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ORIGINAL PAPER

Alien plants of Iran: impacts, distribution and managements

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Abstract Like other developing countries, Iran is threatened by alien plants because of its rich native biodiversity, a wide range of climatic conditions and lack of regulation for importing new plants. In this study, we describe the characteristics, distribution, potential impacts of 52 alien plants based on Generic Impact Scoring System (GISS) assessment and their management. Species were selected from those identified to be invasive or with the risk to be invasive of those introduced to Iran over the past 30 years. From the 52 selected alien plants, the most common were herbaceous and annual plants from the Fabaceae and Asteraceae families. South America and Eastern Asia are the main areas of origin to Iran. The highest portion of naturalized plants are detected in croplands as weed. *Eichhornia crassipes* and *Ailanthus altissima* had the highest GISS environmental and socio-economic impact score of the 13 invasive alien plants we identified, and *Pueraria montana* var. *lobata* and *Hydrilla verticillate* had the highest scores of the casual and naturalized species. The Hircanian zone was the most invaded area and it could be considered as a potential biological invasion hotspot in Iran. Non-selective alien plant management and a high reliance on herbicide application, especially those with high potential of herbicide resistance, could be main obstacles of successful alien species removal or control. Iran requires specific management programs to tackle the introduction and spread of alien plants and to reduce their impacts on biodiversity, ecosystem services and human livelihoods. Considering the high diversity of climatic conditions in Iran, from arid to subtropical, studies on the effect of climate change on new invasions or range expansion of current invaders and their impacts should also be a priority.

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Introduction

In the last decade, there has been increased evidence about the negative impacts of alien species on the environment, the economy and human well-being in all parts of the world (Vilà et al. 2011, Rumlerová et al. 2016, Nentwig et al. 2018). Providing data about the current status and distribution of problematic alien plants is essential for reducing significant adverse impacts (Simberloff, 2013; Pyšek et al. 2020; Gallardo et al. 2019; Sohrabi et al. 2020). Moreover, it is important to rank species by the magnitude of the impacts they can cause. The Generic Impact Scoring System (GISS) is one of the best developed impact-assessment because it covers both environmental impacts and socioeconomic impacts (Nentwig et al. 2010, 2016; Sohrabi et al. 2021). The information generated through completing impact assessments can provide decision-makers and other stakeholders guidelines for prioritization of the threats imposed by alien species and identify species to be targeted by management (Nentwig et al. 2010, Pergl et al. 2016, Rumlerová et al. 2016).

Invasive plant species can greatly undermine conservation or restoration goals where biodiversity is valued, for instance in nature reserves or ecologically significant habitats (Del Vecchio et al. 2015; Blackburn et al. 2019). They can also cause problems in agricultural lands (MIPAG 2012). Management of invasive plant species may be possible, but collectively and individually they are a problem that requires long-term solutions (MIPAG 2012). Not all invasive plants behave the same or are at the same stage of invasion within region. Managing invasive plants demands a commitment to vigilance and some level of regular sustained actions (van Wilgen et al. 2020). Mechanical, chemical, biological control and integrated management are the primary methods of alien plant control (Francis 2019). The methods used to control alien plants within countries like Iran are not always reported. Furthermore, prevention (i.e. reducing the risk of introducing potentially invasive alien plants to new areas) and early warning such as permission for eradication of all individuals and their propagules in seminal populations (Pluess et al. 2012) are essential components of management for newly arrived species.

Iran, with an area of 165 million ha, is located between 25 and 40° N latitude and 44–64° E longitude. Most parts of Iran are located in the arid belt of eastern hemisphere in West Asia, bordering the Caspian Sea in the north and the Persian Gulf in the south. Environmental features have an important influence on plant diversity and richness of Iran, which is divided in four ecological zones (Hyrcanian, Khalij-o-Omani, Zagross and Iran-o-Touranian) with species plant richness decreasing with altitude (Heshmati 2007). The Hircanian zone in the North extends throughout the south coast of the largest lake in the world, the Caspian Sea and the northern part of the country. Mountains dominate the landscape of this ecoregion. The Zagros ecological zone to the west of Iran covers a mountainous area of about 4,749,000 ha with semi—arid climate and temperate winter. The Iran-o-Touranian is surrounded on almost all sides by mountain ranges is dominated by the central Iranian plateau, an immense area covering 1,648,000 km2 in the center of Iran and encompassing a great variety of climates, soils and topography. Based on topographic and altitude conditions, Iran-o-Touranian area is divided into two mountainous regions with a cold climate and a desert with a hot and dry climate. Finally, the Khalidj-o-Ommanian Zone, with an area of 2,130,000 ha extends throughout the southern parts of the country where it is dominated by a sub-equatorial climate (Heshmati 2007).

The mean annual precipitation in Iran is below 250 mm in about 70% of the country. Only 3% of Iran, receives above 500 mm yr − 1 (Mesgaran et al. 2017). Today more than 30% of the country is covered by forests and agricultural land (http://knoema.com/atlas/Iran/topics/Land-Use). The majority of Iran's cropping activities take place in the west, northwest, and northern parts of the country where annual precipitation exceeds 250 mm (Mesgaran et al. 2017). Suitable conditions for the cultivation and use of introduced plants into the country have been supported historically. Currently, extensive agricultural production to achieve food self- sufficiency, environmental changes (Mansouri Daneshvar et al. 2019) along with a lack of a robust quarantine system is increasing the introduction and establishment of new invasive plants (Sohrabi et al. 2017, 2020,).

The relevant information about invasive plant species of Iran is not adequate or comprehensive except for a preliminary analysis of the potential negative impacts of a limited number of species (Sohrabi et al. 2021) and the particular focus on allergenic, allelopathic and competitive abilities of some invasive plants (Sohrabi et al. 2021). A key component of plant invasions in Iran is the lack of clear information and outlining impacts to identify the most harmful alien plants based on their status. Knowing the species with the most important impact is vital to ameliorate their negative effects by appropriate management options. Therefore, the present study attempts to review the status, distribution, management and potential impacts based on GISS of alien plants that have been introduced in Iran in the last three decades. This study is more comprehensive than previous ones and covers more species, their distribution, and the inclusion of management methods.

Methods

The selection of plants

Currently, there is not a complete list of alien plants in Iran. Therefore our analysis is based on past studies that cover alien plants with evidence of invasion risk to Iran as well as those that have been introduced to Iran in the last three decades. The selected plants are classified according to the stage they reached in the casual/naturalization/invasion process (Richardson et al. 2000). Casual aliens are alien plants that may flourish and even reproduce occasionally in an area but do not form self-replacing populations and rely on repeated introductions for their persistence. Naturalized species (synonym: established species) form self-sustaining populations for several life cycles without direct intervention by people, or despite human intervention; they often recruit offspring freely, usually close to adult plants, and their persistence does not depend on ongoing input of propagules. Invasive species are a subset of naturalized species that produce reproductive offspring, often in very large numbers at considerable distances from the parents and/or site of introduction, and have the potential to spread over long distances. And the life form categories were included fern, herb, fern, shrub, tree and vine.

Sources of information

The information of their actual and potential impacts was obtained from journal articles, scientific reports, books and book chapters, and online databases such as CABI (Centre for Agriculture and Bioscience International), GISD (Global Invasive Species Database), and GBIF (Global Biodiversity Information Facility) along with some direct field observations (Supplementary file).

Information on their distribution and management was found in Iranian grey literature, interviews with specialists from Agricultural Centers of Iran and personal observations. The gathered information allows for the determination of their taxonomy, history and potential impacts before they start to spread across large areas, possibly further increasing their abundance (Sohrabi et al. 2021, 2017; Meighani et al. 2021; Pouramir and Yaghoubi 2021; Amini et al, 2020; Yaghoubi et al. 2020; Heshmati et al. 2019; Mirzajani et al. 2019; Bidarlord et al. 2019; Zand et al. 2017; Pahlevani and Sajedi 2012; Sajedi et al. 2012; www.cabi.org and http://www.iucngisd.org).

GISS methodology

GISS is applied to determine alien plants impacts according to environmental and socioeconomic, with each group divided into six different categories (Nentwig et al. 2016). Each species on our list was assessed for its impact in the 12 categories (impacts 1.1 on plants or vegetation through mechanisms other than competition, 1.2 on animals through predation, parasitism, or intoxication, 1.3 on species through competition, 1.4 through transmission of diseases or parasites to native species, 1.5 through hybridization, 1.6 on ecosystems, 2.1 on agricultural production, 2.2 on animal production, 2.3 on forestry production, 2.4 on human infrastructure and administration, 2.5 on human health and 2.6 on human social life) for which data were available. In each of these categories, we classified impact on a six-degree scale reflecting impact intensity. The scores range from 0 (no impacts known) to 5 (major impact) (Sohrabi et al. 2021).

To analyze the impacts of the 52 species assessed by GISS, we calculated the ‘‘logarithmic sum’’ of all values scored across the six categories ($\log_{10}$ (Σ(10^impact values)) for each species and impact group (environmental, socioeconomic) (Sohrabi et al. 2021).

A chi-Square analysis applied across three alien species status and life-form to indicate the relationship between impact scores and the life cycle of alien plants (Supplementary Table 1).

Results and discussion

Status, life form and origin of alien plant species

We have identified 52 alien species classified as 20 casual, 19 naturalized and 13 invasive following Richardson et al. (2000) definition (Table 1).

In terms of life history and life form, the data set included 28 perennial and 23 annual species. The life form of the studied species includes 31 herbs, 9 trees, 7 vines, 4 shrubs and only 1 fern. Similar patterns were observed for alien plants in China, where a high portion of alien plants are herbaceous (Jiang et al. 2011). On the contrary, Rahman et al. (2010) reported 45% shrubs as the most frequently encountered invasive species followed by herbs (41%) and vines (14%) in North-Eastern Bangladesh. Some plant ecological strategies, associated with specific life forms (e.g. being perennial) can convey an advantage for their ability to establish in a specific ecosystem (Pyšek and Richardson 2007). According to Weber et al. (2008), the majority of invasive plants are perennials.

The screened species belong to 28 families. The most prevalent were Asteraceae (14.5% of species), Fabaceae (12.5%), Amarantaceae (8.3%) and Poaceae (6.1%) (Table1). In other parts in the world, Asteraceae, Fabaceae and Poaceae have also been reported with the highest frequency in invasion (Rahman et al. 2010; Kull et al. 2012; Dorjee et al. 2020; Inderjit et al. 2018). Along with being the richest families in the world, some biological characteristics can be mentioned for their predominance such as fixing nitrogen (Fabaceae family), ability for long distance dispersal (e.g. seeds with pappus of Asteraceae family) and high tolerance to abiotic stress (Poacaea family) (Barkley et al. 2006; Landi et al. 2017; EL Sabagh et al. 2020). The largest proportion of Asteraceae species occurs in arid and semiarid regions of subtropical and lowers to middle temperate latitudes (Barkley et al. 2006).

Most of these 52 plant species come from the Americas (25) and the east of Asia (12) (Table 1). America is a very common origin for Asian countries. For example, the origin of most alien plants of Turkey is also from America and Asia (Yazlık et al. 2018a). In North-Eastern Bangladesh (Rahman et al. 2010) and China where over half of all aliens have an American origin (52%), followed by those with European (14%) and Asian (13%) origin (Jiang et al. 2011). Different studies have noticed the importance of life forms and geographical species origin as factors related to invasion success (van Kleunen et al. 2015; Giulio et al. 2020; Cao Pinna et al. 2020). Functionally being similar to native species occurring in the same habitat type and the long history of trade within the Old World can be as affective pattern for the origins of alien plants as shown in other regions (Keller et al. 2011; Divíšek et al. 2018).

GISS impact assessment

There were no significant differences in GISS impact scores between invasive, naturalized and casual species, thus we can consider all casual and naturalized species potentially invasive. (LSD test; p-value = 0.09). Three mechanisms accounted for over 80% of environmental impacts: competition, poisoning/toxicity, and chemical impact on ecosystems. The species with the highest impact rank (> 4.15 of mean score) score were *Eichhornia crassipes*, *Ailanthus altissima, Imperata cylindrica, Amsinckia menziesii, Paulownia fortunei, Euphorbia maculate, Prosopis juliflora, Fallopia japonica, Hydrilla verticillata* and *Ipomoea purpurea* (Table 1). Notice that some of these species (i.e. *Hydrilla verticillata*, *Paulownia fortunei*, *Fallopia japonica* and *Pueraria montana* var. *lobate)* are casual species and *Amsinckia menziesii* is naturalized in Iran (Table 1). The highest rank of environmental and socio-economic impacts belong to *Hydrilla verticillata* and *Fallopia japonica* as perennial potential invasive plants, and *Anoda cristata* and *Xanthium strumarium* as potentially invasive annual (Fig. 1). The lowest rank (< 3.12 of mean score) was for *Gleditsia triacanthos, Yucca filamentosa, Acalypha australis* and *Sesuvium portulacastrum*. A chi-Square analysis across three alien species status and life-form indicate that the impact scores

Table 1 list of 52 alien plants in Iran and their main characteristics

Scientific name	Family	Life form	Common name	Native range	Invasive status	GISS score (environmental)	GISS score (socio-economic)	GISS score (total)
Eichhornia crassipes	Pontederiaceae	herb	Water hyacinth	South America	Invasive	4.34	4.14	4.55
Ailanthus altissima	Simaroubaceae	tree	Tree of heaven	East Asia	Invasive	4.34	4.11	4.54
Imperata cylindrica	Poaceae	herb	Cogongrass	Europe and Africa	Invasive	4.14	4.08	4.41
Amsinckia menziesii	Boraginaceae	herb	Yellow forget-me-not	North America	Naturalized	4.11	4.04	4.38
Fallopia japonica	Polygonaceae	shrub	Japanese knotweed	East of Asia	Casual	4.08	4.04	4.36
Xanthium strumarium	Asteraceae	herb	Common cocklebur	South America	Naturalized	4.08	4.04	4.36
Paulownia fortunei	Paulowniaceae	tree	Dragon tree	China	Casual	4.07	4.05	4.36
Eupatorium cannabinum	Asteraceae	herb	Hemp-agrimony	Ireland and United Kingdom	Naturalized	4.32	2.5	4.33
Prosopis juliflora	Fabaceae	tree	Mesquite	South America	Invasive	4.14	3.5	4.23
Euphorbia maculata	Euphorbiaceae	herb	Spotted spurge	Eastern United States	Invasive	3.69	4.08	4.23
Pueraria montana var. lobata	Fabaceae	vine	Kudzu	East Asia	Casual	4.11	3.36	4.18
Hydrilla verticillata	Hydrocharitaceae	herb	Waterthyme	Asia, Africa and Australia	Naturalized	4.11	3.11	4.15
Ipomoea purpurea	Convolvulaceae	vine	Tall morning-glory	Mexico and Central America	Invasive	3.3	4.08	4.14
Anoda cristata	Malvaceae	herb	Sida	Tropical & Subtropical America	Casual	4.08	3.08	4.13
Xanthium spinosum	Asteraceae	herb	Bathurst burr	South America	Naturalized	3.5	4.01	4.13
Robinia pseudoacacia	Fabaceae	tree	Black locust	The eastern United States	Casual	3.49	4.3	4.12
Centaurea diffusa	Asteraceae	herb	Knapweed	western Asia, south-eastern Europe	Naturalized	4.04	3.04	4.08
Bambusa vulgaris	Poaceae	tree	Common Bamboo	southern China and Madagascar	Casual	3.3	4	4.08
Amaranthus retroflexus	Amaranthaceae	herb	Redroot pigweed	Tropical Americas	Naturalized	3.12	4	4.05
Canna indica	Cannaceae	herb	Indian Shot	South America	Casual	4.01	2.34	4.02

Table 1 (continued)

Scientific name	Family	Life form	Common name	Native range	Invasive status	GISS score (environmental)	GISS score (socio-economic)	GISS score (total)
Eucalyptus camaldulensis	Myrtaceae	tree	River redgum	Australia	Casual	4; 2	3.12	4.01
Ambrosia artemisiifolia	Asteraceae	herb	Ragweed	The United States	Naturalized	3.61	3.51	3.86
Azolla filiculoides	Azollaceae	fern	Mosquito fern	East Asia	Invasive	3.6	3.48	3.84
Araujia sericifera	Apocynaceae	vine	Bladder flower	South America	Invasive	3.61	3.34	3.80
Ulex europaeus	Fabaceae	shrub	Common gorse	Europe	Naturalized	3.5	3.49	3.8
Ambrosia psilostachya	Asteraceae	herb	Western ragweed	The United States	Invasive	3.49	3.51	3.8
Cynanchum acutum	Apocynaceae	vine	Swallow-wart	Southern Europe	Invasive	3.49	3.49	3.79
Paspalum urvillei	Poaceae	herb	Vasey's grass,	South America	Casual	3.01	3.61	3.71
Ipomoea indica	Convolvulaceae	vine	Blue morning glory	Central and South America	Invasive	3.47	3.08	3.62
Physalis angulata	Solanaceae	herb	Cutleaf ground cherry	North America	Naturalized	3.49	3.04	3.62
Acacia saligna	Fabaceae	tree	Golden wreath wattle	Australia,	Casual	3.48	3.08	3.62
Conyza canadensis	Asteraceae	herb	Horseweed	North America	Naturalized	3.41	3.04	3.62
Merremia dissecta	Convolvulaceae	vine	Alamo vine	North of America	Casual	3.32	3.32	3.62
Monochoria vaginalis	Pontederiaceae	herb	Pickerel weed	Asia	Naturalized	3.49	3	3.61
Ammannia coccinea	Lythraceae	herb	Purple ammannia	North of America	Naturalized	3.47	3.04	3.61
Solanum elaeagnifolium	Solanaceae	herb	Silverleaf nightshade	southwestern USA	Casual	3.34	3.08	3.53
Conocarpus lancifolius	Combretaceae	tree	Damas tree	Horn of Africa and South Asia	Casual	3.08	3.32	3.52
Ipomoea triloba	Convolvulaceae	vine	Littlebell	The tropical Americas	Invasive	3.32	3	3.49
Proboscidea fragrans	Martyniaceae	herb	Fragrant devil's claw	Mexico and the southwestern United States	Naturalized	3.01	3.32	3.49
Pistia stratiotes	Araceae	herb	Water lettuce	South America	Invasive	3.14	3.14	3.44

Table 1 (continued)

Scientific name	Family	Life form	Common name	Native range	Invasive status	GISS score (environmental)	GISS score (socio-economic)	GISS score (total)
Amaranthus hybridus	Amaranthaceae	herb	Spiny amaranth	Tropical Americas	Naturalized	3.12	3.05	3.38
Opuntia ficus-indica	Cactaceae	shrub	Sweet prickly pear	Mexico	Casual	3.34	2.12	3.36
Oxalis latifolia	Oxalidaceae	herb	Fishtail oxalis	Central America	Casual	3.34	3.42	3.5
Corchorus olitorius	Malvaceae	herb	Jute mallow	Asia and Africa	Naturalized	3.05	3.04	3.34
Echinochloa oryzoides	Poaceae	herb	Early barnyard grass	Eastern Asia	Naturalized	3.11	3	3.36
Lepidium virginicum	Brassicaceae	herb	Virginia pepperweed	NorthAmericas	Casual	3.05	3	3.33
Amaranthus albus	Amaranthaceae	herb	Tumble pigweed	Tropical Americas	Casual	3.1	3.01	3.3
Amaranthus blitoides	Amaranthaceae	herb	Spreading amaranth	Tropical Americas	Naturalized	2.5	3.1	3.16
Sesuvium portulacastrum	Aizoaceae	herb	Shoreline seapurslane	Tropics & Subtropics	Casual	3.08	2.05	3.12
Acalypha australis	Euphorbiaceae	herb	Asian copperleaf	East of Asia	Naturalized	2.2	3	3.06
Yucca filamentosa	Asparagaceae	shrub	Yucca	America	Casual	2.5	2.36	2.74
Gleditsia triacanthos	Fabaceae	tree	Honey locust	America	Casual	2.3	1.7	2.42

The selected plants are classified according to their stage in the casual/naturalization/invasion process (Richardson et al. 2000). Alien plants are sorted by GISS score (the total score). GISS score range from 0 (no impacts known) to 5 (major impact)

were different across the life cycle of alien plants (Chi-square value = 0.004, df = 2 and *P*-value = 0.99) perennial alien plants had a higher score than the annual ones (Fig. 1 and Supplementary Table 1).

The total logarithmic sum for environmental and socioeconomic groups provides a robust measure for identifying species with the highest overall potential impacts in Europe (Kumschick and Nentwig 2010; Rumlerová et al. 2016). Some naturalized plants, such as *Xanthium strumarium* and *Amaranthus retroflexus* that occur in high abundances in specific croplands, have strong impacts on agricultural lands. This result suggested that the most suspected alien species to be problematic would be more than the 20 species in the country because of their high impact score (logarithmic sum > 4) (Table 1).

In Turkey, the highest economic impacts were reported in agriculture and in the human health sectors, 22 species occurring in agricultural areas were considered as problematic (Yazlık et al. 2018a). The estimated annual economic costs due to plant invasions in Iran are not known. Therefore, there are urgent needs to advance on nationwide information about both environmental and economic impacts of alien plants.

Distribution of alien plant species

The most prevalent invaded areas in Iran are agricultural lands (i.e. crops and orchards) and urban areas. Grasslands, forests, and aquatic areas are less invaded (Fig. 2 and Supplementary Table 2). The main reason for this result would be related to the rate of human activities and population density in those areas. Roughly one-third of Iran's total surface area is arable farmland, while less than one-tenth are forests (https://www.britannica.com). Most casual and

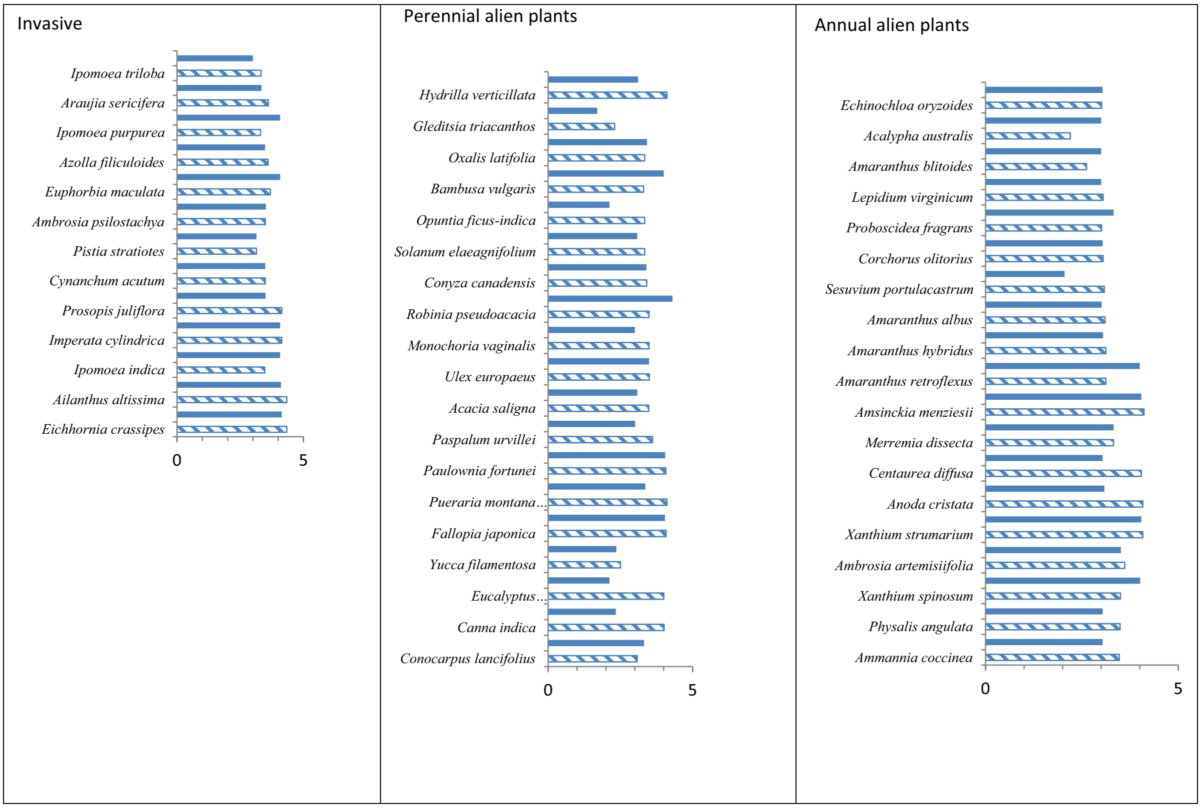
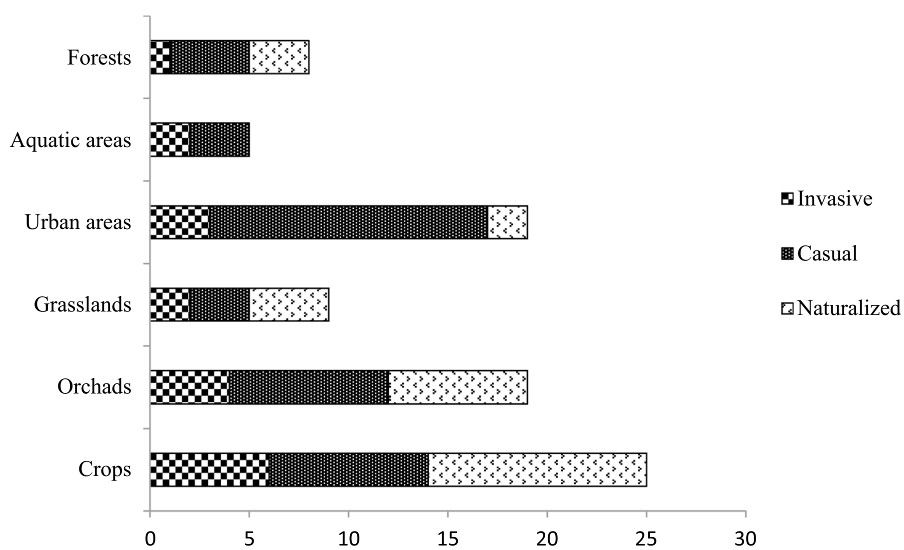


Fig. 1 Alien plants classified as invasive, perennial and annual alien plants (naturalized + casual) ranked according to the logarithmic sum of environmental (striated bar) and socio-economic (solid bar) impact scores of GISS

Fig. 2 Number of alien plant species according their invasive status in different habitats in Iran



naturalized plants are present in urban areas and cropland, respectively (Fig. 2).

The most occupied areas by the 13 invasive species were present in croplands, orchards, aquatic areas and urban areas. *Ipomoea purpurea, Euphorbia maculata, Imperata cylindrica* and *Ipomea triloba* are present in croplands (Fig. 2). *Cynanchum acutum* reduces the production of olive, pistachio, apple, almond, vineyard and sugarcane in Iran (Sohrabi et al. 2017; Mighani et al. 2020). From 3 species of morning glories, *Ipomoea purpurea* and *Ipomoea triloba* are observed in cropland while *Ipomoea indica* are detected in forest in north of Iran (Pahlevani and Sajedi 2012; Amini et al. 2020). *Araujia sericifera* is present in citrus orchards in the Mazandran province in northern Iran (Amini et al. 2020). *Ammannia coccinea* was reported in wet and muddy habitats of submontane water bodies and in rice fields in northern and northwestern Iran (Naqinezhad and Naseri 2017).

According to Zand et al. (2017), some plants with strong impacts on agriculture such as *Imperata cylindrica, Xanthium strumarium, Euphorbia maculata* and *Amaranthus retroflexus* occur in high

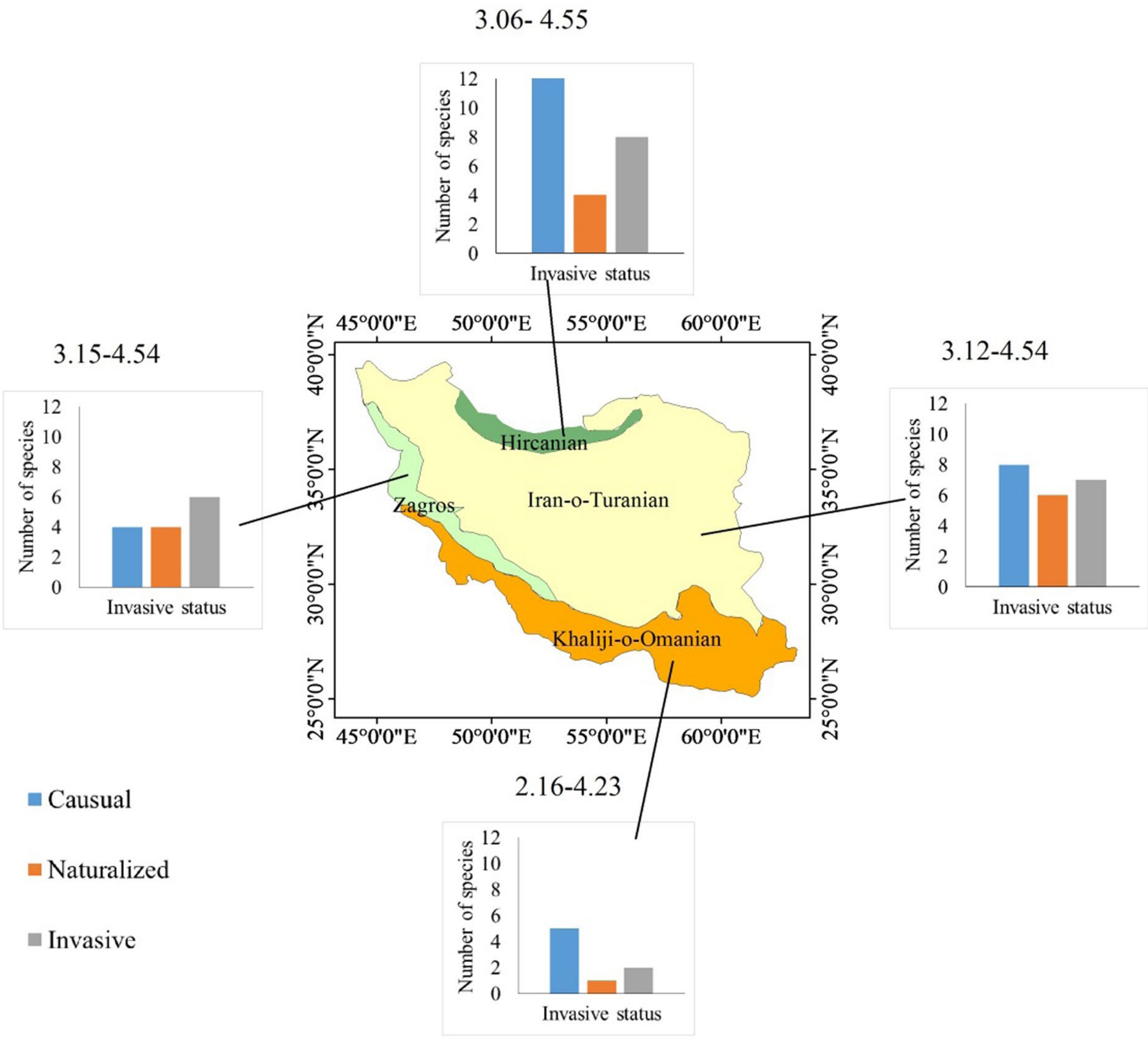


Fig. 3 The distribution of 52 alien plants in Iran and their invasion status. The numbers above each graph are mean GISS score (min-max) for each ecological zone

abundances in different biogeographic regions in the country and colonize a wide range of different habitats (Supplementary Table 2).

The highest numbers of casual and invasive plants are found in the Hircanian zone (Fig. 3), with temperate (mesothermal) climates and fertile soils. Due to soil fertility, mild temperatures, and high rainfalls, this ecological area is suitable to the establishment of many alien plant species. Besides the population density in this zone is higher than other ecological zones in Iran. In Hircanian zone, three aquatic invasive weeds; *Eichhornia crassipes*, *Azolla filiculoides* and *Pistia stratiotes* have adverse effects on ecosystems by eutrophying rivers, lagoons, paddyfields, wetlands and ponds (Banihashemi 2015; Mirzajani et al. 2019; Bidarlord et al. 2019; Sohrabi et al. 2021). The least invaded area is the driest Iranian area Khalij-o-Omanianan zone in the South with desertic climate (www.weatherbase.com and https://en.climate-data.org). Zagros and Iran-o-Touranian zones have a similar number of invasive plants while the number of casual plants is highest in the Iran-o-Touranian zone (Fig. 3). The most important invasive plant for this zone in agricultural lands is *Cynanchum acutum* (Meighani et al. 2021; Sohrabi et al. 2017). The existence of Zagros zone is due to rainfall raised by the Mediterranean system and the Black Sea, which are of undeniable importance due to the predominant arid and semi-arid climate in the country. This area is susceptible to invasion by the species with similar habitat and climate like *Euphorbia maculata, Imperata cylindrica* and *Amsinckia menziesii* (Sajedi et al. 2012; Pahlevani and Sajedi 2012; Sohrabi et al. 2020). With regard to naturalized species, the Iran-o-Touranian zone and the Khalij-o-Omanianan zone have highest and lowest numbers, respectively (Fig. 3). Assigning the largest area to the Iran-o-Touranian zone could explain the highest numbers of naturalized plants in this zone.

Having adequate information about the recent and current distribution of invasive plants is crucial for suitable management plans. For example, the initial distribution of *Cynanchum acutum* was limited to Mugan plain in northwestern Iran (first report, about 20 years ago) while now its distribution is widespread in different regions in Iran from Zagros, Iran-o-Touranian and the Hircanian zone. This situation has also occurred with *Azolla filiculoides*, now detected in Brojerd (Zagros Zone) in addition to Gilan and Mazandaran province (Hircanian zone). *Ailanthus altissima* (tree of heaven) is found in many parts in Iran especially in urban areas, but also in the Hircanian forests. The information on the distribution of small localized populations is important to increase the feasibility of management and to reduce the costs of eradication in comparison to populations of widespread invaders (Pluess et al. 2012).

Management of alien plant species

Only 25 of the species listed in Table 1 receive management in Iran and 9 from 20 of the alien plants with high impact scores (logarithmic sum > 4) are managed (Table 2). It is often necessary to use a combination of at least two methods to control them (State of the World Plants 2017). The most common control methods in Iran are chemical and mechanical control. From 52 species, 23 of them are controlled by herbicides and from these, 14 are herbicides with high potential of emerging herbicide resistance (Moss et al. 2019); in particular acetolactate synthase (ALS) and acetyl-CoA carboxylase (ACCase) inhibitors (Table 2). The high reliance on herbicide application to reduce the negative impacts of alien plants is challenging, especially when the principal method of control are herbicides with only one mode of action (Gherekhloo et al. 2016). It is worth noticing that the frequency of application of herbicides like the acetolactate synthase (ALS) inhibitors and ACCase inhibitors along with high seed production and long distance dispersal capabilities accelerate the risk of resistance to herbicides in these plants (Hutchinson et al. 2007; Gherekhloo et al. 2016; Moss et al. 2019). For example, in Florida, *Lygodium microphyllum*, *Imperata cylindrica*, *Panicum repens*, and *Solanum viarum* are susceptible to herbicide resistance due to repeated application of herbicides of one mode of action (Hutchinson et al. 2007).

Almost no management methods are applied to control one species at a time. Rather, management efforts target several species at a time (Zand et al. 2017; Sohrabi et al. 2020), except in some cases like *Cynanchum acutum* (Meighani et al. 2021), *Eichhornia crassipes* (Yaghoubi et al. 2020), *Monochoria vaginalis* (Hazrati et al. 2019), *Azolla filiculoides* (Delnavaz and Azimi 2009; Sohrabi et al. 2017) and *Imperata cylindrica* (Eskandari et al. 2020). Usually, farmers and land mangers apply herbicides to kill all

Table 2 Common management methods for alien plants, * indicate alien plants with high impact score (> 4)

Plant species	Chemical control	Other control methods (mechanical or physical and cultural control)	Management recommendations	References
Eichhornia crassipes*	**Bispyribac sodium**	**Cutting and collecting**	Combination of biological and physical control	Yaghoubi et al. (2020), Karouach et al. (2022)
*Ailanthus altissima**	Systemic herbicides injection	Cutting	Stem injection	Brundu (2017)
Eupatorium cannabinum	Systemic herbicdes	Manual removal	Manual removal	http://www.iucngisd.org
Imperata cylindrica*	**Glyphosate**	**Moving**	Combination of chemical and physical control	Zand et al. (2017), Eskandari, et al. (2020)
Pueraria montana var. lobata*	Systemic herbicdes	**Cutting and collecting**	Thermal treatment	http://www.iucngisd.org
Amsinckia menziesii*	**2,4-D and MCPA**	Hand weeding	Chemical control	Sajedi et al. (2012), Zand et al. (2017)
*Anoda cristata**	Ghyphosate	Cutting and collecting	Chemical control	Puricelli et al. (2004)
Yucca filamentosa	Systemic herbicides	Hand removal and fire	Combination of chemical, biological and cultural control	Young et al. (2011)
Euphorbia maculate*	**Acyflourfen + bentazon and Metribuzine**	**Hand weeding**	Chemical control	Nejad et al. 2010; Zand et al. 2017
Acalypha australis	Glyphosate	Cultivator	Cultural and chemical control	http://www.agroatlas.ru; crops.extension.iastate.edu
Azolla filiculoides	**Bensulfuron-methyl**	**Collecting boats**	Combination of biological control and physical control	Farahpour (2019), Zand et al. (2017)
Ulex europaeus	Gglyphosate, Metsulfuron	Burn (often after desiccation by herbicide)	Combination of chemical and physical control	Clements et al. (2001); https://www.cabi.org
Ambrosia psilostachya	2,4-D and Dicamba	Cultivator	Chemical and physical control	https://www.cabi.org
Ambrosia artemisiifolia	2,4-D and Dicamba	Cultivator	Chemical and physical control	https://www.cabi.org
Cynanchum acutum	**2,4-D + MCPA, Glyphosate, triclopyr**	**Cultivator**	Combination of chemical and mechanical control	Meighani et al. (2021), Zand et al. (2017)
*Prosopis juliflora**	Systemic herbicides	Cutting and collecting	Combination of biological, chemical, mechanical,	Choge et al. (2022)
Acacia saligna	Systemic herbicides	Cutting and removing seedlings	Seed bank reduction with seedling removal	Cohen et al. (2018), van Wilgen et al. (2001)
Ammannia coccinea	**Bensulfuron-methyl and Bentazon**	Cultivator	Chemical control	Zand et al. (2017)
Merremia dissecta	Systemic herbicides	Hand weeding and collecting	Combination of chemical and mechanical control	keyserver.lucidcentral.org;
Ipomoea purpurea*	**2,4-D + MCPA, ALS inhibitors**	Hand weeding and collecting	Chemical control	Zand et al. (2017)
Ipomoea triloba	**2,4-D + MCPA, Bentazone, ALS inhibitors**	Hand weeding and collecting	Chemical control	Zand et al. (2017)

Table 2 (continued)

Plant species	Chemical control	Other control methods (mechanical or physical and cultural control)	Management recommendations	References
Ipomoea indica	MCPA 500, Dicamba, 2,4-D amine and Glyphosate	Manually removed	Manually removed and then herbicide application	www.cabi.org; keys.lucidcentral.org
Pistia stratiotes	Not recommended	Dug out and collecting	Biological control	Cilliers (1991)
Corchorus olitorius	**2,4-D and MCPA**	**Cultivator, Grazing, Hand weeding**	Chemical control and physical control	Zand et al. (2017)
Proboscidea fragrans	2,4-D and Dicomba	Collecting	Chemical and physical control	Prostko and Chandler (1998)
Gleditsia triacanthos	Dicamba + 2,4-D	Cutting	Cut Stump and basal bark-applied herbicides	Harmoney (2016)
Conyza canadensis	**Bentazone**	**cultivator**	Chemical and physical control	Zand et al. (2017)
Amaranthus retroflexus*	**Metribuzine, Rimsulfuron, Bentazone**	**Cultivator, Hand weeding**	Chemical and physical control	Zand et al. (2017)
Amaranthus hybridus	**Metribuzine, Rimsulfuron, Bentazone**	**Cultivator, Hand weeding**	Chemical and physical control	Zand et al. (2017)
Amaranthus blitoides	**Metribuzine, Rimsulfuron, Bentazone**	**Cultivator, Hand weeding**	Chemical and physical control	Zand et al. (2017)
Amaranthus albus	**Metribuzine, Rimsulfuron, Bentazone**	**Cultivator, Hand weeding**	Chemical and physical control	Zand et al. 2017
Lepidium virginicum	Flumioxazin with Pendimethalin	Hand weeding	Chemical and physical control	Zand et al. (2017)
Solanum elaeagnifolium	2,4-D amine + Picloram	Mowing and cutting	Chemical control and Biological control	Wu et al. (2016), Olckers and Zimmermann (1991), Hanwen et al. (2016)
Paspalum urvillei	Accase-inhibitors	Grazing	Chemical control and grazing	Zand et al. (2017)
Echinochloa oryzoides	**Accase-inhibitors**	Grazing animal (ducks)	Grazing	Pouramir and Yaghoubi (2021), Phan et al. (2010)
Hydrilla verticillata	Not recommended	Collecting	Biological control	Hofstra and Champion (2006)
Monochoria vaginalis	**Bensulfuron-methyl**	Remove by hand	Cultural control (crop rotation) and chemical control	Hazrati et al. (2019); www.cabi.org
Conocarpus lancifolius	Glyphosate	Cutting	Physical control	www.cabi.org
Araujia sericifera	Systemic herbicides like Glyphosate	Physical removal	Physical + chemical control	weeds.dpi.nsw.gov.au/Weeds/MothVine
Opuntia ficus-indica	Stem-injections of MSMA	Grubbing, cutting and removing	The integration of biological and chemical control	www.cabi.org
Oxalis latifolia	Systemic herbicides	Harrowing and rotary tillage	Combination of deep tillage and desiccation	www.cabi.org
*Robinia pseudoacacia**	Systemic herbicides	Cutting	Physical and chemical control	Sádlo et al. (2017)
*Eucalyptus camaldulensis**	Drilling stems and filling with herbicide	Digging out seedlings and young trees	The interaction of livestock and seed predators	www.cabi.org; Meeson et al. (2002)

Table 2 (continued)

Plant species	Chemical control	Other control methods (mechanical or physical and cultural control)	Management recommendations	References
*Bambusa vulgaris**	Spraying the regrowth with herbicides such as glyphosate or amitrole	Cutting down all stems and culms	Combination of chemical and physical control	www.cabi.org
Paulownia fortunei	Herbicide injection	Cutting down	Combination of chemical and physical control	www.cabi.org
Yucca filamentosa	Glyphosate	Cutting	Combination of chemical and physical control	www.cabi.org
Sesuvium portulacastrum	Pre and post emergence herbicide	Pulling out	Combination of chemical control and physical control (solarization)	www.cabi.org
*Fallopia japonica**	Aminopyralid or multiple Imazapyr applications	Pulling up plants complete with root systems	Combination of mechanical and chemical control	Boyd et al. (2017); www.cabi.org
Centaurea diffusa*	**2,4-D + MCPA**	Cultivator	Biological control + burning and establishment of perennial vegetation	Zand et al. (2017), van Wilgen et al. (2001)
Xanthium spinosum*	**Prometryn, trifloxysulfuron – sodium**	**Hand-weeding**	Chemical and physical control	Zand et al. (2017)
Xanthium strumarium*	**Prometryn, trifloxysulfuron – sodium**	**Hand-weeding**	Chemical and physical control	Zand et al. (2017)
Physalis angulata	**ALS inhibitors, MCPA + 2,4-D, Bromoxynil**	**Hand-weeding**	Chemical and physical control	Zand et al. (2017)

Alien species that receive management in Iran are highlighted in bold

weeds in crops including invasive plants (Zand et al. 2017). Of the 13 invasive alien plants in Iran, seven species have management plans, but only three of them (*Eichhornia crassipes*, *Azolla filiculoides* and *Cynanchum acutum*) are managed selectively without being completely effective. If the control is not selective, the native plants and the risk of reinvasion can be affected (Byun et al. 2018). Therefore, having a precise and selective program to remove alien plant community is important. For example, the Korean government made efforts to systematically manage 12 invasive alien species that are thought to be the most harmful in the country (Kim et al. 2021). In Turkey, Yazlık et al. (2018b) recommend prevention, early detection and rapid response, and long-term control and containment as strategies to avoid the spread of *Ipomoea triloba* as invasive plant.

In addition, there are shrubs or trees that cause negative impacts but are not managed. For instance, *Ailanthus altissima*, *Prosopis juliflora, Paulownia fortunei, Robinia pseudoacacia* and *Eucalyptus camaldulensis*, *Acacia saligna* and *Conocarpus erectus* have high environmental and socio-economic impacts in Iran (Sohrabi et al., 2021). The production of allergenic pollen of these trees is associated with aeroallergen and other human health problems in Iran (Assarehzadegan et al. 2015; Mousavi et al. 2017; Azimi et al. 2017; Mansouritorghabeh et al. 2019; Sohrabi et al. 2021). In the study of management of *Robinia pseudoacacia* and *Ailanthus altissima* changing cultivation practices to select native species and precision application of herbicide (e.g., "drill-fill" or stem injection) were described as one of the proper management methods, respectively (Brundu 2017; Vítková et al. 2020). Sádlo et al. (2017) proposed a stratified approach for optimal management of *Robinia pseudoacacia,* ranging from not being fully removed in selected areas to strict eradication at valuable sites. *Ambrosia psilostachya* and *Imperata cylindrica* were designated as the highest priority species for containment (Sohrabi et al. 2020). Developing selective management plants for invasive and potentially invasive plants are necessary, especially in urban areas and grasslands where management practices are absent. To complete this goal, compiling information about the biological and ecological traits of invasive plants is needed to develop effective management strategies (Sohrabi et al. 2020; Ni et al. 2021). For example, the phenology studies of invasive weeds inform on plant growth and susceptibility to herbicides and the effects of biological control agents (Cipollini et al. 2009; Sohrabi et al. 2016; Taylor et al. 2020).

Changing the nutrient application in soils might be considered as another potential method to manage alien plants population in invaded areas. For instance, using sawdust (high C:N ratio) lowered available nitrogen in soil and decreased invasion of *Phalaris arundinacea* by 59% (Iannone and Galatowitsch 2008). Phosphorus application has direct effect on the biomass of mosquito fern (*Azolla* sp); therefore, by limiting P application the growth of mosquito fern would be reduced (Watanabe et al. 1988).

Finally, seed-feeding biocontrol agents have shown to have great potential to control invasive alien plants (Dennill et al. 1999; Gordon, 1999). For example, South Africa has established large biological control programs with much success from 1913 to present (van Wilgen et al. 2020). The native moth, *Cataclysta lemnata* and the alien weevil, *Stenopelmus rufinasus* could be used as biological control agents for *Azolla filiculoides* in northern regions of Iran (Farahpour-Haghani, 2019). The ability of head flies Urophora (*Urophora xanthippe*) to reduce the number of seeds of *Acroptilon repens* along with limited host range, provide a potential biological control agent of knapweed (*Acroptilon repens*) in the weed integrated management in western Iran (Tahmasbi et al. 2016). More scientific and economic investment in biological control methods for impactful invasive plants would benefit the sustainable management of invasive species in Iran. Integrated pest management could be an effective and environmentally sensitive approach to minimize the adverse impact of alien plants. van Wilgen et al. (2001) declared the necessity of an integrated approach involving the combined use of a range of methods to control invasive alien plants effectively. For *Opuntia stricta*, the combining herbicide control on scattered populations and the release of biocontrol agents on to larger infestations (Hoffmann et al. 1999) presents much promise result (van Wilgen et al. 2001).

Besides, the removal of invasive plant and replacement with native species could also be an effective long term control solution for invasive plants. For example, planting native perennial grasses can be significantly important to increase species diversity and productivity (Young et al. 2011). By combining different methods of control and comprehensive information on the life cycles of alien plants and their interactions, the environmentally and long term management would be achievable.

Conclusions

In Iran there are more than 20 alien plant species with high impacts based on GISS. The highest environmental and socioeconomic impacts are reported for perennial alien plants like *Eichhornia crassipes, Imperata cylindrica* and *Cynanchum acutum* that invade wetlands and agricultural lands. *Ailanthus altissima*, *Pueraria montana* var. *lobata* and *Fallopia japonica* occur in urban areas and forests. Applying more restrictions to importing new plants specifically in the Hircanian zone is essential. Hircanian forests, which are known as the wet or Caspian forests, have high environmental and economic values. These forests are a World National Heritage site (https://whc.unesco.org) and should also be considered a potential hotspot for biological invasion in Iran.

Studying the biology and phenology of alien plants is a crucial step to develop an integrated management program aimed to reduce their spread and prevent negative impacts. Improved international cooperation is also critical to reduce the introduction, spread and impacts of invasive alien species on biodiversity, ecosystem services, and human livelihoods (Pyšek et al. 2020). The absence of selective invasive alien plants management leads to lack of full control and it provides the risk of reinvasion in Iran. Therefore, having a precise program to remove the alien plant community especially for perennial ones is important because of the importance of propagule pressure (Byun et al. 2018). The most prevalent management method in Iran is chemical control. There is a need to explore other approaches such as biological control for species that have been controlled through this method efficiently in other countries. The conservation of Iran's rich biodiversity should be a high priority. Education programs and biosecurity efforts at the national scale can reduce the risk of introducing and re-introducing high impact alien plants. There are still large information gaps on the distribution, impacts and successful management of invasive plants in Iran. Moreover, due to the large biogeographical diversity of the country, forecasting and modeling different scenarios between invasions and climate change and other environmental changes are also a research priority.

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