








Monographs on invasive plants in Europe N° 4: *Arundo donax* L.

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ABSTRACT

Arundo donax L. (Poaceae) is considered to be one of the worst invasive plants in the world, and here, we present a synthesis of all aspects of its biology, ecology and management that are relevant to understanding its invasive behaviour. This report presents information on the taxonomy, morphology, distribution, history of introduction and spread, ecology, responses to abiotic and biotic factors, biology, negative impacts, management and uses within the framework of a series of Botany Letters on *Monographs on invasive plants in Europe*. *Arundo donax* (giant reed) originated in subtropical Asia and is invasive in other warm regions worldwide, especially in degraded riparian areas. Introduced for use in agriculture, erosion control and construction in the Mediterranean European region since ancient times, it has become naturalized in several freshwater habitats and in disturbed areas. In its introduced range, *A. donax* shows strong genetic uniformity and no seed production. This situation is reversed in Asia, where this taxon is fertile and morphologically and genetically polymorphic. This perennial grass combines rhizomatous clonal growth with a tolerance to a wide variety of ecological conditions, such as high salinity levels and long droughts. This tall reed can increase the risk of fire, alter the natural drainage of channels and invade very sensitive habitats, posing a serious threat to riparian habitats and freshwater ecosystems. Effective methods to control *A. donax* are tarps on a cleared giant reed field to completely cover the affected zone, rhizome removal using a modified backhoe bucket adapted to separate soil from the rhizomes, and herbicide application on leaves. The combined technique of herbicide treatment plus stem-cutting can be included in management programmes, and this technique needs to be monitored over the long term to assess its success and to ensure native species colonization and ecosystem recovery. Regarding biological control, *A. donax* is host to different insect species that have been released to control it in parts of its non-native range (North America) with some success. However, these different methods of control should continue to be studied, evaluating the risks posed to the environment and the control level achieved. In this context, scientific, political and administrative efforts as well as environmental education are effective assets to address the management of this invasive species.

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1. Taxonomy

1.1. Names and classification

Scientific name: *Arundo donax* L., 1753

Taxonomic position: Monocotyledons; Order: Poales; Family: Poaceae; Subfamily: Arundinoideae Kunth ex Beilschm.; Tribe: Arundineae Dumort.

Common names: Spanisches Rohr, Pfahlrohr [DE], giant reed, Spanish cane, bamboo reed [EN], Spaanse-riet [NL], caña de techar, caña de la reina, caña de Castilla, carrizo grande, caña común, caña india [ES], Canne de Provence [FR], canna commune, canna domestica, canna gentile [IT], cana-do-brejo, canno-do-reino, capim-plumoso, cana-do-reino [PT]

EPPO code: ABKDO

Arundo donax L. (Poaceae) was described by Carl Linnaeus in *Species Plantarum* (1753), based on two

terms signifying “reed”, the genus name *Arundo* that seems to be of Latin origin (used by Virgil) and the epithet *donax* from the Greek δόναξ (used by Theophrastus). This species is the type of the genus *Arundo* L., which is the type of the Arundinoideae Kunth ex Beilschm. subfamily. The species is placed in the Arundineae Dumort. tribe, despite the highly heterogeneous composition of this tribe according to molecular phylogenies (Hardion et al. 2017a, 2017b). Linnaeus described this species from Spain and France (“Habitat in Hispania, Galloprovincia”). The lectotype designated (Jarvis et al. 1993) is conserved in L Herbarium, Leiden, Nederland (Herb. A. van Royen No. 912.356–93). Among the numerous synonyms of *Arundo donax*, several are due to the description of improperly named genera such as *Amphidonax* Nees, *Donax* P. Beauv., and *Scolochloa* Mert. & W.D.J.

Koch. *Arundo sativa*, one of the synonyms of *Arundo donax* described by Lamarck, exemplifies its human use (cf. 6. Uses). Several other taxa described in Asia, where populations are characterized by larger morphological and genetic variation (Hardion et al. 2014), are now considered synonyms of *A. donax*: *A. bifaria* Retz., *A. bengalensis* Retz. and *A. coleotricha* (Hack.) Honda (= *A. donax* var. *coleotricha* Hack.). An extensive taxonomic revision of Asian populations would be necessary to resolve the systematic ambiguity. The most cited varieties of this species are *A. donax* var. *versicolor* (Mill.) Stokes (= *A. donax* var. *variegata* Vilm.), describing a phenotype with variegated leaves often used as an ornamental plant. The mention *A. donax* var. *macrophylla* in recent literature should correspond to the cultivar *A. donax* “*Macrophylla*” with broad leaves. Among the genus *Arundo*, four other species are currently accepted (Hardion et al. 2012): the circum-Mediterranean *A. micrantha* Lam., the Italo-Balkan *A. plinii* Turra, the Ligurian *A. donaciformis* (Loisel.) and the Taiwanese *A. formosana* Hack.

1.2. Morphological description

The present description only considers the clonal lineage of *A. donax* that occurs in the Mediterranean Basin and is invasive in other warm regions worldwide, widely described in European floras (e.g. Bolòs and Vigo 2001), without consideration of native populations occurring in Asia. The invasive *A. donax* is a rhizomatous geophyte, producing robust culms measuring up to 6 m high (Table 1). Culms could be pluriannual, with a main axis flowering the first year and producing ramifications the following years. This species forms dense clumps due to the reduced length of its rhizome internodes (Figure 1). The rhizome is solid and thick. Culms are sea green (the



Figure 1. The giant reed, *Arundo donax* L. (Poaceae), with ~5 m high flowering culms.

first year) to yellowish (when branching), with a mean internode length of approximately 10 centimetres and glabrous nodes supporting one leaf and one bud. These nodes can also easily produce adventive roots and new culms with tillering or culm fragmentation. Leaves possess glabrous sheaths split to the base and a large glabrous limb (up to 6 centimetres) with hairy yellowish auricles. The ligule is very short (1 mm), membranous and briefly ciliate. The inflorescence is a large panicle consisting of approximately one thousand spikelets. This panicle opens at the end of the summer and then compresses after pollination. The spikelet contains two glabrous glumes of equal lengths and three to five florets. Each floret possesses one aristate lemma (c. 11 mm long) with long hairs (c. 5 mm) inserted on the first quarter and a smaller palea (c. 7 mm) with a truncated apex. The lemma also possesses two short teeth at the base of the terminal awn, which often look like tears between the three lemma ribs.

1.3. Distinguishing features

In Europe, *A. donax* is often confused with other Mediterranean *Arundo* spp. or even with *Phragmites* species. Therefore, Table 2, Figures 2 and Figures 3 summarize several distinguishing features that can be used to differentiate them.

Table 1. Morphological parameters for *Arundo donax* estimated on 165 culms from 11 Mediterranean localities (Data from Hardion et al. 2012).

Variables	mean \pm SD	1 st – 4 th quartiles	min – max
Culm height ^a	4.8 \pm 6.7	4.4–5.2	3.1–6.2
Panicle length ^b	53.4 \pm 11.9	44.5–61.5	23.5–79.2
Culm diameter ^c	24.2 \pm 4.5	21.0–27.3	13.0–35.7
Number of nodes per culm	41.7 \pm 4.7	39.0–45.0	26.0–52.0
Leaf length ^b	57.0 \pm 12.4	48.0–64.5	22.2–93.0
Maximal leaf width ^b	5.8 \pm 1.5	4.7–6.8	1.5–10.1
Culm internode length ^b	10.1 \pm 1.8	8.7–11.3	5.8–14.6
Rhizome diameter ^c	32.1 \pm 8.5	26.8–38.1	11.7–52.0
Rhizome internode length ^c	7.7 \pm 0.3	5.0–1.0	2.0–19.0
Lower glume length ^c	11.2 \pm 1.1	10.4–12.1	9.5–13.5
Upper glume length ^c	11.1 \pm 0.7	10.5–11.5	9.9–12.5
Lemma length ^c	11.2 \pm 0.9	10.5–11.6	9.0–13.3
Palea length ^c	6.7 \pm 0.5	6.4–7.1	5.0–7.4
Lemma hairs length ^c	5.6 \pm 0.3	5.4–5.8	5.0–6.1

^ain m; ^bin cm; ^cin mm

Table 2. Comparative characters to distinguish *Arundo donax* from other Mediterranean *Arundo* and *Phragmites*.

	<i>Arundo donax</i> ^a	<i>Arundo micrantha</i>	<i>Arundo plinii</i> ^b	<i>Phragmites</i> spp.
Glumes	equal	equal	equal	unequal
Lemma hairs ^c	on its 1st quarter	at its 1st quarter	at its 1st quarter	on the pedicel
Florets per spikelet	3–5	1–2(3)	1–2(3)	3–10
Panicle shape ^d	erect	erect	erect	drooping
Stem nodes	glabrous	glabrous	hairy	hairy
Leaf ligule	short membranous	short membranous	short membranous	ciliate
Leaf auricle	large	medium	medium	short to absent
Leaf sheath	glabrous	poorly hairy	hairy	hairy
Leaf direction ^d	bilateral	bilateral	bilateral	often unilateral
Rhizome thickness ^e	thick	thin	thin	thin
Rhizome internode ^e	< 1 cm	> 1 cm	1 cm	1 cm
Rhizome section ^e	solid	hollow	hollow	hollow with aerenchyma

^aonly considering the Mediterranean morphotypes; ^bincluding *A. donaciformis* for these characters; ^csee Figure 3; ^da character to observe well after anthesis; ^esee Figure 2.

2. Distribution and status

Arundo donax is widespread in tropical and subtropical regions worldwide (Figure 4) and even in temperate regions but rather under cultivated conditions. It is widely dispersed and naturalized in all similar climates in many regions of the world, including southern Africa, the USA, Mexico, the Caribbean, South America and the Pacific Islands (Häfliger and Scholz 1981).

2.1. Native range

The exact native range of *Arundo donax* is still a controversial issue since different authors suggest that its origin is the Middle East or Eastern Asia (Polunin and Huxley 1987) and other scientists suggest a Mediterranean origin (Zeven and Wet 1982). This second hypothesis was discredited given the extensive clonality and sterility of *A. donax* in the Mediterranean (Hardion et al. 2012). In the Old World, *A. donax* is considered native from Asia (Middle East and East Asia), where this species presents a larger morphological variation than that in other areas. In this area, species taxonomy should be revised to test the occurrence of other species or

varieties currently hidden under the name *A. donax*. In fact, Hardion et al. (2014) described the phylogenetic origin of the invasive clonal lineage in the Middle East (Pakistan and Afghanistan). However, three other lineages were also detected along Himalayan slopes (India and Nepal) and in China (based on plastid DNA markers). Very few publications from Asian authors focus on the species, and it appears not threatened and not in decline in its native range. Based on the literature, *A. donax* is probably native to the following countries:

Asia: Bangladesh, Bhutan, Japan, Pakistan, Thailand, Afghanistan, Cambodia, China, India, Iran, Laos, Malaysia, Myanmar, Nepal, Turkmenistan, Uzbekistan, and Vietnam.

2.2. Introduced range

Currently, *A. donax* has been introduced in several warm countries worldwide (Figure 4), but it is considered an invasive species mainly in countries with a subtropical or Mediterranean climate. As a result, among the dozens of publications addressing the invasiveness of *A. donax*, a large majority of them were published by US institutions, and the others were mainly published by

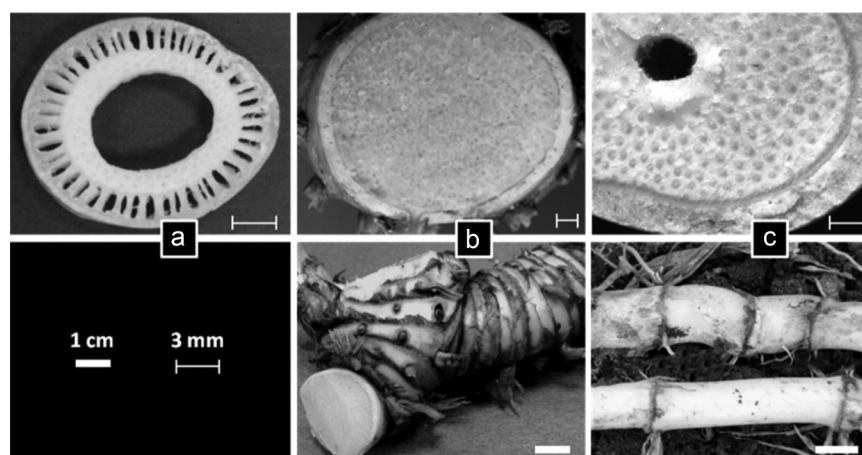


Figure 2. Rhizome features distinguishing (a) *Phragmites australis* with cortical aerenchyma, (b) *Arundo donax* with solid rhizome, and (c) *Arundo plinii* with a reduced lumen within a thick parenchyma.

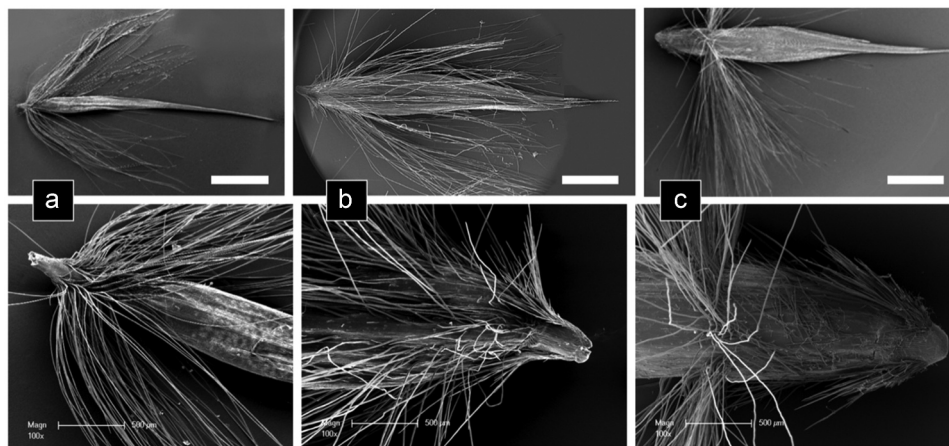


Figure 3. Floret features distinguishing (a) *Phragmites australis* with lemma hairs inserted on the rachilla, (b) *Arundo donax* with long hairs inserted all along the basal quarter of the lemma, and (c) *Arundo plinii* with long hairs inserted in a ring at the first quarter of the lemma.

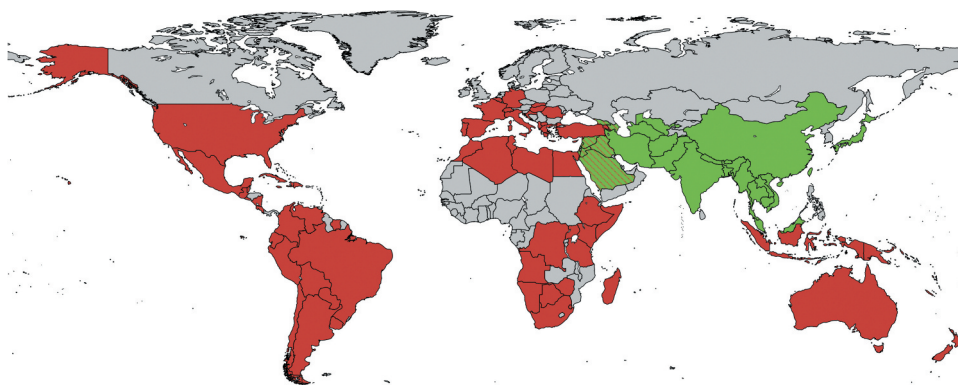


Figure 4. Distribution of *Arundo donax* among native (green) and introduced (red) range. Hatched areas correspond to countries for which this status is questioned or debated in the literature.

Mediterranean, South African and Australian institutions. According to the Global Invasive Species Database and other literature, *A. donax* could be considered an invasive species in the following countries – the list also includes Mediterranean countries where *A. donax* has been invasive for a very long time:

Africa: Algeria, Morocco, South Africa, Swaziland, and Tunisia.

America: Brazil, Dominican Republic, Haiti, Mexico, and the USA.

Europe: France, Portugal, Spain, Italy, Greece, and Romania.

Oceania: Australia, Fiji, French Polynesia, Micronesia, New Caledonia, and New Zealand.

2.3. History of introduction and spread

In the Mediterranean Basin, this species was recently described as an invasive archaeophyte (*i.e.* species introduced before 1500 AD; Hardion et al. 2014), which invaded riparian ecosystems and human disturbed lands several hundred years ago. Currently, it has become a structuring species of Mediterranean lowland landscapes, and its large

distribution demonstrates its substantial human use. *Arundo donax* has always been considered an alien species in the New World. It was initially introduced into southern California from the Mediterranean in the 1820s for numerous uses (*e.g.* erosion control, musical instruments, and farming) before its rapid spread in riparian habitats (Bell 1997). It is also considered an invasive species in South Africa, where it was introduced in the late 1700s for erosion control (Canavan et al. 2017). In Australia, it was introduced during the 19th century (Haddadchi et al. 2013).

3. Ecology

3.1. Response to abiotic factors

3.1.1. Climate

Giant reed is extremely tolerant to different climates (Perdue 1958), surviving and growing under a wide variety of temperature and rainfall conditions (Mariani et al. 2010) with however a preference for warm and subtropical climates (2019). Its regeneration is very sensitive to temperature, implying that

A. donax development is limited in areas with very cold winters. Although this species can tolerate low temperatures during the dormancy phase, if frost occurs once growth has begun during the spring, then the frost severely damages the plant (Perdue 1958; Dudley 2000; Decruyenaere and Holt 2001). According to Spencer and Ksander (2006), below 7°C, the rhizome stops producing new shoots (ramets), while above 30°C, shoot inhibition occurs. Regarding precipitation, *A. donax* tolerates values between 300 and 4000 mm (Duke 1975). In addition, this invasive plant has been found to colonize high altitudes, up to 4000 m in Central America (Tropicos database 2007).

3.1.2. Soil moisture, soil pH, salinity and nutrients

Arundo donax is considered an emergent aquatic plant (Cook 1990) or a hydrophyte that needs a certain degree of soil moisture for its initial establishment (Bell 1997). However, the plant is capable of colonizing an entire riparian area, from the riverbank to higher elevation areas with low soil moisture values where the riparian forest changes completely (DiTomaso and Healy 2003). The ability of *A. donax* to grow under water-deficient conditions is due to the rhizomes penetrating deep soil layers to obtain the existing moisture. This trait allows giant reed to be resistant to drought conditions (Sher et al. 2003). After the first year of growth, *A. donax* becomes relatively tolerant to drought but also survives in very wet and saline soils (Pilu et al. 2012). *Arundo donax* is capable to tolerate high electrical conductivities in the soil water of 35–45 dS m⁻¹ (i.e. extremely saline conditions) and to produce a high yield under these conditions when used as a bioenergy crop, leading some authors to consider it a halophyte plant (Williams et al. 2008; Williams and Biswas 2009). *Arundo donax* is indifferent to the mineralogical nature of a substrate (Perdue 1958), being able to grow in clay, sandy or stony soils, even semi-saline estuaries (Grossinger et al. 1998; Quinn and Holt 2008), and tolerates a soil pH ranging from 5.0 to 8.7 (Duke 1975). According to Rieger and Kreager (1989), *A. donax* is always observed occupying riverbanks with high nutrient contents.

3.1.3. Fire

Arundo donax presents high productivity (high growth rate), consolidating its dominance in riparian ecosystems since it is able to regrow immediately after fire and faster than native vegetation (Bell 1993). One possible explanation of its dominance is the accumulation of reserves in the rhizomes, which are not affected by fire (Coffman 2007). In addition, this species can use very effectively the elevated nutrient soil levels post-fire released by mineralization during the fire (Zedler et al. 1983). Coffman et al. (2010), in a study carried out in riparian woodlands along the

Santa Clara River in southern California, found that the growth of *A. donax* was greater than that of native plants. On average, giant reeds grew 3 to 4 times faster in height than native riparian plants, up to 2.62 cm/day (average 0.72 cm/day), and reached up to 2.3 m in height in less than 3 months after a fire. *Arundo donax* density was approximately 20 times higher and productivity was 14–24 times greater than those of native plants one year post-fire. This fast growth after fire events is one way how *A. donax* can change ecological interactions in riparian ecosystems, which change from being habitats regulated by floods to habitats regulated by fire that are structurally simpler and more homogeneous (Deltoro Torró et al. 2012).

3.2. Response to biotic factors

Arundo donax is capable of invading different habitats; however, it most often invades riparian habitats because these habitats have high levels of nutrients and disturbances, providing the best conditions for the establishment of this species. Disturbances commonly occur in riparian zones and generate areas without competition that are particularly vulnerable to being colonized by *A. donax* (Planty-Tabacchi et al. 1996; Boland 2006). In the more vegetated parts of riparian habitats, the erect and branched shape of woody native plants may restrict the expansion of *A. donax*. However, the higher productivity of *A. donax* even in situations in which it is diminished by competition with native species suggests eventual competitive exclusion of native species, as confirmed by Quinn and Holt (2009). In summary, woody species can to some extent limit the extension of *A. donax* (see also section 6.7 Ecological control and restoration) but there is overall little biotic resistance to its establishment. Conversely, *A. donax* can exclude native species due to its high productivity levels based on its physiology and its clonal growth, which allows it to occupy the substrate vertically (stems) and horizontally (rhizomes).

3.3. Habitats and syntaxonomy

In its native area, *A. donax* grows along lakes, streams, drains and other wetlands near water because it needs a high supply of water in its first growth stages (Bell 1997). In general, its preferred habitats range from moist well-drained soils to those with a water table at or near the surface and disturbed areas such as riverbanks (Ewel et al. 2001).

In Europe, the most common habitats of giant reeds are riparian zones of river basins and include: i) riparian environments and wetlands along temporary (EUNIS habitat code C2.5) or permanent water courses (EUNIS habitat codes C2.2 and C2.3), ii) seasonally flooded grasslands on sub-saline soils (EUNIS

habitat code E.3), and iii) retrodunal depressions (EUNIS habitat code B1.4). In the Mediterranean area, the largest *A. donax* populations occur in riparian areas and floodplains, from wet sites to dry riverbanks far from permanent water in terrestrial ecosystems (Deltoro Torró et al. 2012). In addition, this species is common in agricultural habitats along field borders (EUNIS habitat code I), especially in ditches, grasslands (EUNIS habitat code E5.44), ruderal areas, disturbed areas, roadsides and urban zones (EUNIS habitat code J) (Sanz Elorza et al. 2004). According to the database of the European Nature Information System (EUNIS 2020), the habitat classification for *A. donax* is described as “*Arundo donax* beds” with the EUNIS habitat code C.3.32. and described as “*very tall thickets of Arundo donax lining water courses of the Middle East and Central Asia; similar formations of the Mediterranean basin, where the species is an old introduction, are included*”.

In the USA, *A. donax* can be found in several places where it was planted for erosion control in the early 1800s (Mariani et al. 2010), such as in California and in Texas, along the Rio Grande River with an abundant naturalized population, where it invaded riparian ecosystems (Häfliger and Scholz 1981). In California, the establishment of *A. donax* after flood events was studied by Else (1996), who showed the highest deposition and establishment frequency occurring on depositional bars and not in the permanent water channel. In Central and South America, it is also very common to find giant reeds invading riparian systems and wetlands (Flores Maldonado et al. 2008).

In Oceania, particularly in Australia, and in South Africa, *A. donax* occurs as a weed in waterways, drainage lines, swampy areas, roadsides, wet disturbed sites, waste areas, old gardens and urban bushlands in temperate, subtropical and tropical environments (Canavan et al. 2017).

3.4. Ecological interactions

Arundo donax leaves contain a number of toxic and unpalatable natural minerals and chemicals, such as silica, cardiac glycosides, and alkaloids, that protect the plant from native insects (Bell 1993). In general, the presence of these toxic chemicals and minerals protects the plant from predators that might attempt to feed or reproduce on it. Despite this, a variety of insect herbivores have been found to be associated with *A. donax* plants in North America, in the Mediterranean area of Europe, South Africa and across southern Asia (Kirk et al. 2003; Goolsby and Moran 2009; Cortés et al. 2011a; Canavan et al. 2017). One of the most commonly associated species is *Tetramesa romana* Walker (Hymenoptera: Eurytomidae), the Arundo wasp, which is an insect monophagous to the *Arundo* genus (*A. donax* and *A. plinii*) and a potential

biological control agent producing galls in the stems and lateral shoots (Claridge 1961; Goolsby and Moran 2009; Moran and Goolsby 2009). *Rhizaspidiotus donacis* Leonardi (Hemiptera: Diaspididae) is another insect identified with a high potential impact on the growth of the giant reed (Moore et al. 2010; Cortés et al. 2011a, 2011b). In southern California and northern Mexico, the shoot fly *Cryptonevra* sp. (Diptera: Chloropidae) and the aphid *Melanaphis donacis* Passerini (Hemiptera: Aphididae) (Dudley and Lambert 2007) are particularly common on *Arundo*-infested sites. In France, *Phoethedes dulcis* Oberthür (Lepidoptera: Noctuidae) has been recorded feeding on giant reeds (Dufay 1979). A moth borer *Diatraea saccharalis* Fabricius (Lepidoptera: Crambidae) has been reported attacking the lateral shoots and stems of giant reeds in Barbados (Tucker 1940), and *A. donax* is an important food source for *Zyginidia guyumi* Sohi and Mann (Typhlocyloinae: Cicadellidae) in Pakistan (Ahmed et al. 1977). In South Africa, through field surveys and a literature review, Canavan et al. (2017) observed 13 herbivores feeding on *A. donax* populations, with two specialist herbivores from its native range, and shared native herbivores with *Phragmites* spp. The most widespread insect found in South Africa was *Tetramesa romana*. Other invertebrates that have been recorded feeding on stems, shoots and leaves were *Dimorphopterus zuluensis* Slater (Hemiptera: Lygaeidae), *Melanaphis donacis*, *Hyalopterus pruni* Geoffroy (Hemiptera: Aphididae), *Haplothrips gowdeyi* Franklin (Thysanoptera: Phlaeothripidae), *Chilo partellus* Swinhoe (Lepidoptera: Crambidae), *Sesamia capensis* Le Ru and *Sesamia calamistis* Hampson (Lepidoptera: Noctuidae), *Busseola fusca* Fuller (Lepidoptera: Noctuidae), one species of the order Diptera (Chloropidae) and one species of the order Coleoptera (Curculionidae) (Canavan et al. 2017). The insect species *T. romana* (Arundo wasp) and *R. donacis* (Arundo armoured scale) have shown the most promising features as biological control agents (see 6.6. Biological control) and host specificity for giant reeds (Goolsby and Moran 2009).

4. Biology

4.1. Phenology

The phenological cycle starts with new shoots emerging from rhizomes in spring. Towards the end of August, the lower leaves of the giant reed in their first year of life begin to dry (Saltonstall et al. 2010). This process continues during autumn, when the water content of the aerial part decreases, in parallel to a gradual lignification, with a loss in green colour and a reduction in its physiological activity (Zembal and Hoffman 2000). This process is due to progressively lower temperatures, among other factors (Wijte

et al. 2005; Pompeiano et al. 2019). In addition, in this season, flowering takes place, and the stems appear crowned by feathery inflorescences. These processes are accompanied by a transport of soluble carbohydrates through the phloem, from the aerial part to the subterranean storage organs, which translates into a lower content of these compounds in the leaves in autumn than in spring and summer (Decruyenaere and Holt 2001). In fact, there is an alternation in *A. donax* between the allocation of nutrients to the aerial part in spring and summer and to the underground part in autumn and winter (Dudley 2000). *A. donax* blooms at the end of summer, between August and October, although the seeds it produces are not fertile in its introduced range (Lewandowski et al. 2003). After winter, with the start of the second growing season, the lateral branches are emitted from the axillary buds present in the nodes (Decruyenaere and Holt 2001). These branches constitute 75% of the leaf area of a mature *A. donax* plant.

4.2. Physiological data

4.2.1. Response to nutrient availability

Nutrient enrichment in riparian areas has led to numerous invasive species invading these ecosystems (Hood and Naiman 2000; Richardson et al. 2007). In addition to nutrient-rich alluvial deposits, the generalized use of fertilizers and the abundant deposition of organic matter originating from anthropic activities (agriculture, livestock, wastewater, etc.) cause these environments to become ideal areas for the establishment and growth of *A. donax* (Jiménez-Ruiz et al. 2011). According to Quinn et al. (2007) and Jiménez-Ruiz et al. (2011), the growth of *A. donax* is modulated by nutrient availability. In sites with high nitrogen concentrations, *A. donax* does not exhibit dormancy and the mass of rhizomes expands actively laterally, which constitutes a competitive behaviour (Coffman 2007). In contrast, in nutrient-poor environments, *A. donax* growth is more conservative, limited to replacing old stems and exhibiting a period of dormancy during the winter (Decruyenaere and Holt 2005).

In addition, giant reeds have been shown to experience a positive effect from nitrogen addition, as it increases their height and results in more rapid root growth (Sher et al. 2003; Coffman 2007). In the natural environment, Boland (2006) observed similar results in that rhizomes in flooded areas that were rich in water and nutrients grew faster than those in environments with less water and nutrients.

4.2.2. Response to drought and flooding

Arundo donax does not need a constant supply of water (Gasith and Resh 1999) since it is capable of

withstanding long periods of drought accompanied by alternating periods of low and excessive humidity (Perdue 1958), as well as being able to grow in semi-arid habitats (Hoshovsky 1987). This drought-resistance ability of *A. donax* is due to the thickness of its stems and to its rhizomes since its roots can penetrate to deep depths and can reach the existing moisture in those layers (Else and Zedler 1996). Another trait that plays an important role in its drought response is the capacity of the giant reed to retain a high degree of leaf-level net photosynthesis rate (P_n), producing new shoots that quickly become independent of rhizome reserves once they emerge and gain biomass under water-deficit stress conditions (Haworth et al. 2016). These plant characteristics make it capable of growing in drylands (Perdue 1958). However, Mann et al. (2013) suggested that giant reeds are affected by drought conditions (mild and severe droughts) during the first year of growth. In another study carried out in the Mediterranean area to evaluate the effect of drought tolerance at early stages, the plant growth and leaf gas exchange parameters of *A. donax* were significantly affected as soil water availability decreased to less than 40% (Romero-Munar et al. 2014). These results suggest that although giant reeds are able to grow under water-stress conditions, drought can affect them significantly in the earliest growth stages, when the plants need a certain degree of soil moisture for establishment (Pilu et al. 2012; Webster et al. 2016).

Mann et al. (2013) studied the effect of flooded conditions on newly planted rhizome fragments to characterize the environmental tolerance of giant reed under greenhouse conditions. These results support the hypothesis that *A. donax* needs adequate soil moisture to become established (early stages), but prolonged and heavy flooding is also harmful to the survival of young plants throughout their first year (Bell 1993).

4.2.3. Response to light availability

According to Spencer et al. (2005), *Arundo donax* tolerates low levels of radiation and it is able to persist and grow under intermittent and low-light conditions, which implies that the plant could take advantage of sun flecks within the resident plant community (Spencer 2012). Other results have suggested that shade may hinder its establishment on riverbanks (Coffman 2007). Its ecological optimum seems in any case to be in full light conditions: in environments with high light intensity, nutrients and water resources, the highest growth rates of *A. donax* were as high as 20 tons of dry weight per ha (Perdue 1958). Under these conditions, giant reed sprouts exhibited increases in length of up to 10.2 centimetres per day (Dudley 2000). This rapid development is because all the growth of the giant reed is invested in

photosynthetic tissues with high photosynthetic capacity (Rossa et al. 1998) and is supported by high water consumption.

4.3. Reproductive biology

Arundo donax is considered sterile (i.e. non-fructiferous) throughout its whole introduced range. Hundreds of spikelets were examined for seed production in the USA and in the Mediterranean without success (Johnson et al. 2006; Hardion et al. 2015). Almost every node that is free of apical dominance is able to produce a new stem. Its sterility is due to the defective development of the male and female gametophytes. In anthers, Balogh et al. (2012) observed that fewer than 10% of microsporocytes go through meiosis, and only some microspores (early stage pollen grains) were observed in older anthers. Hardion et al. (2015) observed numerous sclerified and empty anthers, and some anthers contained few collapsed pollen grains without cytoplasm. Among the multitude of abortive pollen grains, Mariani et al. (2010) observed some normal forms, but none of these three studies observed germination of a pollen tube for the invasive *A. donax*. Balogh et al. (2012) observed fewer than 10% of the ovaries enlarging as mature caryopses. However, none of these pseudo-caryopses produce seedlings under various growth conditions. In effect, microscopic examinations of ovule development stages revealed early failure of megasporocyte development. Mariani et al. (2010) also observed failure of megasporogenesis but at the next stage. In its native range, *Arundo donax* produces seeds in Iran, Afghanistan, Pakistan, India, Nepal and Bhutan (observations of herbarium samples; Hardion et al. 2014).

The invasive clonal lineage of *A. donax* possesses $2n = c.108\text{--}110$ (<http://ccdb.tau.ac.il>). Even if this number indicates a high ploidy level, the smaller chromosome number described in *Arundo* is $2n = c.72$, e.g. for Asian populations of *A. donax* (Larsen 1963; Christopher and Abraham 1971; Mehra and Kalia 1975; Kalia 1978). The invasive *A. donax* is most likely a pseudo-triploid form generated from native populations with $2n = 72$. Such triploid formation should be recurrent, as observed in *A. plinii* (Hardion et al. 2015). The whole genus *Arundo* probably diversified after such events of reduplication from $2n = 48$ to $2n = 72$ (Jike et al. 2020).

4.4. Local expansion and long-distance dispersal

The main extension strategy of the invasive clonal lineage is vegetative multiplication by rhizome growth or stem fragmentation. In the absence of fertile seeds in the non-native area, the local expansion of giant reeds is supported mainly by vegetative growth (new stems generated remain connected at all levels) as well

as by asexual reproduction (Johnson et al. 2006). According to Boland (2006), the expansion by vegetative growth is the result of two processes:

(a) The growth of the rhizomes, which is considered the main trait responsible for the local expansion of *A. donax* (Else and Zedler 1996; DiTomaso 1998). The expansion of the plant in this way is a slow process with a mean expansion of the basal edge of only $0.29 \pm 0.04 \text{ m}^2$ per year (Boland 2006).

(b) The rooting of lignified stems. Boland (2006) demonstrated in a field study that stems on the ground and rooted stems are capable of growing up to 7.4 times faster than rhizomes in areas subject to disturbances due to floods that occur in riparian ecosystems.

Although stem fragments may play a role in the dispersal of *A. donax*, rhizome fragments are mainly responsible for this process (Decruyenaere and Holt 2001; Quinn 2006). The dispersal of *A. donax* is helped by fragments of rhizomes that can produce new shoots under a wide range of rhizome sizes and the vast majority of environmental conditions, and in comparison to stem fragments, rhizomes retain the ability to regrow for a much longer period (Decruyenaere and Holt 2001; Quinn 2006). In relation to the rhizome fragments and their size, Santín-Montanyá et al. (2014) carried out a study in greenhouse conditions to determine the production of new shoots by different rhizome sizes (<1 cm, 1 cm, 3 cm, and 5 cm) of giant reed in Spain. Only, shredded rhizomes of fragments size ≤ 1 cm were not able to regrow (Santín-Montanyá et al. 2014). The production of fragments (rhizomes or stems) that allow dispersion and colonization over long distances is a rare phenomenon under natural conditions, even under favourable conditions for its generation, such as intense rainfall and the resulting floods (Boland 2006, 2008). The high rates of fragment production described in the literature (Else and Zedler 1996) are due to mechanical removal of the species, such as the extraction of rhizomes and their subsequent crushing together with the aerial part.

4.5. Genetic diversity

Most of the 12 phylogenetic studies focusing on *Arundo donax* show low or no genetic diversity in the invaded range (including the Mediterranean) and genetically variable individuals in Asia (Table 3). Based on plastid mini- and microsatellites, Hardion et al. (2014) found the nearest relative of the invasive clone of *A. donax* in a Middle East lineage distributed along the Indus Valley. They also found three other lineages along the Himalayan slopes and in China. Ahmad et al. (2008) documented the occurrence of only one genotype across the southern USA using SRAP markers, Hardion et al. (2012) documents a genotype in the Mediterranean with AFLPs, and Canavan et al. (2017) documented a genotype in

Table 3. Review of 12 molecular studies estimating the genetic diversity of *Arundo donax*.

Authors	Date	Markers	Sampling	Genetic diversity	Number of geno-types or lineages
Khudamrongsawat <i>et al.</i>	2004	Isozymes, RAPD	California (USA)	Moderate	-
Ahmad <i>et al.</i>	2008	SRAP, TE	USA	Null	1
Mariani <i>et al.</i>	2010	AFLP	Mediterranean; Asia	Low; moderate	1; ≥ 1
Hardion <i>et al.</i>	2012	AFLP	Mediterranean	Null	1
Haddadchi <i>et al.</i>	2013	ISSR	SE Australia	Moderate	1
Tarin <i>et al.</i>	2013	nSSR	N America; Mediterranean	Low; high	6; 129
Zeng <i>et al.</i>	2013	ISSR	China	High	3
Hardion <i>et al.</i>	2014	cpDNA	Mediterranean; Asia	Null; high	1; 3
Pilu <i>et al.</i>	2014	SSR, maize genes	Italy	Low	3
Touchell <i>et al.</i>	2016	ISSR	USA; Nepal	Low; moderate	1; 2
Canavan <i>et al.</i>	2017	nSSR, cpDNA	South Africa	Null	1
Malone <i>et al.</i>	2017	AFLP	SE Australia	Low	2

SRAP, sequence-related amplification polymorphism; TE, transposable elements-based markers

South Africa with SSRs. Using AFLP, Malone *et al.* (2017) showed the occurrence of two lineages in Australia, which may have been the gathering of an invasive clone, and another Asian lineage expanded through Indonesia. Based on the SSRs in the maize genome, Pilu *et al.* (2014) found some genotypic differences in Italy, without geographical structuring. In contrast, Tarin *et al.* (2013) found a very high genetic diversity in the Mediterranean (129 genotypes from 203 samples and a Nei genetic diversity of 0.929) and a weak diversity in North America, using 10 SSRs specifically developed from *A. donax*. The authors surprisingly noted that sampling confusions with *Phragmites* were possible, but they screened these putative errors with control genotypes of *Phragmites*. In comparison to the results of other studies in the Mediterranean, the results of the study calls for further uses of these specific SSRs in broader sampling in the Mediterranean as well as for Asian populations using newly collected fresh material. As a preliminary result, Canavan *et al.* (2017) did not find genetic diversity in South Africa using these 10 SSRs. To date, new generation sequencing and large SNP datasets have not been used to estimate genetic diversity or resolve phylogenetic relationships within *Arundo*.

5. Impacts

5.1. Uses and positive impacts

Arundo donax has been used for millennia for different purposes, such as for furnishings, wind instruments, agriculture, construction, medicinal and veterinary uses, food and energy. The aerial part of the giant reed has been used to make mats, lattices, and multiple household utensils, such as baskets and containers, based on the lightness and high stability of these parts (Fernandes and Mendoça de Carvalho 2004; Martínez *et al.* 2014). Giant reed stems have played an important role in Western culture through their influence on music development over the past 5000 years ago. The reeds of woodwind instruments (clarinets, saxophones, Galician bagpipes, etc.) are

made of *A. donax* stems (Fernandes and Mendoça de Carvalho 2004). In agriculture, these stems have been used to support orchard crops that are climbers, to prop up branches, and to stake tomato plants. Additionally, the stems can be used to hit trees (olive, almond, etc.) to harvest and to collect fruits (Martínez *et al.* 2014). As a construction material, the stems are used to build structural elements or agglomerated boards (Flores Yepes 2005).

Giant reed shoots have been consumed occasionally, but they are bitter (Kunkel 1984; Rivera Núñez and Obón de Castro 1991). Rhizomes and leaves have been consumed raw or cooked (Coyle and Roberts 1975) or dried and ground to make bread (Chiej 1984). Giant reed stems and leaves contain a wide range of harmful chemical substances, which probably serve as protection against insects and herbivores (Miles *et al.* 1993). The stems and leaves contain cardiac glycosides and curare-mimetic indole alkaloids (Ghosal *et al.* 1972), triterpenes and sterols (Chandhuri and Ghosal 1970), hydroxamic acid (Zuñiga *et al.* 1983), numerous other alkaloids and silica (Jackson and Núñez 1964). Recent studies have shown that *A. donax* has great potential to be used in the development of new drugs for the treatment of human diseases (Al-Snafi 2015) since it has antibacterial and antifungal properties (Shirkani *et al.* 2014). Due to its high fibre and low protein contents, leaves are not well digested; however, *A. donax* is used in a commercial diet supplied to cows to improve milk yield, which is attributed to the presence of elements reported as galactogogues (Behera *et al.* 2013).

More recently, several researchers have investigated the phytoremediation potential of *A. donax* in heavy metal-contaminated soil. According to Cristaldi *et al.* (2020), the plant showed good phytostabilization abilities and may also be suitable for phytoextraction with a longer exposure time. Another important current use of the giant reed is biomass production for energy generation, either for the production of solid fuels for thermal uses or for the production of second-

generation biofuels (Curt et al. 2012). Under optimal conditions, *A. donax* can grow 10 cm/day, which places it among the fastest growing plants. It can produce more than 20 tons of dry matter (DM) per hectare (Perdue 1958; Bell 1997). In Italy, giant reeds can produce up to 60 tons DM/ha (Angelini et al. 2005), and in California, this plant can produce up to 155 t DM/ha (Giessow et al. 2011). At present, numerous studies are being carried out on the energy applications of *A. donax* (Lemons e Silva et al. 2015).

5.2. Negative impacts

Arundo donax has become one of the most threatening species in riparian habitats. The species can be considered as a transformer *sensu* Richardson et al. (2000), due to its ability to deeply change the character, condition, form and nature of the invaded ecosystems at the landscape level. Richardson et al. (2000), in their definition of transformer species, cite *A. donax* as an example in the category of excessive users of water and light resources. Changes in ecosystem functioning can also be related to an increase in the regularity of the fire regime induced by the high density of this species (Scott 1994; Brooks et al. 2003).

Impacts on invaded biological communities

The dense root systems of giant reeds can inhibit the acquisition of water and nutrients by native species, while their aerial parts can form a dense cover that prevents the germination and growth of native species (D'Antonio and Vitousek 1992; Cabin et al. 1999). As a result, the uses of riparian ecosystems are altered, producing negative effects on the biological communities that the riparian environments host, i.e. a loss of habitats for animals, which entails a reduction in the intermediate trophic level and modification of the food chain. Specifically, birds find few opportunities to shelter or nest in giant reed populations. The main stems of *A. donax* are vertical and lack a sufficiently robust horizontal structure to support nests (Zemba 1998; U.S. Fish and Wildlife Service 2002). Some studies in North America have shown that the cover of *A. donax* and the richness of birds such as *Vireo belli pusillus* Coues and the threatened species *Empidonax traillii extimus* A.R. Philips in California (Bell 1997) are significantly and negatively related at all times of the year, and any increase in the density of giant reed fields is accompanied by a decrease in the health and abundance of the avian community (Kissner 2004). Not surprisingly, invertebrates, one of the main sources of food for birds, are 50% less abundant and diverse in giant reed fields than in native plant communities (Herrera and Dudley 2003). The dense structure of giant reed populations limits the penetration of light and prevents the development of a diverse shrub layer; thus, the habitat that is generated lacks sufficient heterogeneity to support

a diverse invertebrate community (Herrera and Dudley 2003). Another factor that influences the biological deficiencies of giant reed populations in comparison to native plant populations is the decreased availability of bare soil under *A. donax* for terrestrial fauna and a greater possibility of desiccation (D'Antonio and Vitousek 1992). In addition, although the ranges of organic matter decomposition are similar in *A. donax* and native plant communities, in areas invaded by giant reeds, a double layer of litter is formed without interstitial spaces appropriate for the colonization of invertebrates (Bell 1997; Herrera and Dudley 2003). In a recent study carried out by Maceda-Veiga et al. (2016), the authors highlight an impoverishment of native flora and arthropod fauna in *A. donax* invaded habitats, suggesting that the presence of giant reeds produce major changes in riparian food webs displacing native riparian vegetation.

Altered or increased fire susceptibility of invaded ecosystems

The high biomass productivity of *A. donax* and its low attractiveness to herbivores based on the harmful chemical substances it accumulates (Bell 1997) lead to a large amount of fibrous leaves and stems that can reach 15.5 kg/m² in some riparian communities in the USA (Giessow et al. 2011). In comparison to native riparian vegetation, the giant reed has a lower moisture content and higher surface/volume ratio; thus, giant reed fields have a propensity to catch on fire, alter ecosystem processes and have adverse effects on native species, both animals and plants (Frandsen and Jackson 1994). Structurally, *A. donax* favours the transmission of fire from the shrub layer to the tree layer due to its verticality. In addition, the rhizomes of giant reeds survive fires and regrow immediately after a fire due to accumulated reserves, and they grow faster than native vegetation (Bell 1997). Thus, fire contributes to the conversion of mixed riparian plant communities with native species to pure monocultures of *A. donax*, with a loss in biodiversity.

An excessive user of water

A. donax has the capacity to increase water loss in rivers due to its high water consumption (up to 2,000 l of water per square metre) (Iverson 1994; Watts and Moore 2011). For example, in the Santa Margarita River Valley in California, it has been estimated that the elimination of *A. donax* over an area of approximately 405 hectares would save an amount of water equivalent to that consumed annually in an urban area of twenty thousand inhabitants (Bell 1997). According to Giessow et al. (2011), the leaf transpiration rate of *A. donax*, based on its water use value, is extremely high (40 mm/day) compared to that of most other plants in a field study carried out in southern California. In comparison with mixed riparian

vegetation, from 0.9 to 1.6 mm/day (Johns 1989), the water use of *A. donax* is much higher, which implies a large potential water use reduction that could have significant implications for both ecosystems and humans.

Impacts on the nearby aquatic environmental conditions

A. donax modifies riparian microclimates because it does not generate the structural cover necessary to provide sufficient shade to river-edge habitats, so water is warmer, unlike the river-edge habitats in riparian forests of willow and poplar, which provide shade on riverbanks (Chadwick and Associates 1992; Bell 1997; Dudley 2000). As a result, the riparian areas dominated by *A. donax* tend to have much warmer water temperatures, resulting in a decrease in dissolved oxygen concentrations and lower abundance and diversity of aquatic animals, including fishes (Dunne and Leopold 1978). In addition, this lack of plant coverage causes an increase in pH in the shallow sections of rivers due to an increase in light and thus photosynthetic activity of algae. Finally, a high pH facilitates the conversion of ammonium (NH_4) into ammonia (NH_3) in a cascade of harmful effects for aquatic species and those that use this water (Chadwick and Associates 1992; Bell 1993).

An erosion promoter

Arundo donax plants also negatively affect the hydrology and geomorphology of rivers, which also affects human activities (Quinn and Holt 2004). Giant reeds on riverbanks serve as walls, concentrating the energy of water flow in the riverbed, which leads to the excavation of the riverbed and collapse of riverbanks during floods (Else 1996; Dudley 2000). During these events, the aerial parts and rhizomes of the monospecific and very dense “forests” of *A. donax* can accumulate, forming dams, plugging bridges and preventing the proper functioning of flood control structures, with potentially serious consequences. According to Spencer et al. (2013), in comparison to rivers in native forests, rivers with giant reeds along the river banks have a higher risk of river flooding (up to 19% more). Moreover, the masses of roots (rhizomes) colonize riverbanks and fluvial terraces, altering the flow regime and modifying the morphology of the riverbeds (Bell 1997).

6. Management

6.1. Preventive strategies and considerations

Decisions regarding the population management of invasive species may be affected by various factors, such as the biology of the species and available

management options, and the objectives and work plan for their control need to be defined (Andreu and Vilà 2007). There are essentially three management options for addressing invasive species: (a) prevent their entry (exclusion), both unintentional and intentional; (b) detect them rapidly and eradicate them immediately upon entry (early detection and rapid response); and (c) minimize their impact with containment and control strategies (Genovesi and Shine 2004). These strategies are possible in the early stages of an invasion, when populations are small or localized. When invasive species occur at medium to large scales, the appropriate interventions to remove them is to contain them and map them (Deltoro Torró et al. 2012). On the other hand, Bradley (1997) proposed that control of invasive species should start in areas that are less invaded and progress gradually towards the nucleus of the invasion, not before ecologically restoring the former.

In the case of *A. donax*, that is already widespread in southern Europe, one of the most important aspects to address for containing it, is to limit its spread downstream that occurs mainly during flood events by the dispersal fragments of rhizomes and stems. Thus, management of *A. donax* is essentially an intra-basin phenomenon, starting downstream (Bell 1997). Furthermore, if this approach is combined with some control methods, the end result is riparian areas devoid of vegetation and vulnerable to erosion or reinvasion by other exotic species. Therefore, any elimination of *A. donax* should be accompanied by restoration of the area, with the goal of recovering the characteristics of the ecosystem (Moody and Mack 1988). Since the control methods that are available differ in effectiveness, period of application, cost and environmental impacts, planning is crucial to the success in each case. The duality of *A. donax* as an invasive species involved in the degradation of riverbanks and, at the same time, as an energy crop must also be considered when establishing control measures to prevent its expansion into vulnerable areas. It is recommended that *A. donax* should not be grown near habitats vulnerable to its invasion and special measures should be taken during harvesting and transport to avoid dispersal of stem fragments or rhizomes. A code of good practice could be adopted, similar to initiatives taken to limit the risk associated with non-native tree plantations (Brundu and Richardson 2016). Continuous surveillance and monitoring, especially in vulnerable areas, are essential for proper detection, for example, using remote sensing techniques (Jiménez-Ruiz 2016) for the detection of species at low densities. Dissemination of materials (guides, manuals, etc.) to support the detection and control of the species would be beneficial.

6.2. Manual removal

Traditionally, *A. donax* is managed by manual removal (stripping) of the aerial parts of the plants. However, this technique only serves as a temporary control because over the mid-term (6 months later), new stems emerge from the rhizomes, and the species consolidates its dominance over native riparian vegetation. Studies carried out in several riparian areas of Europe indicate that because of sporadic stripping (not continuous or repeated), there is actually an increase of as much as 15% in the density of reed stems with respect to the initial invasion (Deltoro Torró et al. 2012). Other works describe similar situations (USEPA 1997; Guthrie 2007). This method is labour intensive and can only be applied over small areas; therefore, it is not generally or economically effective.

6.3. Mechanical control

The mechanical control of *A. donax* consists of the complete removal of aboveground plant biomass with heavy machinery. When this is carried out once a year, it is referred to as one-cut stumping (Quinn and Holt 2008). This is not a very effective strategy, however, due to the tendency of the plant to re-sprout in response to the loss of aboveground biomass. Field study results outlined by Mota (2009) show that 5 successive *A. donax* clearings every 20 days caused an 80% decrease in height of the re-sprouted stems and a reduction in number with respect to the initial status. The results of Godé et al. (2008) also indicate that up to 9 successive clearings are necessary to eliminate one reed field. There is evidence that the elimination of re-sprouted stems additionally leads to a decrease in belowground plant biomass (Sharma et al. 1998). However, this species can grow in darkness for 100 days (Decruyenaere and Holt 2005) or from rhizomes buried 1 m deep (Else 1996; Boose and Holt 2002). It must also be taken into account that this species has a very high photosynthetic rate (Rossa et al. 1998), which causes the stems to become independent of the rhizome reserves once they emerge to the surface. In fact, in terms of *A. donax* performance, a positive correlation between biomass loss and several indirect negative effects (for example, reduced water efficiency) existed. This scenario could reduce the competitive ability of the giant reed against native vegetation and lead to a reduction in its occupied area (Jiménez-Ruiz and Santín-Montanyá 2016), thereby facilitating more successful control of this species in Mediterranean (semi-arid) environments.

The rhizome removal method consists of the extraction of rhizomes from the soil with heavy machinery after aerial biomass removal. This can

be conducted at any time of the year, but it is less damaging to work in relatively dry conditions as the amount of substrate that adheres to the rhizomes is reduced, minimizing soil loss. Rhizomes are generally found in the first 50 centimetres of substrate, although they can reach greater depths. Unfortunately, this methodology involves the extraction of a large amount of soil and substantial alteration to the riparian environment, which must be restored to prevent erosion and recover characteristic vegetation. Even under drought conditions with low moisture content, rhizomes sprout after mechanical removal (Bell 1997). For this reason, it is important that periods between clearings are short. If buds generated from rhizomes are eliminated, then their reserves will be depleted quickly. With rhizome removal, it is possible to achieve almost complete eradication of *A. donax*, but it specifically requires that rhizomes and substrate are totally removed. Hence, reprofiling and intensive recuperation efforts are necessary to counteract the negative effects involved.

6.4. Physical control

Physical control in invasive plant management refers to the physical manipulation of plants or their habitat (Enloe and Loewenstein 2015). This approach refers to a number of different techniques, including controlling invasive plants by altering their environment, such as water level manipulation, barriers with opaque textile coverings, nutrient manipulation, and aeration. To control *A. donax*, there are two main methodologies: textile coverings and flooding. These methods are very costly and are difficult to apply in many settings; one could not use flooding in water-scarce regions, for example.

A textile covering is a completely opaque cover used on a cleared reed field (after cutting) to deprive the plants of light. The rhizomes die due to exhausting their reserves. Although San Martín et al. (2019) found that one full calendar year was effective, other authors suggest that textile coverings should be applied for two whole vegetative seasons (Jiménez-Ruiz and Santín-Montanyá 2016). This method is suitable to control monospecific *A. donax* plantations devoid of native vegetation.

Flooding takes advantage of the intolerance of *A. donax* rhizomes to anoxia. This procedure requires first cutting the reed field and removing aerial biomass. Then, a water cover of at least 20 centimetres must be established uninterrupted for at least 3 months. Flooding is a suitable method for clumps close to a river and located at a level slightly higher than the river. Studies from

Valencia (Spain) showed us that the ideal season to carry out flooding is in winter, during the vegetative dormancy of *A. donax* (Deltoro Torró et al. 2012). Efficacy is high, up to 100% according to studies carried out in riparian areas of Spain (Mota 2009; Ollero 2010).

6.5. Herbicide application

The management of *Arundo donax* with herbicides has mainly been carried out with broad-spectrum herbicides such as glyphosate (Spencer et al. 2009; Puértolas et al. 2010). However, control with herbicides may be restricted in sensitive areas such as riparian habitats. Therefore, managing invasive weed species requires knowledge of both the invasive weed and the invaded ecosystem (Deltoro Torró et al. 2012).

More recently, specific glyphosate formulations and different active substances (asulam and trifloxysulfuron) have been proposed to control this invasive species (Odero and Gilbert 2012; San Martín et al. 2019). Spencer et al. (2008) in California noted that one foliar application of glyphosate solution at 3% or 5% was effective in controlling old populations of *A. donax*. In herbicide-sensitive habitats, such as in riparian habitats, some studies show that glyphosate injections into *A. donax* re-sprouts reduced the number of live stems by 80% one year after application (Spencer 2014). Bell (1997) reported that this species was controlled with a 2 to 5% glyphosate solution on cut stems, and Jackson (1994) recommended a glyphosate solution of 1.5% for the control of adult plants of *A. donax* as spot treatment with a foliar spray by ground equipment. Santín-Montanyá et al. (2013, 2014) tested different chemical treatments for the control of *A. donax* in a field study carried out in the Harnina River Basin in Spain (Mediterranean climate). Glyphosate (10 L per ha of formulated product) directly applied over-the-top of plants and glyphosate applied on new sprouts were excellent means of controlling the regrowth of *A. donax*. The combined technique of herbicide treatment and stem-cutting can be included in management programmes for Mediterranean protected areas. However, studies available on the dosage and efficacy of glyphosate on *A. donax* are scarce in this kind of sensitive riparian areas (Lowrey and Watson 2004). The mid- and long-term effects of repeated applications of glyphosate on re-sprouting species, such as *A. donax*, are virtually unknown, and therefore, studies to assess the mid-term prognosis for control are needed to test the usefulness and the sustainability of this technique.

6.6. Biological control

Concerning biological control, different studies have been carried out with the aim of releasing insects to

assess the herbivory effect on giant reeds (Goolsby and Moran 2009, 2019; Moran and Goolsby 2009). Some potential herbivores that occur in Asia and the Mediterranean area present high levels of herbivory effects; larvae of *Cryptonevra* sp. feed along the fibres of the leaves of new shoots, and adults of *Tetramesa romana* cause elongated galls around side shoots and induce internodal shortening (Kirk et al. 2003). In Mediterranean Cortés et al. (2011a), Cortés et al. (2011b)) found that *Rhizaspidiotus donacis* Leonardi (Hemiptera: Diaspididae) has a significant impact on *A. donax* growth since caterpillar feeding causes a “witch’s broom” effect by reducing shoot growth, reducing photosynthesis, and thinning of *Arundo* stands. In the USA, the biological control of *A. donax* with herbivorous insects was also investigated, and some arthropods were found to be associated with giant reeds but did not feed on the plants (Herrera and Dudley 2003; Kirk et al. 2003). The *Arundo* wasp, *Tetramesa romana* Walker (Hymenoptera: Eurytomidae) and *Arundo* armoured scale *Rhizaspidiotus donacis*, native insects from the Mediterranean region, were released in North America with some success (Goolsby and Moran 2009; Goolsby et al. 2011). Ecophysiological responses of different herbivorous insects on *A. donax* were assessed taking into account whether these species are capable of reducing the transpiration and growth rates of giant reeds (Moore et al. 2010). The results showed that in comparison to when groups of only the *Arundo* wasp occur, when both herbivores, *R. donacis* and *T. romana*, occur in high densities at the same time, physiological processes of *A. donax* are reduced (55% reduced biomass). *T. romana* directly affects the carboxylation capacity of Rubisco, while *R. donacis* reduces the rate of electron transport (Moore et al. 2010). However, a recent study conducted in Texas (USA) has shown that in natural habitats, freshly planted *A. donax* grows in dense clumps and proliferates regardless of being infested by *T. romana*. The authors concluded that *T. romana* under field conditions is a parasite that is well-adapted to *A. donax* and does not kill the stems. Hence, according to Showler and Osbrink (2018), exotic wasps cannot be considered effective biological control agents against *A. donax* in the USA. Among the prospects for improving biological control, new species from the core native range of *A. donax* in Asia should be investigated as source of biological control agents. It should be kept in mind that the implementation of this type of control is a long process including rigorous risk analysis to avoid non-target impacts (Paynter et al. 2020).

6.7. Ecological control and restoration

Native riparian species can help control *A. donax* as they compete for resources effectively. Live branch

coverage is a new methodology that involves establishing a dense vegetation cover of native riparian species that compete for resources and space. According to Deltoro Torró et al. (2012), *Salix* species are the most suitable for this method, so they should be favoured to optimize the results. These are abundant species in most European fluvial courses, and willow is well adapted to floods and provides good protection for banks. These authors carried out one experiment in Spain with *Salix* spp. (willow) that confirmed that live grafted branches of willow should be planted in winter months (during the dormancy period of giant reed). Coffman (2007) confirmed that *Salix* species are capable of competing for space and resources with *A. donax*, decreasing its productivity. On the other hand, plants such as *Populus* sp., *Tamarix* sp., *Sambucus* sp. and *Cornus* sp. can also be used but with less success (Deltoro Torró et al. 2012). Coverage with live branches is very effective, but there are clear conditions that make it successful: first, stem cutting must be carried out, and second, the riverbanks need to have a shallow gradient to maintain some level of flooding (which *A. donax* does not tolerate). These results highlight the importance of restoration with native species after the removal of *A. donax*, especially in nutrient-rich environments.

6.8. Integrated management

Integrated weed management can offer a solution to control or at least contain this species by limiting its spread. At present, giant reeds can be controlled by mechanical treatments such as stem cutting and removal by digging, although these measures may be ineffective and/or insufficient due to the high reproduction rate of this plant. Herbicides, which are widely used in agriculture, have certain disadvantages when used in the natural environment, mainly due to their low specificity and the possibility of their accumulation in soil and organisms. The selection of herbicides in an integrated programme is fundamental to ensuring effective control. Herbicides with short half-lives or herbicides at low doses are commonly used so that the environment can easily recover after treatment. Chemical treatment is cheaper but not always effective in controlling this species and may not be the best option in herbicide-sensitive habitats such as riparian areas. Mechanical treatments are often effective although more expensive than chemical treatments. Recent research in temperate environments has shown that in comparison to other methods, the joint application of mechanical and chemical (herbicide) treatments is cheaper and more effective at eradicating this

species (Spencer et al. 2008; Santín-Montanyá et al. 2013, 2014; San Martín et al. 2019).

The control of *Arundo donax* should be encouraged through integrated management programmes that use biological control through natural enemies. For example, *Tetramesa romana* Walker (Hymenoptera: Eurytomidae) and *Rhizaspidiotus donacis*, native insects from the Mediterranean region, have been released in North America with some success (Moore et al. 2010; Goolsby and Moran 2019). Additionally, the combination of physical and ecological control by native species can be employed on local populations with high ecological values where other control options are not available. There are some studies on *Salix* species competing for space and resources with giant reeds (Coffman 2007). Live branch coverage with other plants, such as *Populus* sp., *Tamarix* sp., *Sambucus* sp. and *Cornus* sp., have also been used with less success (Deltoro Torró et al. 2012).

A multidisciplinary approach is necessary to address the damage posed by this invasive species. Greenhouse and field experiments are important to determining the control options for *A. donax* at early stages of invasion and to measure the combination of multiple techniques in short-term and long-term studies. New studies to assess the utility of measures in combination with other methodologies are needed. In addition, cost-effectiveness should receive more consideration by researchers and administrations that manage nature conservation.

7. Cost analysis of management

The costs and possible impacts on the environment differ between different control methods in a significant way (Table 4). The control of giant reeds is possible with traditional methods, such as the use of herbicides or the mechanical extraction of rhizomes. Nevertheless, it is also possible to control *A. donax* with other methods less frequently used, such as opaque tarps, prolonged flooding or ecological restoration with native riparian species. Given that the different methods differ in their unintended effects on the environment and in their application costs, the choice of the most suitable method will depend on multiple variables from regulatory aspects to the types of interventions, including the characteristics of the giant reed population, the location of the action and the potential to apply additional treatments in successive years. The most economical method is spraying glyphosate on sprouts post-cutting and is approximately 1.28 € per m² (including three stem-cuttings). According to Deltoro Torró et al. (2012), mechanical treatment is very expensive at 21.97€ per m² (rhizome extraction with heavy machinery). With integrated management, depending on the treatment, re-cutting can increase the effectiveness of the initial treatment

Table 4. Recommendations for the method selected.

Control Methods	Use	Time of application	Benefits
Cutting	In small areas, when it is necessary to intervene quickly or it is not possible to use other methods.	Any time. The best results at the end of summer, when rhizomes are active.	The substrate and close vegetation are not modified. No use of chemical products. Low cost.
Rhizome extraction	In adults populations with the rhizomes on surface	In summer, with dry conditions to avoid the soil loss.	No use of chemical products. Close vegetation not modified. Good control.
Herbicide sprayed	In small and homogeneous populations far-off water courses.	During the vegetative period.	Low soil alterations. Good control. Low cost.
Cutting + Herbicide sprayed on sprout	In extended and homogeneous populations	Cutting in spring and Herbicide on sprout in summer.	Low soil alterations. Good control. Less unintended effects.
Cutting + Herbicide brushed onto sprout	All types of populations	During the vegetative period.	Low soil alterations. Good control. No derived effects. Less herbicide consumption.
Textile covering	In small and homogeneous populations	Any time	Not use of chemical products. Good control. High cost.
Covering of live branches (ecological control and restoration)	In populations close to river	End of summer	Restorations with native species. Good control. Medium soil alterations. High cost.

10-fold but represents an additional cost that ranges between 10 and 40%.

8. Conclusion

Arundo donax is an introduced, well-established invasive species in southern Europe. In general, the genus *Arundo* shows low genetic diversity in its invaded range, and some aspects of the giant reed, such as its phylogenetic relationships within *Arundo*, are still unclear. It propagates via rhizome elongation and fragmentation, while the flowers of the large inflorescence are sterile in the invaded range. In addition, giant reeds have been used in Mediterranean areas to address the needs of local people, and currently, they can be cultivated as bioenergy crops.

The giant reed is invasive in riparian areas and its uncontrolled presence can reduce native plant species richness, which is damaging for

Mediterranean riparian habitats. Optimal management and control measures must be applied to mitigate the negative impacts of this species in freshwater ecosystems. Currently, there is a need to increase the efficiency of current control techniques, and this requires a better understanding of the invasive potential of this species and its responses to different control methods. In fact, the difficulty in controlling this species lies in its morphology, modes of growth and propagation (vegetative growth), physiology and tolerance to a wide variety of ecological conditions. Most of the actions that have been carried out to control this species have not been successful since they have been based on temporarily eliminating it. Control measures against *A. donax* involve herbicidal control, biomass cutting and removal, biological control and ecological methods. Based on recent results, biological control should be encouraged by competent authorities in Europe for weed management as a useful integrated management tool (Shaw 2007). At present, integrated management programmes, in addition to continuous technological change, natural area manager participation, technology transfer, and the policy environment, are key components for achieving control of this species. Specific programmes should be developed to increase knowledge of *A. donax* biology and the efficiency of control methods.

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No potential conflict of interest was reported by the authors.

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