crassipes* (1.30–1.96), *Salvinia molesta* D.S. Mitchell (0.96–1.39) and *Nymphaea lotus* L. (0.82–1.35). This indicates a potential strong environmental and/or social negative impact that could be of special importance in habitats subjected to seasonal water shortage or with low water level (e.g., under possible future scenarios of climate change). *Pontederia cordata* has been found to strongly compete against *Zizania palustris* L. (Minnesota Department of Natural Resources 2008), an aquatic species that is key for the maintenance of migrating waterfowl (Aagaard et al. 2019).

The WRA questionnaire also asked about the efficacy of herbicides for the species control, and a positive answer was given. However, although the species can be controlled by herbicides, in Europe herbicides in natural aquatic systems are not considered adequate management methods due to potential negative impacts and are not allowed as a control tool. Therefore, other possibilities for population management must be considered. The impact caused by the species has lead to initiatives to control its population in several countries, including some areas of the native range (USA, South Africa, etc.). Potential control methods previously used include mechanic harvesters, lowering water levels in winter to freeze and desiccate pickerelweed roots, and cutting during spring and summer using airboats (McDowell 2006). Other methods relay on hand cutting and digging up roots and rhizomes (Stafford 2014; Aquaplant 2021). Despite *P. cordata* seeds do not appear to remain viable for more than a year (Whigham and Simpson 1982), removing the flowers before seed set is certainly an important measure to use to prevent dispersal and reinvasion. However, physical control is difficult because it can re-establish from seeds and remaining rhizomes. Deeping the edges of the ponds can be also applied since this species generally grows in shallow water (< 0.5 m). Monitoring will be required afterwards to keep the plant under control (Aquaplant 2021). Level of difficulty in control will increase with invaded area. The convenience of adopting biological control as management tool could be investigated. Biological control has been effective for other species such as *P. crassipes*, *Pistia stratiotes* L., *Salvinia molesta* D.S. Mitch., *Myriophyllum* *aquaticum*, and *Azolla filiculoides* Lam. (Hill and Coetzee 2017). *Xubida infusella* (Walker) (Lepidoptera: Pyralidae) seems to be effective to control both *P. cordata* and *P. crassipes* (Stanley et al. 2007). Hence, in natural areas, control measures should better rely on physical methods (desiccation, machinery, geotextiles, etc.) or biological control and the feasibility of each approach should be critically analysed for each specific case (Dana et al. 2019).

Harmonia$^+$ was used as a control protocol, which yielded a score of 0.836 (maximum impact score 1.00). This result clearly was in consonance with the results obtained by applying WRA protocol, which reflects the invasive potential of *P. cordata*. (for details, see Table S2).

It can be concluded that *P. cordata* exhibits a great potential to become invasive and to enlarge its current European distribution establishing in countries where it is still absent or not widely distributed (e.g. Portugal, Spain, Greece, France, etc.). This species has caused detrimental environmental, agricultural and socio-economic impacts in South Africa (Wansell 2021). Therefore, effective regulation measures are recommended in the European Union, as has been done for other weeds from the Pontederiaceae family (European Parliament and European Council 2016). The species is not included in the national lists of regulated alien species of several countries such as Portugal (Presidência do Conselho de Ministros 2019) or Spain (Ministerio de Agricultura, Alimentación y Medio Ambiente 2013). However, as for other Pontederiaceae, due to its rapid growth and biomass production under high levels of nutrients and to its tolerance to heavy metal pollution, the species has been proposed for phytoremediation of contaminated waters (DeBusk et al. 1995; García Chance et al. 2019; Xin et al. 2020). Similarly, other researchers have found that the intercropping of this species in rice fields greatly reduce the incidence of pests and the use of agro-chemicals (Wang et al. 2021). Hence, the convenience of a general and complete banning across the entire European Union must be carefully evaluated taking into account the trade-off between the risks and the benefits of its use outside of sensitive areas where water depuration is not feasible by other methods. After the results obtained in this study, and given the repercussion of any legal measure, an analysis at habitat level that included a larger number of variables would be desirable as a second step to more solidly base the legal measures, since it would provide a ground to decisions taking on a site-by-site basis.

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Authors' contribution

EDD, JGL, FV: writing of the original draft; EDD and JGL: field work; FV: herbarium consult.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Questions of Weed Risk Assessment (Pheloung et al. 1999).

Table S2. Questionnaire and answers of Harmonia$^+$ (D'hondt et al. 2015).

This material is available as part of online article from:
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