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Do Wetland Vascular Plants Introduced in Morocco Also Become Invasive?

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Abstract—The propagation of exotic species is a complex process influenced by taxa-specific factors, in addition to climate and anthropozoogenic activities. However, the introduction of plants outside their native range does not always lead to their naturalization and/or the invasion of native ecosystems. Once non-native species have become established, they become extremely difficult to eradicate or control. Moroccan wetlands are crucial to the conservation of biodiversity, but they are susceptible to invasive hygrophilous plants. The invasive potential of introduced hygrophytes in Morocco was assessed through an extensive documentation review on their distribution, biology, ecology, uses, considering both their updated scientific names and their synonymy. Three groups of hygrophytes with varying invasive potential have been identified, based on their bioclimatic distribution, intrinsic propagation ability and use. The high invasiveness group (species with high invasiveness in other countries) includes *Populus nigra* L., *P. alba* L., *Cotula coronopifolia* L., *Gomphocarpus fruticosus* (L.) W.T. Aiton, and *Arundo donax* L. With the exception of *Cotula coronopifolia*, which is naturalized in Morocco, none of other highly invasive in other countries species has reached naturalized and/or invasive status. The status of these introduced hygrophytes in Morocco, as well as those with moderate (*Heliotropium curassavicum* L., *Cotula anthemoides* L., *Pistia stratiotes* L., *Cyperus eragrostis* Lam., and *Paspalum distichum* L.) or low invasive potential [*Azolla filiculoides* Lam., *Modiola caroliniana* (L.) G. Don, *Salix babylonica* L., *Asclepias curassavica* L., *Eclipta prostrata* (L.) L., *Triglochin striata* Ruiz & Pav., and *Eichhornia crassipes* (Mart.) Solms], is compared with that of other regions of the world. Although *Pistia stratiotes* has invaded wetlands in several regions, its invasion is currently limited in Morocco due to environmental and management factors. As a result, more botanical studies of Moroccan wetlands are needed, as many introduced species are currently poorly known and their status may change, while new introduced hygrophytes may also be encountered. Assessing the invasive potential of introduced hygrophytes will enable in part the implementation of proactive measures to better protect local wetlands against invasive species.

Keywords: hygrophytes, invasive potential, plant distribution, plant use

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INTRODUCTION

Plant invasion represents a serious risk to both wild and modified environments worldwide. This issue is intricate and challenging to address due to the large number of exotic species introduced into new habitats, and existing invaders continue to expand rapidly. Numerous human activities, such as farming, aquaculture, planning and transportation, advance both the deliberateness and inadvertent spread of species over their natural dispersal barriers. Although the arrival of alien species poses a danger, it is crucial to comprehend that just introducing them does not ensure their establishment in the new environment (Hulme, 2009; Bellard et al., 2016). The causes of failure are many, including initial dispersal failure, and environmental and demographic randomness. The success of invaders with advantageous biological characteristics faced with such enormous obstacles sometimes includes numerous invasion attempts, the development of highly favorable new environments, and the unleashing of natural enemies (Sax, 2001; Young et al., 2022).

The widespread biological invasion process can be broadly described in five stages, each with geographic, biotic, and environmental barriers or combinations of failure factors: transport, introduction, establishment, naturalization, and spread and negative influence (Goodwin et al., 1999; Kolar and Lodge, 2001; Byun et al., 2018). The first step of biological aggression is the introduction of a species outside its natural range, potentially appropriate because of the increasingly internationalized world (Meyerson and Mooney, 2007; Byun et al., 2018); this is certainly the most critical step for controlling incursions. An establishment phase refers to any non-native species that manages to spread and reproduce spontaneously, not significantly affected by local abiotic and biotic factors (Blackburn et al., 2011; Byun et al., 2018). Economic, environmental or human damage caused by a non-native species generally determines its invasive status. If weeds are not controlled early, their spread can lead to a difficult and costly eradication process in the future. Decision makers may choose to avoid or limit the effects of invasive plants based on their potential for damage and their distribution pattern (Gallardo and Aldridge, 2013).

Naturalized plants often thrive in diverse environmental conditions and exploit local resources efficiently. The transition of an introduced plant to its naturalized status can be considered a potential precursor to the invasive stage. However, not every naturalized plant becomes invasive as this also depends on several factors, including its ecological characteristics, local environment conditions, and human activities potentially favoring its spread (Richardson et al., 2000a, 2000b; Byun et al., 2018). The propagation of a species, as its distribution range development, is regulated by the success of its regeneration, the dispersal of its dissemination structures locally, and its spread over long distances through anthropozoogenic activities. Multiple parameters influence the success of invasive species, including their biology and ecology, and local climatic and site circumstances (Richardson et al., 2000a, 2000b; Gallardo and Aldridge, 2013).

The climate change could affect the presence and success of non-native species. Some non-native species may have some benefits over native ones in a changing climate, allowing them to spread and potentially outcompete native species for resources (Hellman et al., 2008; Bradley et al., 2010; Bellard et al., 2013; Hong et al., 2021). The introduction of non-native species outside their original habitats, whether intentional or accidental, can pose a serious threat to native biodiversity, natural and agricultural environments, and can cause significant economic damage in the long run. These non-native species have the potential to modify environmental structure and function, as well as species dynamics communities by reducing nutrient availability (Hulme, 2009; Simberloff et al., 2013).

Invasive plants have a more significant impact in wetlands, which constitute sinks for a wide range of materials (sediments, propagules, water, and nutrients). Wetlands are more vulnerable to invasive plants, as many of them occur in monospecific communities, altering the habitat structure in the process. Although wetlands cover 6% of the world land surface, 24% of the world's most invasive plant species are known to occur in these areas (Moll, 1998; Zedler and Kercher, 2004). Wetlands often collect waste and enriched water, helping to create new niches for opportunistic plant species (Zedler and Kercher, 2004). Invasive species, particularly by modifying the water regime and physico-chemistry in wetlands, may impact native species by outcompeting them, and can dominate the ecosystem and result in habitat structural changes (Howard and Matindi, 2003; Catford, 2017).

Moroccan wetlands are so important for biodiversity conservation that they hold about 36% of the Moroccan vascular flora as specific, facultative or opportunistic taxa (Ennabili et al., 2021). By Khabbach et al. (2020), the vascular flora of Moroccan wetlands includes 16 introduced hygrophytes, five of which are naturalized (*Azolla filiculoides* Lam., *Cotula anthemoides* L., *C. coronopifolia* L., *Eclipta prostrata* (L.) L., and *Triglochin striata* Ruiz & Pav.) and one invasive (*Pistia stratiotes* L.), while *Paspalum distichum* L. and *Cyperus eragrostis* Lam. are reported as both naturalized and invasive taxa. *Eichhornia crassipes* (Mart.) Solms also is a threat to Moroccan wetlands as it has been experimented in Morocco in phyto-remediation (Mandi et al., 1992) and was observed in municipal open spaces in Tetouan (1995) and Fez (2019). Because of the environmental and socio-economic consequences of invasive species, this work attempts to identify the main factors of propagation of all these Wetland Introduced Species in Morocco (WETI) based on available information in terms of their distribution, biology and socio-climatic context. This should facilitate the assessment of the potential danger of the introduced plants in terms of invasion of local wetlands, and guide measures for their timely management.

DATA COMPILATION AND PROCESSING

The invasive potential of an introduced plant species involves a combination of inter- and intraspecific and environmental factors. For example, rapidly reproducing species have a higher tolerance to environmental stress and may compete with native species for resource using within local ecosystems (Mitchell et al., 2006; Gioria and Osborne, 2014). To assess the invasive potential of the seventeen taxa selected in this work, a comprehensive literature search was conducted on their distribution, biology, ecology, valorization, and uses, considering both their updated scientific names and synonyms as reported in Morocco. This reference search specifically focused on multidisciplinary Web databases and other relevant information sources such as Google Scholar, Scopus, Web of Science, Journal Storage, African Plant Database (APB), International Union for Conservation of Nature (IUCN), and National Center for Biotechnology Information (NCBI).

All of the WETI have received different attention from the researchers, with too much information available for some and very little for others. These data were used to set up comparative criteria, namely the global distribution (global climates) and national one (local climates), and floristic regions of Morocco based on approximately 10% of the references listed,

Table 1. Proportion (%) of floristic regions and bioclimatic zones of Morocco in which the species grows. Corpus: Fennane et al. (1999), Mokhtari et al. (2013), Khabbach et al. (2020)

Taxon	Floristic regions	Bioclimatic zones
Arundo donax	100	100
Populus alba	90.9	100
Populus nigra	72.7	100
Paspalum distichum	63.6	100
Eclipta prostrata	45.5	100
Cotula coronopifolia	27.3	85.7
Gomphocarpus fruticosus	27.3	57.1
Heliotropium curassavicum	18.2	85.7
Cotula anthemoides	18.2	42.9
Asclepias curassavica	18.2	28.6
Modiola caroliniana	9.1	42.9
Salix babylonica	9.1	42.9
Cyperus eragrostis	9.1	42.9
Azolla filiculoides	9.1	14.3
Pistia stratiotes	9.1	14.3
Triglochin striata	9.1	14.3

the dispersal mode (sexual and/or asexual reproduction, seed and/or vegetative parts dissemination factors...)—26%, the ecological plasticity (pH, temperature, conductivity, soil type, humidity, drought, salinity, flood tolerance...)—20%, the interaction with other organisms (predators, pathogens, pollinators, allelopathy...)—9%, the intra-specific diversity (genotypes, provenances...)—8% and the plant use (phytoremediation, soil stabilization, ornamentation, trade, windbreak, biogas production, traditional medicine, food...)—18%. Occurrence of WETI is estimated by global and local climates, and floristic regions.

PLANT DISTRIBUTION

The global distribution of WETI shows that except of the arctic and subarctic climates, the species considered in this work cover all global climates, either in native or introduced range. Morocco lies in a transition zone between the two main global climates: temperate on the one hand and desert or tropical on the other. Morocco's climate is typically Mediterranean, i.e. a subtropical climate, with oceanic, continental and arid variants (MTE2D, 2020). Some of these climates and/or variants concern the native areas of WETI, and their introduction in Morocco therefore relates primarily to a territorial dimension.

In North Africa, as elsewhere in the Mediterranean, bioclimatic zones have been characterized using a spatial approach based on Emberger's pluviothermal diagram, which combines various climatic variables related to plant distribution. This climatic index defines six types of local climates, known as Mediterranean bioclimates or bioclimatic zones: hyper-arid or Saharan (covering 55% of the territory), arid (13%), semi-arid (22%), sub-humid (9%), and humid and per-humid (approximately 1%) (Mokhtari et al., 2013). Eleven floristically uniform main units (regions) have been identified, based on the latest floristic knowledge of the country (Fig. 1). The geographical distribution of WETI doesn't show a clear relationship with invasive status. It varies from 9.1 to 63.6% of floristic regions for invasive taxa (*Pistia stratiotes*, *Paspalum distichum*), 45.5% for naturalized taxa (*Triglochin striata*, *Eclipta prostrata*) and 100% for other introduced taxa (Table 1).

The occurrence of the studied species in specific bioclimatic zones, shown in Fig. 2. WETI are most successful in semi-arid and sub-humid bioclimatic zones; they are also often found in the most densely populated areas of Morocco. This suggests that climatic conditions do not necessarily determine WETI distribution, and other factors need to be carefully considered in order to understand and deal with the dynamics of invasive wetland species. This shows once again the bioclimatic azonality of wetlands and the role of their intrinsic parameters, such as the habitat's physico-chemical quality, and human intervention (Ennabili et al., 2021).

PLANT BIOLOGY

All WETI tolerate a wide range of climatic conditions and can live in diverse environments at almost any time, excluding *Salix babylonica*, *Modiola carolin-*

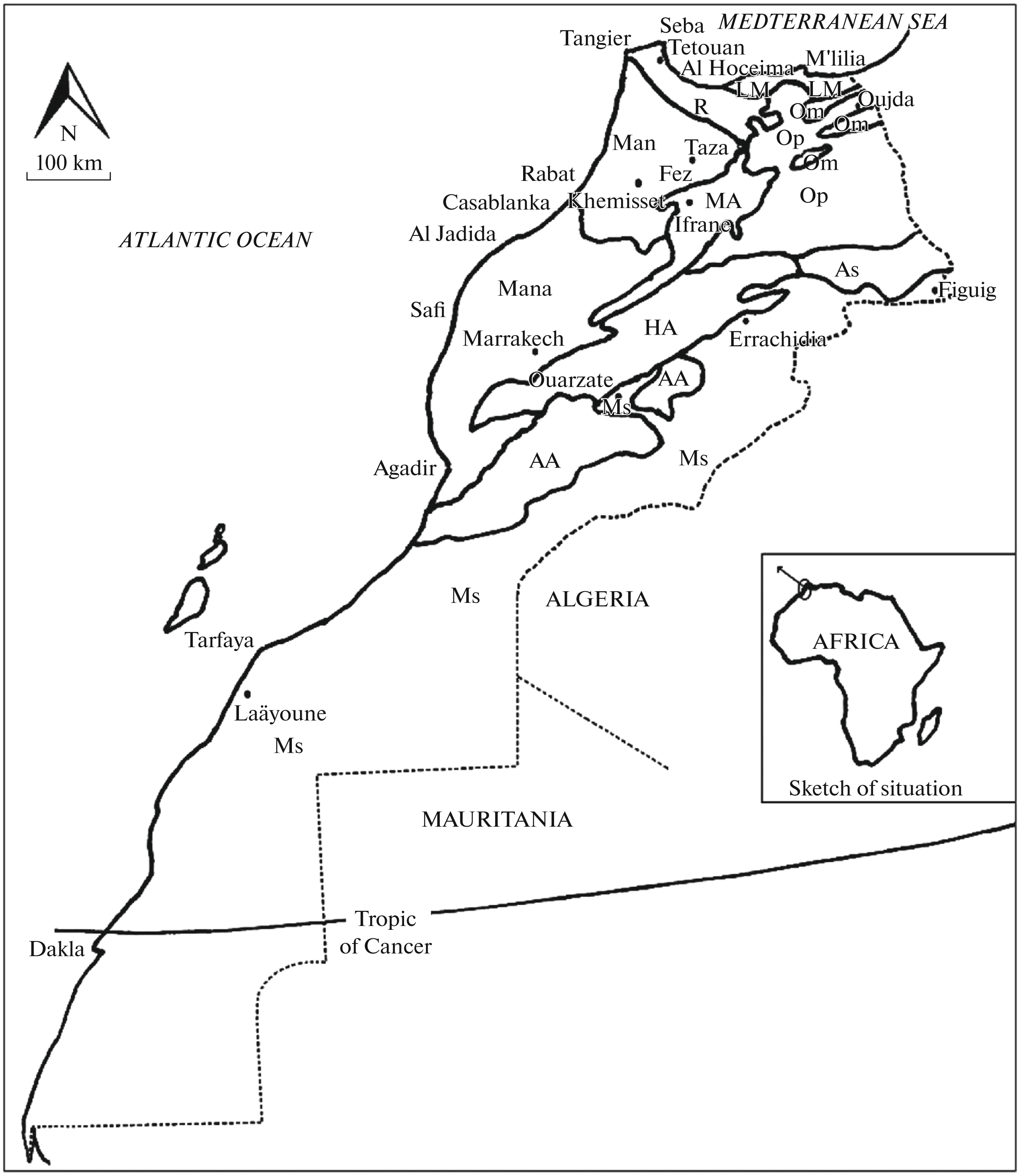

Fig. 1. Floristic regions of Morocco. Caption: Anti Atlas (AA), Saharan Atlas (As), High Atlas (HA), Mediterranean Coastline (LM), Middle Atlas (MA), Middle Atlantic Morocco (Mam), North Atlantic Morocco (Man), Saharan Morocco (Ms), Mountains of the Eastern Morocco (Om), Plateaus of the Eastern Morocco (Op), and Rif (R). Source: Khabbach et al. (2020).

iana, *Gomphocarpus fruticosus*, and *Cotula anthemoides*, for which there is insufficient data (Naidoo, 1994; Verloove and Reynders, 2007; Sadeghi et al., 2014; EPPO, 2017; Gilman et al., 2018; Yigermal et al., 2020; CABI, 2022; Minogue and Wright, 2022; IUCN, 2022). This suggests their potential for successful establishment in new bioclimatic zones. *Azolla filiculoides* also has phenotypic variations, as a result of its ability to tolerate abiotic stress and its adaptations to specific ecological conditions, including phosphorus availability, salinity, frost and drought (Janes, 1998; Fernández-Zamudio et al., 2010; Murren et al., 2015; Kösesakal and Yıldız, 2019). *Arundo donax* can thrive in a wide range of soils, pH and temperatures, and tolerates excessive salinity, but fears shade and high-mountain habitats (CABI, 2022). Pre-

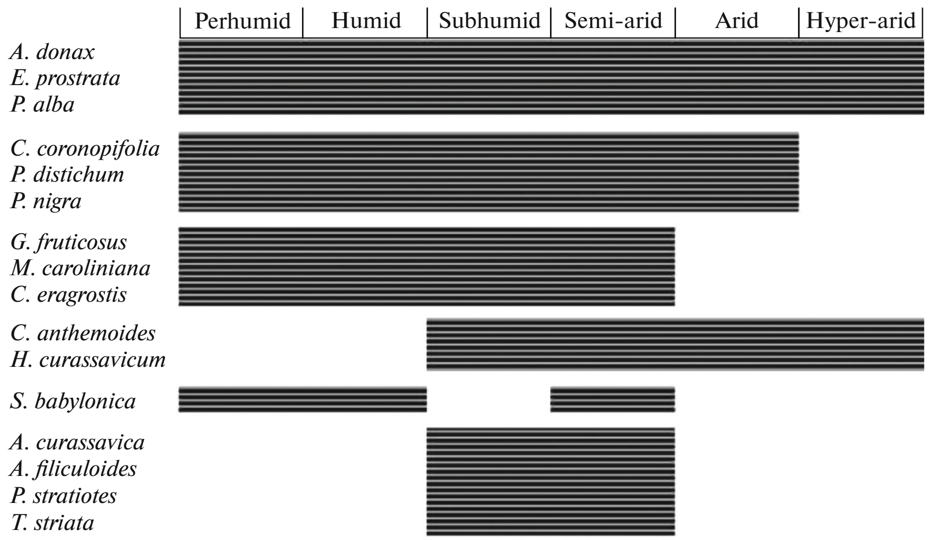

Fig. 2. Distribution of introduced wetland taxa in bioclimatic zones of Morocco. Corpus: Fennane et al. (1999), Mokhtari et al. (2013), Khabbach et al. (2020).

ferring anthropized and humid habitats, *Cotula coronopifolia* has a low frost and shade tolerance (Klein, 2011); *Eichhornia crassipes* is affected by frost and excessive salinity (Kriticos and Brunel, 2016). *Paspalum distichum* does not withstand high-mountain habitats (Carr, 2010); and *Pistia stratiotes* generally has a limited tolerance to salinity (CABI, 2022). Limiting factors for several taxa, such as high-mountain habitats, drought, frost, shade and salinity, are mitigated by the diversity of Moroccan wetlands. The spread of *Cotula coronopifolia* would be favored by the increased anthropization of wetlands. *Pistia stratiotes* thrives best in phosphorus-rich eutrophic waters, in contrast to *Azolla filiculoides* (Ennabili, 1999; Fernández-Zamudio et al., 2010; Chadli et al., 2023).

In addition to the eco-physiological characteristics mentioned above, the reproductive strategy of WETI is a major contributor to their spread. All WETI have the ability to propagate sexually and vegetatively, with the exception of *Modiola caroliniana* and *Cotula anthemoides*, which have apparently not been studied in this respect (Naidoo, 1994; Janes, 1998; Verloove and Reynders, 2007; Klein, 2011; EPPO, 2017; Gilman et al., 2018; Şapci and Vural, 2018; CABI, 2022; IUCN, 2022). Vegetative reproduction is characteristic for *Arundo donax* (Ennabili, 1999; Pilu et al., 2012), *Azolla filiculoides*, *Pistia stratiotes*, and *Eichhornia crassipes* (Fernández-Zamudio et al., 2010; CABI, 2022; Barbosa et al., 2019; Chadli et al., 2023); *Populus alba* and *P. nigra* are also propagated by offspring (Sbay and Taroq, 2003; Caudullo and de Rigo, 2016). *Modiola caroliniana*, *Populus alba*, *P. nigra*, *Asclepias curassavica*, *Cotula coronopifolia*, and *Paspalum distichum* are self-compatible and can produce viable seeds through self-pollination (Toorn, 1980; Dickmann and Kuzovkina, 2014; CABI, 2022). Propagules (seeds or rhizome's fragments) and even whole plants can be dispersed over long distances by water, during regular periods or floods, by wind and/or by anthropozoic action (Toorn, 1980; Thompson, 1988; Radosevich et al., 2003; Klein, 2011, Haddadchi et al., 2013; Caudullo and de Rigo, 2016; Khabbach et al., 2019; Keller et al., 2021; CABI, 2022; IUCN, 2022).

Allelopathic species such as *Azolla filiculoides*, *Populus alba*, *P. nigra*, *Gomphocarpus fruticosus*, *Pistia stratiotes*, and *Arundo donax* possess defense mechanisms against herbivores and/or inhibit the growth of other plants in their immediate environment (Sbay and Taroq, 2003; Caudullo and de Rigo, 2016; Ndhlovu et al., 2022; CABI, 2022). However, WETI generally have enemies, except for *Modiola caroliniana*, *Heliotropium curassavicum*, *Gomphocarpus fruticosus*, *Cotula coronopifolia*, *C. anthemoides*, *Triglochin striata*, and *Cyperus eragrostis*. Pests are mainly Coleoptera, Lepidoptera, Hemiptera, Arachnida, Diptera, and Neuroptera insects, damaging *Azolla filiculoides*, *Populus alba*, *Salix babylonica*, *Asclepias curassavica*, *Eclipta prostrata*, *Pistia stratiotes*, and/or *Eichhornia crassipes* (Thompson, 1988; Hill, 1997; Hill and Cilliers, 1999; Khabir et al., 2009; CABI, 2022). Fungi, usually Ascomycota and Basidiomycota, ravage *Pistia stratiotes*, *Eichhornia crassipes*, *Arundo donax*, and/or *Paspalum distichum* (Hill and Cilliers, 1999; CABI, 2022).

PLANT USE

In view of their aesthetic and decorative value, all WETI are reported as ornamental plants; most of them are also used in medicine and ethnomedicine (CABI, 2022; IUCN, 2022). *Azolla filiculoides*, *Populus alba*, *P. nigra*, *Pistia stratiotes*, *Eichhornia crassipes*, and *Arundo donax* are used in phytoremediation or rhizofiltartion for their properties of bioaccumulation and/or tolerance of eutrophic environments (Mandi et al., 1992; Khabbach et al., 2020; Ennabili and Radoux, 2021; Rezooqi et al., 2021; CABI, 2022; IUCN, 2022; Wibowo et al., 2023). *Populus alba*, *P. nigra*, and *Arundo donax* are used to fight erosion and stabilize the soil, and as windbreaks (Ennabili et al., 1996; CABI, 2022; IUCN, 2022). *Azolla filiculoides*, *Populus alba*, *P. nigra*, *Pistia stratiotes*, *Eichhornia crassipes*, *Cyperus eragrostis*, and *Arundo donax* are a source of human and bovine food, and biofertilizer (Ennabili et al., 1996; Al-Snafi, 2015; Karmiris et al., 2016; Rakotoarisoa, 2017; Thiégba et al., 2020; CABI, 2022; IUCN, 2022). *Populus alba*, *P. nigra*, *Salix babylonica*, and *Arundo donax* are widely exploited in industry for production of construction and industrial wood, and paper (Sbay and Taroq, 2003; Mariani et al., 2010; Yao et al., 2020; IUCN, 2022).

Extraction of colorants and/or flavors is also practiced from some of WETI, i.e. *Cotula anthemoides*, *C. coronopifolia*, *Eichhornia crassipes*, and others (Gopika et al., 2018; CABI, 2022; IUCN, 2022). The widest range of local and regional use of WETI is then recorded in *Populus alba*, *P. nigra*, and *Arundo donax*. The expanding range of WETI can be partially explained by their widespread use.

INVASIVE POTENTIAL

Based on an analysis of biogeographical, biological and potential use data, WETI can be categorized into three groups according to their invasive potential: high (*Populus nigra*, *P. alba*, *Cotula coronopifolia*, *Gomphocarpus fruticosus*, and *Arundo donax*), moderate (*Heliotropium curassavicum*, *Cotula anthemoides*, *Pistia stratiotes*, *Cyperus eragrostis*, and *Paspalum distichum*), and low for the other taxa. This shows how the invasive status of introduced plants depends on local climatic and socio-economic conditions. With the exception of *Cotula coronopifolia*, which has naturalized in Morocco (Khabbach et al., 2020), none of the other potentially invasive (invasive in the other countries) species failed to naturalize.

In many parts of the world, including North America, South Africa and Argentina, *Populus nigra* is listed as an invasive or potentially invasive species (CABI, 2022). *Populus alba* is also naturalized in many areas and aggressive or invasive in others (Starodubtseva et al., 2014; WeedUS, 2022). *Cotula coronopifolia* is considered an invasive plant in the Mediterranean region (Spain and France) and is not included in the category of the most dangerous invasive plants (Thiébaut, 2007). Data analysis shows that *Arundo donax* has a high invasive potential, although it is intrinsically a moderate spreader, due to its increasing local use. Actually, this species is recorded as one of the world's hundred most damaging outdoor invasive species (CABI, 2022; GISD, 2023).

WETI with moderate invasive potential, mentioned in this study, include *Pistia stratiotes*, an invasive species, *Cyperus eragrostis* and *Paspalum distichum*, both naturalized and invasive species, and *Cotula anthemoides*, a naturalized species, as reported by Khabbach et al. (2020). According to these authors, *Heliotropium curassavicum* has not passed the naturalization stage, even though it is one of the most widespread weeds in the Mediterranean basin and has been designated as invasive in Europe, Africa, the Arabian Peninsula and beyond (Hegazy, 1994; Hegazy et al., 2008). *Pistia stratiotes* has been successfully invaded wetlands in several regions of the world, and its invasion is currently influenced by a number of environmental and management factors (Khabbach et al., 2019; CABI, 2022; Chadli et al., 2022). *Cyperus eragrostis* is also ranked as an invasive species with a moderate risk in Europe (Weber and Gut, 2004).

WETI with low invasive potential are included (in other countries) in the group of naturalized (*Azolla filiculoides*, *Eclipta prostrata* and *Triglochin striata*) or established (*Modiola caroliniana*, *Salix babylonica* and *Asclepias curassavica*) plants (Khabbach et al., 2020). *Azolla filiculoides* is cited as an invasive species in several studies, but naturalized in many areas (CABI, 2022). *Eclipta prostrata* is a widely naturalized plant and considered as a common weed in many countries (Jeričević, M. and Jeričević, N., 2017). However, *Asclepias curassavica* is classified as a noxious weed or invasive one in various tropical and subtropical regions (CABI, 2022). *Eichhornia crassipes* is one of the aggressive species (GISD, 2023), and in the lack of on-site control measures, it can ever infest local water bodies.

CONCLUSIONS

WETI have a considerable invasive potential, due to their extreme ecological plasticity, and physiological suitability, in addition to anthropozoogenic factors. As has been highlighted in other parts of the world, they are particularly able to disperse rapidly once the conditions are suitable. Global climate change, coupled with wetland management and quality issues, can also contribute to the spread of these introduced species. The currently recognized invasive status of these species in Morocco does not correspond to that reported in other regions of the world. Most of the species identified locally as naturalized or invasive belong to taxa with medium or low invasive potential. Differences in national policies on the management of exotic species can lead to divergent interpretations, even between countries with similar climatic conditions.

Some WETI may not have achieved the same level of spread (naturalization and/or invasion), as in other regions of the world, because of unfavorable environmental or biotic factors, competition with other native plants, natural enemy pressures or over-exploitation of the produced biomass. This suggests more specific studies of WETI to better understand their invasive potential and develop management strategies for limiting their propagation risk. In addition, botanical investigation needs to be extended to all Moroccan wetlands, as new non-native wetland species can be expected.

AUTHOR CONTRIBUTION

AE designed the work and contributed to the data collection and processing. RB and CC jointly contributed to the collection, processing of data and writing of the manuscript. All authors read and approved the final manuscript.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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