*Review on Invasive Tree of Heaven (*Ailanthus altissima *(Mill.) Swingle) Conflicting Values: Assessment of Its Ecosystem Services and Potential Biological Threat*

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Review on Invasive Tree of Heaven (*Ailanthus altissima* (Mill.) Swingle) Conflicting Values: Assessment of Its Ecosystem Services and Potential Biological Threat

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Abstract Globally, invasions by alien plants are rapidly increasing in extent and severity, leading to large-scale ecosystem degradation. One of the most widespread invasive alien plant species in Europe and North America, Tree of Heaven (*Ailanthus altissima* (Mill.) Swingle) was introduced intentionally for use as an ornamental plant in the 18th century. Since then, it has spread and is now frequently found in a number of countries. Today, Tree of Heaven is considered one of the worst invasive plant species in Europe and is also listed as invasive in North America and many other countries. Millennium Ecosystem Assessment is one of many systems trying to list and categorize biological services to humans and to provide a tool for identifying services delivered by natural ecosystems. Invasive species have generally caused degradation of the services, have a major impact on the environment, and are threatening biodiversity and reducing overall species abundance and diversity. On the other hand, some invasive species can provide services useful to human well-being. In the present review *A. altissima* impacts on ecosystems are identified and positive influences on some ecosystem services are weighed against the negative effects on the environment and human health. The aim of the present review is to resume the general knowledge of *A. altissima,* group available references on distribution and ecology according to countries, compare ecosystem services provided or enhanced by *A. altissima* presence and the negative effects it causes, identify gaps in current knowledge, and give recommendations for future lines of research.

Keywords Biological invasion · Tree of Heaven · *Ailanthus altissima* · Ecosystem service assessment · Herbicidal effect · Ecosystem management

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Introduction

Invasive species are recognized as the second-largest global threat (after direct habitat destruction) to biodiversity (Wilcove et al. 1998; Walker and Steffen 1999). Introduced species may become invasive and displace native species, modify habitats, change community structure, affect ecosystem processes or wider ecosystem functioning, impede the provision of ecosystem services, and cause substantial economic losses (Blackburn et al. 2004; Pimentel et al. 2005; Vilà et al. 2010; Gatto et al. 2013; Constán-Nava et al. 2015). They are a product of human redistribution of species to support agriculture, forestry, mariculture, horticulture, and recreation, as well as the results of accidental introductions (van Wilgen et al. 2008). On the other hand, both native and non-native tree species have enormous social, economic, landscape, and ecological importance (Dickie et al. 2014) and provide a number of ecosystem services. A 4-year global assessment of the world's ecosystem services recognized the human-derived benefits of ecosystems within four categories of services: cultural, provisioning, supporting, and regulating (Millennium Ecosystem Assessment 2005). Ecosystem services are the outputs of natural systems from which humans may derive benefits. By this definition, ecosystem services require use or appreciation by people, although not all

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changes in ecosystem services can be demonstrated to result in substantial benefits or harm to people (Wainger and Mazzotta 2011).

Invasive alien trees can not only compromise ecosystem services but also provide numerous and complex services to humans, often making it difficult to evaluate harm to benefits and moreover with benefits come vested interests. Assessing the positive and negative effects of alien invasive species on ecosystems is very complex and models can help in evaluating which of these prevail. Theoretical models suggest that there could be multiple relationships between ecosystem diversity and stability (Ives and Carpenter 2007).

Tree of Heaven (*Ailanthus altissima* (Mill.) Swingle) is considered one of the worst invasive plant species in Europe (DAISIE 2014) and it is also listed as an invasive plant in North America (NISIC, USDA 2014) and many other countries (DAISIE 2014; CARA 1983). It is a tree native to Southeast Asia (Fig. 1), introduced in Europe and North America in the 18th century. Its primary occurrence and distribution areas are cities and other disturbed sites, such as agricultural fields and transportation corridors. In cities, it can cause problems by damaging the infrastructure and archeological remains with its roots, cause allergic reactions, respiratory problems, and skin rashes in the local population (Ballero et al. 2003; Derrick and Darley 1994; Burrows and Tyrl 2013; Celesti-Grapow and Blasi 2004; Luz-Lezcano Caceres and Gerold 2009). In natural environments outside cities, it is rarely present, although generally highly abundant in the Mediterranean (EPPO 2013) due to a preference for Mediterranean climate conditions. There it is shown to negatively impact the environment by altering the local vegetation structure and compromising the ecosystem stability (Vilá et al. 2006; Constán-Nava et al. 2010). The environmental and economic costs of invasive species differ in severity if these plants invade untransformed natural ecosystems or neglected areas of cities. Still, it is often difficult to detect the actual negative impact of an introduced established species and there is an open debate on rules and methods to give a quantitative understanding of basic introduction and establishment principles (Williamson and Brown 1986; Williamson and Fitter 1996; Jarić and Cvijanović 2012; van Wilgen et al. 2013).

Eradication is difficult, as it has a high regenerative capacity. After simply cutting the tree, it soon regrows by means of fast growing stump shoots (Giunti et al. 2010), and the application of herbicides for an efficient control is mandatory (Constán-Nava 2013; Badalamenti and LaMantia 2013). Besides this, its seed dispersal and vegetative growth from long lateral roots are impossible to control. Research into the most efficient methods of its eradication and control is in progress.

One of the positive sides of *A. altissima* wide presence is its possible use as a source of pharmaceutically active compounds, mainly ailanthone (quassinoids). Extracts from *A. altissima* were used in traditional Chinese medicine as a cure for a wide variety of conditions, such as asthma, epilepsy, scabies, seborrhea, and used as an astringent, antispasmodic, antihelmintic, parasiticide, and narcotic (Hu 1979; Kowarik and Säumel 2007). In conventional medicine, quassinoids were also recognized as valuable compounds, as recent studies showed that they could be used to

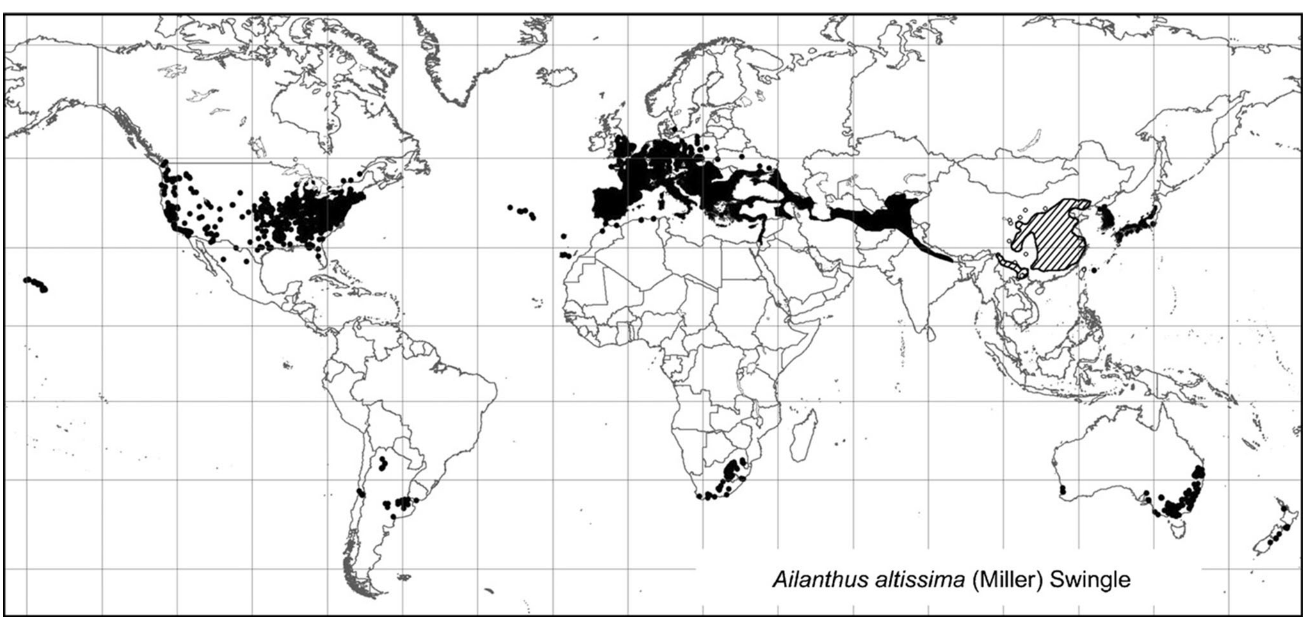

Fig. 1 Distribution of *Ailanthus altissima*. *Drafted* native range, *black* secondary range (Kowarik and Säumel 2007)

treat malaria, HIV, and Epstain–Barr virus infections (Chang and Woo 2003; Tamura et al. 2003). *A. altissima* extracts were shown to have strong herbicidal and insecticidal properties (Kožuharova et al. 2014) and as such could be used in agricultural applications as an environmentally friendly compound. Besides these, *A. altissima* has other possible uses such as wood products, use for environmental rehabilitation, bee pasture, etc.

The aim of the present review is to:

- Summarize the general knowledge on *A. altissima*;
- Give an overview of recent relevant researches on the distribution and ecological properties of *A. altissima* in several European and North American countries where it is mostly spread;
- Summarize available bibliographic records on ecosystem services *A. altissima* can provide according to Millennium Ecosystem Concept (2005) and elaborate the negative impact of *A altissima* on the environment and human health;
- Answer the question: Do we know enough and could there be a positive side to its abundance?
- Identify gaps in current knowledge and give recommendations for future lines of research.

Ailanthus altissima General Features

Description

Ailanthus altissima is a deciduous tree of the family Simaroubaceae, a small group of plants of mostly tropical climates. It has odd pinnately compound leaves of 30–100 cm in length, spirally arranged on the branch. The leaves are composed of 10–40 leaflets of 10–20 cm in length. The leaflets are of lanceolate shape, rounded at the base with two to four glandular teeth on the edge (Hu 1979). On the leaflets base are the openings of 1–8 extrafloral nectaries (Davies 1943), a characteristic which can be used to distinguish *A. altissima* from similar species. Leaf-bearing branches are green with short hairs (Kowarik and Säumel 2007). The bark is gray with white diamond-shaped spots or stripes. Leaf scars, present on older branches and in winter, are heart shaped. Flowers are yellow to red, arranged in terminally located inflorescences. The seeds are enclosed in yellow to red samaras, whose color, size, weight, and thickness are highly variable, and dependent on the location of the tree (Kowarik and Säumel 2007). The samaras are numerous, arranged in clusters on trees, and are primarily dispersed by wind. Roots consist of taproot for storage, and extensive lateral roots, highly variable in length, but known to reach up to 27 m (Kiermeier 1987; Kowarik and Säumel 2007).

The tree can grow up to 18–30 m in height, depending on the geographical zone and habitat type it occupies, and reach the age of 130 years (Lauche 1936; Kowarik and Säumel 2007), although on average it reaches around 50 years of age (Miller 1990). A detailed botanical description is given in the paper by Kowarik and Säumel (2007).

Biology and Ecology

Ailanthus altissima is a winter deciduous species whose seasonal vegetation period starts later and lasts longer than in many other native deciduous tree species. The specific start of the vegetative period is dependent on the habitat latitude. Leaf emergence in moderate climates occurs around April, while flowering starts in mid-April to July. Samaras' ripening lasts until September/October while their releasing occurs in early to middle of the following year (Kowarik and Säumel 2007).

A. altissima reproduces both from seeds and clonally from root shoots. Flowering maturity usually occurs after 3–5 years, although the best seed production is reached at the age of 12–20 years (Miller 1990; Kowarik and Säumel 2007). Seed production is high, but variable with the age and height of the tree. It can reach up to 325,000 samaras arranged in 500 clusters in an 8-year-old tree (Bory and Clair-Maczulajtys 1980). The seeds have a high germination rate, from 64 to 98 %, depending on the collecting and planting season, and are highly viable after longer periods of storage (75 % after 1 year, 60 % after 2 years). Soil composition, altitude, and previous contact with water also have a significant effect on the germination rate (Kowarik and Säumel 2007).

Stem growth is highly rapid, and it is believed to be the fastest growing tree in North America (Knapp and Canham 2000) and Britain (Mabberley 1997) including native and exotic species. Diameter growth rate is higher in younger trees (5–10 mm/year), and begins decreasing in 20-year-old trees (Kowarik and Säumel 2007). An extremely high growth rate is present in seedlings, especially in urban areas where 1-year-old seedlings can be up to 2 m high (Hu 1979). Growth rate is lower in natural environments and in older trees (Kowarik and Säumel 2007), and is in general highly dependent on the habitat type. Vegetative reproduction occurs by growing shoots from extensive lateral roots; new shoots are known to grow up to 27 m from the mother plant (Howard 2004), possibly even more (Kowarik and Säumel 2007).

Regeneration rate is high and serves as an additional pathway to vegetative reproduction. Fragments of stems and roots can produce new shoots, even as small as 1 cm in length (Inverso and Bellani 1991). Additionally, cut stems show prolific production of new shoots which increase in number with successive cuts. One study showed the number of new shoots exceeded the number of cut stems by a factor of 34.4 approximately 2 years after cutting (Kowarik and Säumel 2007).

Dispersion of new individuals is, apart by producing lateral root shoots, accomplished by dispersing samaras by wind, water, and in a small part by animals. The primary dispersion vector is the wind, which moves samaras both individually and in clusters up to 100–200 m from the mother plant (Kota 2005), although the highest portion of seedlings is found at smaller distances (Cho and Lee 2002). Additional wind dispersion of fallen samaras is more pronounced in cities due to less obstructed terrain surfaces, and along transportation corridors, due to air movement induced by vehicles. Rivers can serve as an additional dispersal vector, as it is shown that submergence in water of both samaras and vegetative parts does not affect their viability (Kowarik and Säumel 2006, 2008). Animals which can occasionally serve as dispersal vectors are rodents and birds (Kowarik and Säumel 2007).

A. altissima is highly tolerant to many ecological factors. It has a wide temperature tolerance, although is much better adapted to higher rather than lower temperatures, occurring in the temperate zone. High susceptibility to cold is present in seedlings and saplings and exposure to low temperatures can prevent or reduce their subsequent development (Hildebrand 2006). In an exposure experiment with temperatures between −10 and −16 °C across urban to rural gradients in the Berlin area, complete mortality of 1-year-old saplings was observed (von der Lippe et al. 2005). In contrast, older trees are able to survive extreme cold (e.g., 6-year-old trees survived −33 °C according to Zelenin (1976)), although not without sustaining severe injuries causing slower height gain in the following vegetation period (Kowarik and Säumel 2007). According to Fryer (2010), annual mean minimum and maximum temperatures in *A. altissima* in the North American range are −9 to 36 °C, accordingly limiting the altitudes and latitudes of its occurrence.

It is drought resistant, with several adaptations to water loss: closing stomatas, reducing hydraulic conductivity in roots and relocating food reserves from tap root to lateral roots for a subsequent development of new shoots upon the loss of the primary one (Trifilò et al. 2004). *A. altissima* grows on a broad range of soil types: barren rocky grounds, clay, sand, calcareous, and gravel substrates; it tolerates saline and alkaline soils, nutrient rich and poor, dry and wet, and tolerates submersion of roots in sea water (Kowarik and Säumel 2007) thus exhibiting broad ecological amplitude with respect to soil types. Studies showed that the growth is best on nutrient-rich, loamy soils (Miller 1990), although due to a wide tolerance of many soil types and physicochemical parameters, soil is not a determining factor for its occurrence. It is tolerant to pollution, resistant to many air pollutants, although sensitive to ozone (Gravano et al. 2003). High pollution tolerance is attributed to the high antioxidative capacity of its leaves (Kowarik and Säumel 2007).

Concerning limiting factors, apart from cold, it is highly intolerant to shade, and requires canopy gaps in early development stages to be able to further develop (Miller 1990; Knapp and Canham 2000). Shade and cold as the limiting factors can inhibit the establishment of its seedlings and subsequently determine the limits of its occurrence and distribution.

A. altissima produces a broad variety of active compounds which make it resistant to herbivores and pathogens and also induce an allopathic effect on other plant species. The main component responsible for allelopathy is determined to be ailanthone, a quassinoid shown to be toxic to many plant species (Mergen 1959; Heisey 1990a, 1996, 1999; Lawrence et al. 1991). It is highly concentrated in root bark, while the main pathway for its toxic effect is its release through the roots into the soil (Heisey 1996).

These biological and ecological properties make it a highly competitive species, capable of establishing itself in a wide variety of environmental conditions. Due to its high production of viable seeds, and lateral shoot growth, it is capable of dispersing and establishing new seedlings at a long distance from the mother plant. A tolerance to a wide range of ecological factors enables *A. altissima* to be established on many habitat types, from stony and sterile soils to rich alluvial bottoms. Tolerance to pollution enables its establishment in cities where it grows on walls, cracks of sidewalks, road and railroad edges, abandoned lots and parks (Kowarik and Säumel 2007).

Chemical Properties

A comprehensive study of the volatile oil and phenolic constituents of *Ailanthus altissima* leaves, and their antioxidant, antimicrobial, and phytotoxic activities was performed by Albouchi et al. (2013). It was determined that the plant volatile oils consisted of 139 components, mainly non-terpenic compounds (20.58–45.38 %), sesquiterpene hydrocarbons (19.42–36.20 %) and oxygenated monoterpenes (13.47–24.92 %). The composition was found to be dependent on the plant part, developmental stage, sample preparation method, and analysis. They found 9 phenolic components, although a previous study was made by Kundu and Laskar (2010) where 19 flavonoids were identified in the tissues of *A. altissima*. The relative content of identified compounds was found to vary between samples from different locations. Testing of the extracts for antioxidant, antimicrobial, and phytotoxic activities have shown that they exhibit strong antioxidant and phytotoxic activities (inhibited germination and radicle growth of

Daucus carota L.) and are effective against Gram-positive bacteria, although not against Gram-negative bacteria and yeast *Candida albicans*. The exact component(s) responsible for these effects were not identified here.

The most significant components of *A. altissima* tissues are alkaloids, terpenoids, steroids, and flavonoids, according to Kožuharova et al. (2014) who summarized previous studies. According to the available data, the tissues of *A. altissima* contain 18 alkaloids, 62 terpenoids, 15 steroids, 30 alifatic components, 7 flavonoids, 3 aglycons, and 4 glycosides, the latter three so far isolated only from leaves: several coumarins, organic acids, and lignans. The most significant and specific component for *A. altissima* and the Simaroubaceae family are quassinoids, a group of terpenoids. They are heavily oxygenated, bitter tasting lactones, with over 150 known group members (Fiaschetti et al. 2011). Numerous studies confirmed that quassinoids have a wide range of biological activities, which include antileukemic and anticancer activities, antiamoebal, antimalarial, insecticidal and antifeedant, antiviral, antifungal, antitubercular, and herbicidal activities (Fiaschetti et al. 2011). It is considered that the bioactivity of quassinoids is based on the plasma membrane NADH oxidase inhibition (Morré et al. 1998).

In *A. altissima,* the most significant and active quassinoid is ailanthone. Among these quassinoids, ailanthone has been reported to account for up to 0.01 % of the dried bark (Pedersini et al. 2011). It was first isolated and identified from *A. altissima* in 1964. (Casinovi et al. 1964; Polonski and Fourrey 1964). Its phytotoxic activity was discovered in the 1990s, first as a pure compound (Heisey 1996) and later as a part of *A. altissima* extracts (Lin et al. 1995; Heisey 1996). It was identified as a main phytotoxic component in *A. altissima* extracts by Heisey (1996). Ailanthone is a polar molecule easily extracted by polar solvents like water or methanol. It has the highest solubility in dichlorometane and ethyl acetate, whose extracts have the highest toxicity as reported by Heisey (1996). Later, other phytotoxic compounds have also been identified in *A. altissima* tissues: ailanthinone, chaparrine, and ailanthinol (De Feo et al. 2003).

History of Introduction and Distribution

Ailanthus altissima was introduced into Europe in the 1740s and into North America in the 1780s primarily as an ornamental tree, due to its high esthetic value (Hu 1979). It was first introduced to Europe in France by the French missionary Pierre d'Incarville, who sent seeds from Nanking to Bernard de Jussieu, a Superintendent of the Jardin Royal des Plantes in Paris (Kowarik and Säumel 2007). On receiving the seed of *A. altissima*, Bernard de Jussieu planted a portion of it in Paris, and sent some to England (Hu 1979). Philip Miller, Superintendent of the Physic Garden at Chelsea, and Philip C. Webb, a man with an exotic garden in Busbridge, near London, both received some of the seeds in 1751. The seeds were viable and produced young healthy trees well adapted for outdoor living in the climates of Paris and London (Hu 1979). Upon its introduction it was soon planted as an ornamental tree in landscape parks (Kowarik and Säumel 2007). On account of its tropical look, rapid growth, legendary tolerance to urban life, and beautiful foliage, the popularity of *A. altissima* soared in Europe (Hu 1979). *A. altissima* soon became one of the most commonly planted and highly esteemed trees in European cities (Hu 1979). *A. altissima* has traditionally been used in China in folk medicine, as a fuelwood and timber tree, a food source for silk worms and honey bees, erosion control, and reforestation (Hu 1979; Kowarik and Säumel 2007). Today, it is widely considered an undesired species, as its use is not considered practical anymore due to its invasive properties. Its value as an ornamental plant has also decreased as its male flowers emit an unpleasant odor and it is shown to be a strong allergen.

Today, *A. altissima* is present on all continents except Antarctica covering areas within temperate to meridional zones. It mostly occupies areas of the Northern hemisphere, especially Europe and the USA part of North America (Fig. 1). Generally, it prefers environments altered by human activities, such as cities, transportation corridors, and agricultural fields. In the Southern hemisphere, its distribution is much scarcer and confined to limited areas. It is present in some parts of New Zealand, Australia, South Africa, Argentina, and other locations in temperate climate zones (Fig. 1).

The secondary ranges it occupies have similar climate conditions as its native area, including a long and warm growing season, regular winter frost, and an annual precipitation of more than 500 mm in most parts (Kowarik and Säumel 2007). In North America, it is distributed in areas with a wide range of climatic conditions and elevations (0–2100 m), while in Europe it occupies areas of lower elevation (<1000 m) and milder climate.

The main habitat types in natural environments which *A. altissima* occupies are riparian forests and mesic and xeric woodlands of submeridional and meridional zones (Kowarik and Säumel 2007). Their presences have been reported in floodplains of the Danube in associations with *Populus alba*, *P. nigra,* and *Fraxinus excelsior* (Drescher and Ließ 2006). Along rivers in southern Switzerland, it grows in communities with *Alnus incana* and *F. excelsior*, in shrub communities, *Castanea sativa* forests, meadows, rocky sites, and on natural debris avalanches (Arnaboldi et al. 2002; Kowarik and Säumel 2007). It is widespread in the Mediterranean (Vilá et al. 2006, 2008), often associated with evergreen shrub communities and rarely with *Quercus ilex* forests (Kowarik 1983). In Hungary, it is present on acidic and calcareous grasslands and woodlands (Udvardy 1999). In Slovakia, Austria, and Hungary, it is reported in association with near natural and natural shrub and forest communities. It is reported that it is often associated with *Robinia pseudoacacia* and *Acer negundo* on loess and *Prunus mahaleb* on limestone. In Austria, it may form communities with Chaenopodiaceae and Lamiaceae and on southern facing slopes it is reported to grow with *Syringa vulgaris* (Kowarik and Säumel 2007).

On a south-to-north gradient, its distribution is increasingly being confined to city areas which provide milder winter temperatures. Until the 1980s, its distribution was confined to cities with sub-continental and sub-Mediterranean climates, but since then it began to appear in areas of colder climate. This is believed to be a consequence of several successive years of mild climate which helped the establishment of its seedlings, the most sensitive development stage of the tree (Hildebrand 2006; Kowarik and Säumel 2007; Song et al. 2012). It is the most common urban tree growing in walls, cracks, crevices, along roads and railroads, and abandoned areas (Danin 2000). It generally occupies disturbed areas of low maintenance. In Italy, it is the most common non-native urban species (Celesti-Grapow and Blasi 1998). In Central European cities, it is reported to colonize abandoned urban sites. In Berlin and Vienna, it is associated with built up areas, green parks, and railways (Kowarik and Säumel 2007). Outside of cities, the most suitable areas for its establishment are those adjacent to roads and railroads, edges of agricultural fields, vineyards, and other sites altered by human interference. In the Mediterranean, it is most commonly found along roads and after that on agricultural fields (Hulme 2004; Kowarik and Säumel 2007). *A. altissima* occurs in all stages of succession of urban sites from annual pioneer communities, stages dominated by perennial herbs and grasses, to shrub communities. In colonization of wastelands, it is often associated with *Robinia pseudoacacia* or *Acer* species (Kowarik and Säumel 2007).

The highest abundance in Europe is in Mediterranean areas and central European cities (Kowarik and Säumel 2007). In most European countries, it is declared as invasive (Table 1). In North America, its distribution is less confined to cities although in cities it is more abundant. It is reported in 40 states of the USA, including Hawaii, and 2 states of eastern Canada (USDA NRCS 2014). In both the USA and Canada, it is listed as an invasive species (NISIC USDA 2014), although in Canada its distribution is much more restricted, due to the colder climate. As it is limited by cold, its distribution gets confined by northern borders. For example, it is considered a highly invasive species in Mediterranean countries (EPPO 2013) with a high risk of potential invasion, in comparison to more northern countries such as Ireland, the UK, and Denmark, where it is considered a low-to-medium risk species. In addition, in Denmark, it is considered only a potentially invasive species. In Scandinavian countries, it was not recorded.

Survey of Researches in Europe and North America

Recently, several researches have been made worldwide, mainly regarding Mediterranean areas, Central Europe, and USA, where *Ailanthus altissima* is mostly spread. Studies differ in approach, covering biological and botanical aspects, plant physiology, invasive potential, chemical characterization, ecological aspects, management, herbicide and insecticide aspect, medicinal use, etc. Relevant papers published mostly in the last decade describing occurrence, distribution, and its ecological characteristics are summarized in the Table 1.

Ecosystem Services

Human well-being depends, among other things, on the continued supply of services obtained from ecosystems. Human actions during the last 50 years have altered ecosystems to an extent and degree unprecedented in human history. Biological diversity is a necessary condition for the delivery of all ecosystem services. The Millennium Ecosystem Assessment was called by the United Nations Secretary-General Kofi Annan in 2000 with the objective to assess the consequences of ecosystem change for human well-being and the scientific basis for action needed to enhance the conservation and sustainable use of those systems and their contribution to human well-being. It is one of many systems trying to list and categorize biological services to humans (Daily 1997; De Groot et al. 2002; Millennium Ecosystem Assessment 2005).

Biodiversity can be defined not only as a service in its own right, but also as a foundation for ecosystems to function effectively and thus to deliver services and gain values (De Groot et al. 2002). We must consider deeper issues of "value," such as the intrinsic value of nature and other social issues associated with conservation. These values, while impossible to quantify in economic terms, are clearly fundamental to conservation of the natural world. In order to estimate the costs of invasions, it is necessary to identify and quantify the full range of ecosystem services that are delivered, and secondly to estimate the degree to which these are reduced by invasions (van Wilgen and De Lange 2011). Since there is general agreement that overall

Table 1 Overview of registered presence, declared invasiveness, and scientific researches of *Ailanthus altissima* in Europe and North America

	Declared invasive (yes or no)	Documents declaring invasiveness	Research type (thematic)	Authors
Albania	Yes	DAISIE (2014)	Recorded presence	Vasil (2009)
		EPPO (2013)		
Austria	Yes	DAISIE (2014)	List of neobiota in Austria	Essl and Rabitsch (2002)
		EPPO (2013)		
			Review of possible control methods	Drescher and Lieβ (2006)
			Dispersal and management	Ambrass et al. (2014)
			Ecological characteristics of urban *A. altissima*	Schinninger et al. (2002)
Benelux	Yes	EPPO (2014)	General review, risk assessment, management methods	Verloove (2002, 2006), Branquart et al. (2010), Boer (2013)
		FLORON (2006)		
			Catalog of the neoflora	Lambinon et al. (2004), AEF (2006)
			Atlas of the flora of Flanders and Brussels region	Van Landuyt (2006)
			Established plants in Flanders	Verloove (2011)
Bosnia and Herzegovina	Yes	IZBIS (2013)	Described distribution	Petrović et al. (2011), Kovačević et al. (2013)
Bulgaria	Yes	DAISIE (2014)	Biology, ecology, and control	Vladimirov and Milanova (2010), Vladimirov (2013), Petrova et al. (2013)
			Invasive properties, chemistry, and potential uses	Kožuharova et al. (2014)
Canada	Yes	NISIC USDA (2014)	Manual of vascular plants of NE USA and Canada	Gleason and Cronquist (1991)
			Occurrence and control	Meloche and Murphy (2002)
Czech Republic	Yes	DAISIE (2014)	Testing risk assessment tools for predicting invasions	Pyšek et al. (2002), Krivanek and Pyšek (2006)
		EPPO (2006a, 2013)		
Croatia	Yes	DZZP (2014)	Distribution	Idžojtić and Zebec (2006)
			Invasive alien species lists	Boršić et al. (2008), Novak and Kravarščan (2011)
			Threat and possible control methods	Novak et al. (2009), Lodeta et al. (2010)
			Occurrence	Hulina (2010), Vukojević and Kosić (2012)
Denmark	No		Listed as potentially invasive and rare	NOBANIS (2014)
France	Yes	DAISIE (2014)	General review	Collin and Dumas (2009), Gauvrit et al. (2003), Cachon (2006)
		EPPO (2013)		
			Invasive flora lists and reviews	Muller (2004), Ferrez (2004), Jouet du vent (2007)
			Ecology and distribution	Gama et al. (2006)
			Environmental impact	Brunel (2005), Motard et al. (2011)
			Risk assessment	Fried (2010)

Table 1 continued

	Declared invasive (yes or no)	Documents declaring invasiveness	Research type (thematic)	Authors
Germany	Yes	Neobiota (2006) DAISIE (2014) EPPO (2013)	Listed as present	Schmeil et al. (2006)
			Botanical description	Kowarik and Säumel (2006, 2007, 2008),
			Rivers as dispersal corridors	Säumel and Kowarik (2010, 2013)
			Wind dispersion	Kowarik and Lippe (2006, 2011)
			Competition with *Acer negundo* L. in urban environment colonization	Bachman (2005)
			Assessment of financial cost of caused infrastructure damage	Luz-Lezcano Caceres and Gerold (2009)
Great Britain	No		Listed as present	Stace et al. (2003)
			Listed as invasive in London	GBNNSS (2011)
			Temperature and substrate effects on establishment	Hildebrand (2006)
Greece	Yes	DAISIE (2014) EPPO (2013)	Behavior and effects on ecosystems	Fotiadis et al. (2011)
			General features in inventories of invasive flora	Arianoutsou et al. (2010), (Dal Cin et al. 2009)
Hungary	Yes	DAISIE (2014) EPPO (2006b, 2013)	Occurrence as a new species in autochthonous vegetation structure	Hock and Tóth (2007)
			Reported presence	Tiborcz et al. (2012)
			General features and distribution	Udvardy and Zagyvai (2012)
			Spreading and coenological circumstances	Udvardy (1998)
			Invasion in Hungary	Udvardy (1999)
			Possible control measures	Bolla (2012)
			Data on arthropod species that graze on invasive plants	Ripka (2005)
			Allelopathic effect	Csiszar (2009)
			Isolation of phytosterols	Ansari and Ali (2003)
Ireland	No		Assessed as a medium impact species	O'Flynn et al. (2014)
Italy	Yes	DAISIE (2014) EPPO (2013)	Introduction, threat, and possible uses	Badalamenti et al. (2012)
			Invasive species review and distribution	Celesti-Grapow et al. (2010)
			Control methods	Addario (2007); Giunti et al. (2010)
			Damage to infrastructure and archeological remains	Celesti-Grapow and Blasi (2004)

Table 1 continued

	Declared invasive (yes or no)	Documents declaring invasiveness	Research type (thematic)	Authors
			Herbicidal and insecticidal properties	DeFeo et al. (2003, 2009)
				Pedersini et al. (2011)
			Allergenic effect	Maxia and Maxia (2003); (Ballero et al. 2003)
			Risk assessment	Casella and Vurro (2013)
			Tolerance to pollution	Gatti (2008)
				Gravano et al. (2003)
			Drought resistance	Trifilò et al. (2004)
			Effect on landscape quality	Appiani (2005)
			Eradication	Mazzoleni et al. (2010)
			Origin and development of root suckers	Inverso and Bellani (1991)
			Comparison of the urban flora of different phytoclimatic regions	Celesti-Grapow and Blasi (1998)
Poland	Yes	IOP PAN (2009)	Distribution	Bąbelewski and Czekalski (2005)
		DAISIE (2014)		
Portugal	Yes	Invasoras (2013)	Increasing public awareness	Marchante et al. (2010)
		DAISIE (2014)		
		EPPO (2013)		
			Invasive species identification guide	Marchante et al. (2008, 2014)
			Potential as an alternate fiber source	Baptista et al. (2014)
			An overview of invasive plant species in Portugal	Marchante et al. (2005)
Romania and Moldavia	Yes	DAISIE (2014)	Plant communities dominated by *A. altissima*	Sîrbu and Oprea (2011)
		EPPO (2013)		
			Mentioned as invasive in agricultural crops	Niculescu and Cismaru (2013)
			Invasive alien plants in Romanian areas	Anastasiu and Nagrean (2005); Anastasiu et al. (2007); Niculescu et al. (2011); Nicolescu and Cismaru (2013)
Serbia and Montenegro	Yes	BioRas (2014)	General features and distribution	Nestorović and Jovanović (2003); Savić et al. (2012)
		EPPO (2013)		Glišić et al. (2014)
			Effects of nitrogen forms on growth	Đukić et al. (2012)
			Occurrence and control by autochthonous insects	Petrović et al. (2013)
			Invasive plants lists	Vasić (2006); Stešević (2006); Stešević and Petrović (2010)

Table 1 continued

	Declared invasive (yes or no)	Documents declaring invasiveness	Research type (thematic)	Authors
Slovakia	Yes	SAŽP (2003)	General review and possible management methods	Eliáš (2008, 2009)
			Study of leaf litter decomposition in alien and native species	Halabuk and Gerhátová (2011)
			Invasive woody plant species occurrence in a botanical garden	Kelbel (2012)
			Inventory of alien flora	Medvecká et al. (2012)
Slovenia	Yes	ARSO (2010) DAISIE (2014)	Distribution in Goriška region	Arnšek (2009)
			General review	Bačič (2008)
			Non-native and invasive tree species of Slovenian forests	Kutnar and Pišek (2013)
Spain	Yes	MAGRAMA (2013) DAISIE (2014) EPPO (2013)	Ecology and control	Constá -Nava et al. (2010), Constán-Nava (2013)
			Atlas of invasive plants	Sanz-Elorza et al. (2004)
			Invasive species in the Balearic islands	Moragues and Larrucea (2005); Forteza and Mayol (2005)
			Effects of fire on regeneration rate and distribution	Meggaro and Vilà (2002)
			Assessment of invasive potential	Constán-Nava and Bonet (2012)
			Dispersal and establishment	Delgado et al. (2009)
			Effects on soil properties	Castro-Diez et al. (2008, 2009)
			Occurrence in urban forests	Sobrino Vesperinas et al. (2011)
			Impact assessment	González-Muñoz et al. (2013)
			Invasive species in Mediterranean islands	Hulme (2004)
			Impact of invasive alien species on Mediterranean islands ecosystems	Vilá et al. (Vilà et al. 2006, 2008)
Switzerland	Yes	FOEN (2006) EPPO (2008)	Distribution and invasive potential	Arnaboldi et al. (2002)
			Afterfire spread of alien species	Maringer et al. (2012)
			Anatomical and auxometric features	Arnaboldi et al. (2003)
			Inventory of alien species	Wittenberg (2005)
			Proposed substitutes for invasive alien plants	Gigon (2007)
Ukraine	Yes	DAISIE (2014) EPPO (2013)	Distribution	Fedorenko and Pylypenko (2012)
			Occurrence	Bagrikova (2010); Volutsa (2010); Fedorenko and Pylypenko (2012)

Table 1 continued

	Declared invasive (yes or no)	Documents declaring invasiveness	Research type (thematic)	Authors
USA	Yes	NISIC USDA (2014)	Ecological impact of allelopathy	Lawrence et al. (1991)
			Establishment in forests	Knapp and Canham (2000);
			Effects of diseases	Schall and Davis (2009)
			Invasive plants guide	Kaufmann and Kaufmann (2007)
			Manual of vascular plants of NE US and Canada	Gleason and Cronquist (1991)
			Control	Pannill (1995)
			Invasive plants handbook	Randall and Marinelli (1996)
			General features and distribution	Fryer (2010)
			Herbicidal effects of extracts	Heisey (1990a, 1990b, 1996, 1997); Heisey and Heisey (2003)
			Description	Miller (1990); Howard (2004)
			Dispersal, establishment, and growth	Kota (2005)
			Identification of ailanthone in the tissues	Lin et al. (1995)

biodiversity is important for preserving ecosystem functions and services (Loreau et al. 2006; Díaz et al. 2006), invasive species as new biological components scale up the number of species present in the ecosystem.

In a wide range of terrestrial, marine, and freshwater ecosystems, accidental or voluntary introduction of non-native species by humans has altered local biological community interactions, triggering dramatic and often unexpected changes in ecosystem processes and causing large monetary and cultural losses (Millennium Ecosystem Assessment 2005). The experiences of such assessment have shown that it is hard to demonstrate, quantitatively and unequivocally, the link between ecosystem changes and changes in human well-being.

Invasive alien species have generally caused degradation of the services; they have a major impact on the environment, and are threatening biodiversity and reducing overall species abundance and diversity (van Wilgen et al. 2007). On the other hand, some invasive species can provide services useful to human well-being. In some systems, multiple services occur; examples of such systems are arid parts of the world, coastal systems, urbanized coasts, tropical forests, and also cultivated lands, some of these highly transformed and managed by humans for the purpose of providing food and fiber, often at the expense of other ecosystem services.

Invasive alien species influence can be analyzed through the assessment of ecosystem services loss as well as through their impact on animal health, crop and pasture production, etc. (van Wilgen et al. 2008; Dickie et al. 2014). In the present paper, the available records on *A. altissima* are viewed as the relationship between service loss and new services acquired due to its presence (Tables 2, 3).

Ailanthus altissima as a highly invasive species compromises the biodiversity, particularly in natural habitats and protected areas with rich biodiversity (Meloche and Murphy 2006; Hulme et al. 2008; Casella 2011; Casella and Vurro 2013). When present in neglected areas of cities with already limited and compromised biodiversity, its negative effects are less expressed. On the other hand, *A. altissima* provides a number of ecosystem services. We summarized all services with available data independently of their economic effect (Table 2) and negative effects caused by *A. altissima* (Table 3). *A. altissima* can affect ecosystem services in three categories (provisioning, regulating, cultural and supporting). So far there is no economic rigorous assessment of *A. altissima* presence consequences. Isolated studies have been done, i.e., authors Luz-Leczano Caceres and Gerold (2009) have calculated for the state of Hesse (Germany) that uncontrolled damages by *A. altissima* are 5 Million €/year and have compared several control strategy methods.

Table 2 Ecosystem services, as defined by the Millennium Ecosystem Assessment (2005), and example of their provision by *Ailanthus altissima*

Category	Example service provided by *A. ailanthus*	Citations
Provisioning	Medicinal	De Carnieri and Casinovi (1968), Hu (1979), Okunade et al. (2003), Tamura et al. (2003), Chang and Woo (2003), De Feo et al. (2005), Gambari and Lampronti (2006), Kowarik and Säumel (2007), Caboni et al. (2012)
	Agriculture pharmaceutical use	Heisey (1990a, 1996), Lawrence et al. (1991), Heisey and Heisey (2003), Pedersini et al. (2011), De Feo et al. (2003), De Feo et al. (2009), Lin et al. (1995), Kožuharova et al. (2014), Albouchi et al. (2013), Tsao et al. (2002), Lü and Shi (2012)
	Honey production	Dalby (2000), Kowarik and Säumel (2007)
	Timber tree	Hu (1979), Gill (2004), VDOF (2009), Brandner and Schickhofer (2010)
	Food for silk worms	Hu (1979), Kowarik and Säumel (2007)
	Fuelwood and charcoal material	Hu (1979), VDOF (2009), Barclay (2013)
	Paper production	Baptista et al. (2014)
	Essential oils source	Cheng et al. (1992)
Regulating	Erosion control	Hegi (1906), Singh et al. (1992), Hu (1979), Howard (2004), Kowarik and Säumel (2007), Zhang (2014)
	Land reclamation	Witte (1952), (Gutte et al. 1987), Zhang (2014), Enescu (2014)
	Reforestation	Udvardy (1998), Kowarik and Säumel (2007), Zhang (2014)
	Shelterbelts	Adamik (1955), Enescu (2014)
Cultural	Ornamental, shade, and privacy	Hu (1979), Lee et al. (1997)
Supporting	Primary production	Kowarik and Säumel (2007)
	Nutrient cycling	Kowarik and Säumel (2007)
	Soil formation	Kowarik and Säumel (2007)

The review of ecosystem provisioning services has shown that *A. altissima* could be a useful species in aiding many contemporary needs of modern civilization (Table 2). Wide usage in the past has proven that successful applications are possible in many areas, today maybe the most important being a source of active compounds and environmental restoration for which it was highly valued in its native area throughout history (Hu 1979). The most relevant services of *A. altissima* are described in the following sections. For its original purpose, as an ornamental species in urban environments, it was introduced due to its resistance to pollution and herbivory of native insects and has replaced other, more susceptible, species used at the time (*Tilia* sp.).

The negative sides of *A. altissima* utilization, known through the consequences of its past usage, must, however, be taken into account. Uncontrollable seed dispersal and vegetative propagation have caused its diffusion in the environment in the past, and have consequentially caused its utilization to be abandoned. Insufficient or non-existent management has resulted in its wide distribution in urban and suitable natural environments, where it today damages infrastructures in cities, displaces native vegetation, and changes the community structures of invaded areas. In addition, the control efforts, although succesful, can hardly be used to eliminate it entirely from the environment. It must thus be considered that all the potentially positive effects of *A altissima* presence could be outweighed by the efforts and costs of the necessary management actions if the tree spreads and densifies excessively.

Medicinal Effect

Plants are among the main sources of biologically active chemicals. It has been estimated that about 50 % of the prescription products in Europe and USA originate from natural products or their derivates (Kožuharova et al. 2014). Despite the domination of synthetic chemistry as a method to discover and produce drugs, the potential of bioactive plants or their extracts to provide new and novel products for disease treatment and prevention is still enormous. In fact, over the past decades herbal medicine has become an item of major importance. Various plants have been screened for active ingredients (Kožuharova et al. 2014). Besides the fact that plant chemicals are used as models in the pharmaceutical industry, there is a renaissance in demand for wild plants, which can be used for food and medicine (Portraits 2014). Wild plant collection refers to the collection of medicinal and aromatic plants from their natural habitats. This activity needs to be carried out carefully as it can put pressure on the local resources. In the case of invasive alien plants, this is not an issue and collecting them can even provide income, especially for vulnerable groups in rural parts. Local plant

Table 3 *Ailanthus altissima* negative effects

Categories	*A. altissima* mechanisms	Authors
Biodiversity decrease	Ailanthone release—herbicide effect	Mergen (1959), Heisey (1996), Heisey and Heisey (2003)
	Replacement of natural vegetation	Vilà et al. (2006), Constán-Nava et al. (2010), Fotiadis et al. (2011), Motard et al. (2011), Kožuharova et al. (2014)
	Altering soil properties	Castro-Díez et al. (2008, 2009)
Invasive properties	Fast growth	Hu (1979), Knapp and Canham (2000), Kowarik and Säumel (2007)
	High seed production, efficient dispersion by wind and water (rivers), establishment	Bory and Clair-Maczulajtys (1980), Kota (2005), Kowarik and von der Lippe (2006, 2011), Kowarik and Säumel (2007, 2008), Delgado et al. (2009), Säumel and Kowarik (2010, 2013)
	Vegetative reproduction	Bory and Clair-Maczulajtys (1980), Inverso and Bellani (1991), Kowarik (2003), Hunter (2000)
	Tolerance of environmental conditions	Udvardy (1998), Miller (1990), Trifilò et al. (2004), Hildebrand (2006), Kowarik and Säumel (2007), Traveset et al. (2008)
	Resistance to pollution and herbivory	Gravano et al. (2003), Gatti (2008)
	Fast regeneration	Addario (2007), Giunti et al. (2010), Constán-Nava et al. (2010), Constán-Nava (2013), Badalamenti and LaMantia (2014)
	Allelopathic effect	Lawrence et al. (1991), Csiszar (2009)
Human perspective	Bad smell	Mitchell and Rook (1979), Shah (1997)
	Allergen	Mitchell and Rook (1979), Maxia and Maxia (2003), Ballero et al. (2003), Derrick and Darley (1994), Burrows and Tyrl (2013)
	Can cause dermatitis	
	Rarely causes myocarditis	
	Toxic	Mitchell and Rook (1979), Perry (1980)
	Damaging infrastructure and archeological remains	Celesti-Grapow et al. (2004), Luz-Lezcano Caceres and Gerold (2009)

resources usage by human groups is crucial for ensuring sustainable ecosystem development (Pardo de Santayana and Macía 2015). For example, authors Quave and Pieroni (2015) suggest that wild plants have a crucial role for communities in rural area of Albania and its collection contributes to biodiversity conservation. Pharmacological use of *Ailanthus altissima* is mentioned in early Chinese writings (Howard 2004). Several uses of plant parts or extracts exist: fresh stem bark to treat diarrhea and dysentery; root bark for heat ailments, epilepsy, and asthma; fruits as an emmenagogue and to treat ophthalmic diseases; and leaves as astringents and used in lotions in seborrhea and scabies treatments (Kowarik and Säumel 2007).

Laboratory studies show that *A. altissima* has a potential role in modern medicine (Howard 2004). In fact, *A. altissima* has been the subject of numerous studies, and its bioactive compounds, as well as pharmacological effects, have been widely studied (Kožuharova et al. 2014). Numerous studies have been performed screening compounds with antiproliferative and cytotoxic and antiviral activity (Kožuharova et al. 2014).

Investigations exhibit the presence of several and interesting compounds such as alkaloids, terpenoids, quassinoids, steroids, flavonoids, and volatile oil among others; among these compounds, alkaloids, terpenoids, and aliphatic compounds are common major constituents of *A. altissima* (Kožuharova et al. 2014). Moreover, Okunade et al. (2003) reported that extracts and isolated compounds from seedlings of *A. altissima* were assessed for antiplasmodial activity in vitro. Two quassinoids, ailanthone, and 6-alpha-tigloyloxychaparrinone, isolated from the active extracts, showed activity against both chloroquine-resistant and chloroquine-sensitive strains of *Plasmodium falciparum* in vitro. This was the first report of the isolation and antiplasmodial activity of 6-alpha-tigloyloxychaparrinone from this species (Okunade et al. 2003).

Finally, researchers think that chemicals in the bark of the tree of heaven may have drying effects, decrease fever, or decrease spasms and that other chemicals found in the tree of heaven might kill worms and parasites and have some effects against cancer cells (WebMD 2006).

Herbicide Effect

Nowadays, the development of new herbicides that are less harmful to the environment, safer for workers and consumers, and active at lower rates of application is an important research goal. Moreover, compounds from plants and microorganisms are a logical source to investigate for new herbicides (Heisey and Heisey 2003). In recent years, big efforts have been made to find more environmentally friendly and naturally occurring bioactive compounds for potential development in weed-control programs in agriculture and environment management (Pedersini et al. 2011). However, even if much interest exists in using products to control weeds in agroecosystems, few products have actually been developed into commercial herbicides (Cutler and Cutler 1999).

Ailanthus altissima contains a very powerful herbicidal compound, ailanthone, which can compete with synthetic herbicides (Heisey 1996, 1997). The herbicidal effects of *A. altissima* tissue extracts have been extensively researched, and while the obtained results on the intensity of these effects show potential for future applications, several obstacles were also identified, such as low-selectiveness and fast degradation by soil microorganisms. These obstacles, if eliminated or modified in the future, would make *A. altissima* a good source plant for environmentally friendly herbicides.

The allopathic effect of *A. altissima* was first proposed by Mergen (1959) who reported a toxic effect of foliage and stem water extracts on other plant species. Only one of 46 tested species (*Fraxinus americana* L.) showed no reaction to the extracts. To date, this toxicity has been proven to affect many other plants, including weed, crops, and trees, through preemergence and postemergence treatments (Mergen 1959; Heisey 1990a, 1996; Pedersini et al. 2011; Lin et al. 1995). In the preemergence treatments, all species were reduced in germination and growth at the highest doses of extracts application, but dicots tended to be more sensitive than monocots (all dicots were significantly reduced in shoot biomass and seedling emergence with the lowest applied dose), while with the postemergence treatment, herbicidal effects were even more evident, causing damage, inhibiting growth or killing the plant (Heisey 1996). Thus, as the lowest applied dose in the cited study had a significant damaging effect, the minimal effective dose to spray is yet to be determined. The effects of inhibitions differ according to the parameters taken into account. For example, while the inhibition of seed germination exhibits a linear relationship with toxin concentration, the inhibition of radicle growth is more properly described by non-linear functions. These results suggest that either a single compound exhibits more than one mode of action, or multiple compounds are responsible for *A. altissima* inhibitory effects (Lawrence et al. 1991).

In contrast to all the other species tested, *A. altissima* seedlings did not exhibit any detectable injury from postemergence applications of ailanthone (Heisey 1996), indicating the presence of a protective mechanism in the producer species to prevent autotoxicity. The lack of autotoxicity is not surprising when viewed in the light of evolution. However, the mechanism by which *A. altissima* avoids autotoxicity is unknown. Attachment of acyl, glucosyl, or other groups to ailanthone and its subsequent compartmentalization in vacuoles is a likely possibility (Heisey 1996).

Ailanthone is shown to be very biodegradable, with its toxicity persisting 3–5 days, as demonstrated by Heisey (1996). Short persistence may be advantageous from the standpoint of safety to humans and the environment, but it can limit herbicidal efficacy (Cutler and Cutler 1999). Sasnow (2012) has studied the mechanisms for ailanthone decomposition and isolated the soil bacteria responsible for the breakdown of ailanthone. Although some investigations demonstrated that ailanthone shows herbicidal and insecticidal properties, its toxicity seems to be too high for such applications. Its toxicity is in the same order of magnitude as that of the approved synthetic herbicidal molecules. However, it is much more toxic than a classic weed-killer on the white mouse (Collin and Dumas 2009). Lawrence et al. (1991) quoted several modes of transmission of toxins from *A. altissima* to neighboring individuals (leaching from leaves, decaying of root material, release from roots and shoots into the soil). Moreover, in 1996, Heisey indicated that the release of ailanthone from roots, branches, and trunks of *A. altissima* appears to be the most likely source of input since ailanthone concentrations are highest in the bark of these tissues. Their investigations demonstrated that the uptake of *A. altissima* toxins by neighboring species takes place through the soil (Lawrence et al. 1991). The data suggest that when *A. altissima* toxins are incorporated in a neighboring species, they will exist in an active state following uptake and are possibly sequestered in the recipient plant's tissues (Lawrence et al. 1991).

Heisey (1996) demonstrated that ailanthone is most soluble in polar solvents such as water and methanol and has lower solubility in non-polar solvents such as hexane. Little is known about the production, storage, or movement of the ailanthone in the *A. altissima* tree, but its water solubility suggests ailanthone could be readily translocated (Heisey 1996). Additionally, we have to consider that most of allelochemicals indicate a poor performance under field conditions compared to laboratory conditions. Moreover, many allelochemicals exhibit rapid dissipation under natural conditions and thus fail to give the desired results (Mohammadi 2013). Regarding the production of inhibitory compounds, they are located in, and presumably were produced by, the vegetative tissues of young *A. altissima* plants (Lawrence et al. 1991). However, investigations would have to be done in the future in order to determine where exactly these chemicals are produced (Gustafson 2010). In addition to influencing the spatial distribution of plant species, allelochemicals may provide an environmental stress that contributes to genetic change within associated plant populations (Lawrence et al. 1991). Quite apart from the existence of an allelopathic interaction, questions remain regarding not only the origin and the maintenance of the allelochemical system, but also the mechanism of the transmission (Gustafson 2010; Lawrence et al. 1991).

At the moment, the use of *A. altissima* extracts as herbicides is not possible on a commercial scale, in the largest part due to non-selectivity, as it is shown to damage useful plants such as crops. Fast biodegradability would also require repeated applications which are not practical in larger productions. Prior to the application of ailanthone as a herbicide, these matters would have to be resolved by further studies.

Insecticide Effect

The interest carried by the consumers in food quality and the lightning development of organic farming caused a lot of scientists to take an interest in the recognition of natural agents which could play a role in the fight against crop parasites. In 1998, Pachlatko stated that, in the future, many more new natural products useful for crop protection will be identified from diverse natural sources and that it is likely that biotechnology will significantly expand its influence on crop protection. This was a good prediction; nowadays, organic and synthetic pesticides are essential for agricultural and forestry management systems, but these chemicals have important drawbacks, such as toxicity, in particular for human health and environmental impact (Pedersini et al. 2011).

Sustainable agriculture in the 21st century will rely increasingly on alternative interventions for pest management. Botanical pesticides are of increasing interest today, due to the problems related to the negative effects of conventional pesticides on the environment and the beneficial fauna (De Feo et al. 2009). A review of sublethal effects, taking into account recent data, has revealed new insights into the effects of pesticides, including influences on learning performance, behavior, and neurophysiology (Desneux et al. 2007). In addition, some biological measures can actually prevent economic damage to agricultural crops, because unlike most insecticides, biological ones are often very specific. There is less danger of impact on the environment and water quality and they offer a more environmentally friendly alternative to chemical insecticides (Moazami 2002). Moreover, novel, environmentally compatible, pest control agents are needed in order to replace pesticides that have been withdrawn for economic or regulatory reasons (De Feo et al. 2009) bearing in mind that botanicals can be just as toxic as synthetic pesticides. Botanical pesticides could also be used where pests have developed resistance to conventional pesticides (Moazami 2002). Birds are particularly vulnerable to losses in invertebrate populations due to the use of insecticides and herbicides (Hooper et al. 2003). Especially important are those insecticides and herbicides that are persistent organic pollutants, since they have effects on large spatial and temporal scales. Many of the more persistent chemicals are being phased out and replaced by others with much lower toxicity that is less persistent.

Ailanthus altissima is also studied as a source of insecticidal compounds (Tsao et al. 2002; De Feo et al. 2009). Plant secondary metabolites play an important role in plant–insect interactions and therefore such compounds may have insecticidal, hormonal, and antifeedant activities against insects (De Feo et al. 2009). From an ecological perspective, such compounds can be considered as chemical weapons to ward off predators and competitors for limited resources and contribute to explaining the ecological impact of *A. altissima* in ecosystems (De Feo et al. 2009). *A. altissima* presents a strong resistance to herbivores (insects), due to the chemical composition of its tissues.

On the other hand, *A. altissima* attracts insects thanks to its flowers and extrafloral nectaries. In fact, the strong smell emitted by numerous flowers attracts bees, beetles, and other insects which pollinate them (FCBN 2012). However, it appears that its tissue is tolerated by certain snails, non-specialized herbivores, for example, *Cepaea hortensis*, the garden snail (FCBN 2012). Nevertheless, these predators do not cause sufficient damage to stop the propagation of *A. altissima*. Rodents do not seem to have an effect on the survival of the seeds of *A. altissima* (FCBN 2012).

Finally, Tsao et al. (2002) reported that the insecticidal activity of *A. altissima* extracts were much less significant than the effect against the growth of plants.

Use of Wood

Ailanthus altissima wood has been used as a fuelwood, in charcoal and timber production (Gill 2004), as it is reported to make a satisfactory material (VDOF 2009; Barclay 2013). The wood is more frequently used in poorer countries, although it is suitable for carpentry and paper production (VDOF 2009; Baptista et al. 2014). In the late 1800s, *A. altissima* was used in afforestation for wood material in some states of the USA and its use was advocated by experts at the time due to the tree's hardiness, rapidity of growth, resistance to smoke, drought, and dust, and tolerance to low-quality soil (Hu 1979). These reports state *A. altissima* wood makes a high-quality firewood, comparable to white oak, black walnut, and birch, and an adequate carpentry material, due to its strength and durability comparable to ash or chestnut. The quality of wood refers to older trees, while the wood of younger, fast growing trees is brittle and easily split. The wood was reported to be usable for cabinet work, musical instruments, woodware, and charcoal. The pulpwood of *A. altissima* was reported to be superior to the species used at the time for the purpose. It was emphasized that the trees for wood exploitation should be harvested before the age of 30, because in older trees the wood begins to deteriorate (Hu 1979). Recent evaluation of *A. altissima* wood quality for the production of wood products reached similar conclusions (VDOF 2009). It was reported to be comparable to commonly used species although with some flaws, such as high moisture content, corky pith, and crooked growth, overcomable by customizing processing methods.

A. altissima pulpwood produces paper with properties comparable to those of *Eucalyptus globulus*, the most common species used for the purpose in temperate regions. The importance of alternative fiber sources is in the increased demand for paper, expected to increase to 521 million tons per year by the year 2021 (Baptista et al. 2014). Due to its fast growth and tolerance of poor soil, drought, and pollution, the utilization of *A. altissima* in paper production would reclaim degraded environments and at the same time aid the conservation of native forests.

The evaluation of possible utilization of different *A. altissima* products and especially of wood was made due to the necessity of reducing eradication costs by marketing harvested trees (VDOF 2009) in such a way making its eradication economically more viable.

Environmental Rehabilitation

Fast growth and low environmental requirements have made *Ailanthus altissima* an ideal species for planting in polluted and degraded environments with the aim of forest restoration, land reclamation, and shelterbelts planting, such as today in China, and worldwide in the past (Chokkalingam et al. 2006). High demand for wood products has caused the overexploitation of forests through centuries. In addition, the possible use of its wood allows the afforestation for timber and pulp production in degraded areas, where the establishment of conventional timber and pulp trees would be difficult. Due to the population growth and an increasing demand and exploitation of natural resources such as food, arable land is reaching its limit, presenting the need for reclamation of degraded lands unable to support growth of most crops and trees (Zhang 2014). In the case of China, where extensive reforestation in the past has caused large areas to be heavily affected by drought (Zhang 2014) and unable to support vegetation, *A. altissima* is being used in reclamation with the aim of reducing evaporation and soil salinity, erosion control, and restoration of forest microclimates. *A. altissima* could be used in such areas in environmental rehabilitation elsewhere, to reclaim polluted lands, stabilize soil in lands prone to erosion, and those adjacent to infrastructure. In addition, degraded environments could be in such ways exploited in obtaining wood resources and possibly plant tissue as a source of active compounds for medicinal and agricultural researches and applications. Considering the extent and rate of environmental degradation induced by the population growth and consumerism, such low requirement species could be of greater importance in the future. *A. altissima* was one of the species planted in the Yellow River delta region in China, where the soil has high levels of salinity due to drought. The environment of the region is additionally highly degraded due to oil exploitation (1960–1990s). Vegetation coverage is low (≈35 %) with halophyte species growing sparsely, which causes frequent erosion and high evaporation. *A. altissima* is reported to tolerate soil salinity of 0.3–0.4 %, high proline content, high ratio of bound to free water, and relative conductivity, indicators of high salinity and stress tolerance, enabling its applications in such high salinity and environmentally degraded areas. It was planted to reduce the evaporation rate and prevent erosion in the area.

It was also used in reclamation of landfill sites and revegetation of acid mine spoils in the USA due to its high tolerance to low soil pH values (Witte 1952; Plass 1975; Gutte et al. 1987).

In reforestation efforts, it was also used in Europe, the Middle East, South America, and New Zealand (Kowarik and Säumel 2007). Tree planting around agricultural fields can increase crop production by reducing evaporation and producing litter that increases soil fertility. Planting as windbreakers can reduce wind speed up to 50 %, prevent erosion, and soil evaporation which is shown to increase crop yield by up to 25 %. *A. altissima* was reported to be one of the best species for planting as shelterbelts in Macedonia (Jovković 1950), while it was also extensively planted for the purpose since the 1950s in the Soviet Union, Austria, Hungary, and Romania. It was planted for erosion control on slopes or edges of traffic lanes, and on dunes of the coast of the Black sea (Kowarik and Säumel 2007).

Other Uses

In its native area, and later in its secondary distribution area, *Ailanthus altissima* has been used also as a food for silk producing caterpillars. It also makes a good source of food for honey bees and the honey is reported to be tasty although initially bad smelling (Hu 1979; Dalby 2000; Kowarik and Säumel 2007).

Leaves can be used in yellow dye production (Chiej 1984) and are edible when cooked although due to their bad smell and toxicity are only known to be eaten in times of scarcity (Tanaka 1976). Seeds are rich in proteins and fatty oils, the latter of which can be used after refining as they are initially bitter tasting (Cheng et al. 1992; CABI 2014).

Effects on the Environment and Impact on Human Health

Biological and ecological properties make *Ailanthus altissima* a highly competitive species, capable of establishing itself in a wide variety of environmental conditions. Due to its high production of viable seeds and lateral shoot growth, it is capable of dispersing and establishing new seedlings at a long distance from the mother plant.

Studies of *A. altissima* effects on natural environments are scarce although it is believed to suppress native populations in favorable conditions, such as in Mediterranean areas. Mediterranean areas, with typical Mediterranean vegetation of maquis and garigue, together with grasslands, shrublands, riparian, and disturbed forests, mesic and xeric woodlands of meridional and submeridional zones seem to be the areas of the highest risk for *A. altissima* invasion. As its establishment is limited by shade, these areas of low level or scarce vegetation, in addition to canopy gaps in forests, are easily invaded. In the case of invaded plots on Mediterranean islands, where *A. altissima* forms almost pure stands, it is shown that it has a negative impact on biodiversity, somewhat decreasing species richness (23.8 ± 3.1 %), with the highest impact on therophyte species (Vilà et al. 2006). In addition, *A. altissima* plots induced changes in soil chemical and physical properties, increasing pH and significantly decreasing C/N ratio. This can present an additional mode of changing species composition, apart from direct competition. In Traveset et al. (2008), a survey of invasive species performance among Mediterranean islands, *A. altissima's* wide tolerance of different habitat types was confirmed, which makes it a high risk species for areas not yet invaded. A study of the distribution outside urban areas in France and West Virginia showed the highest abundancy along roadsides, railroads, or watercourses, while in forests the occurrence was relatively small (5–6 %) (Kowarik and Säumel 2007). Even in environments with no anthropogenic structures, such as the forests of central Spain, the invaded native vegetation was reduced by extensive reforestations in the past or by diseases (Castro-Díez et al. 2009). In Central Spain, *A. altissima* is reported to be naturalized, and growing side by side with *Ulmus minor*, a formerly dominant tree for this area, whose populations have been reduced by vascular wilt disease. In a comparative study of litter decomposition of these species, *A. altissima* litter was shown to decompose faster and release more N per unit of litter mass (Castro-Díez et al. 2009). Higher rates of litter decomposition than in native species may be a way of enriching the soil with nutrients. In Greece, in areas of humid Mediterranean climate, *A. altissima* was found in natural environments in the largest numbers in shrubland, followed by grasslands and forests. A comparative study of the floristic diversity in communities dominated by *A. altissima* and native *Quercus cocciferal/Q. pubescents* showed an increase in diversity in stands dominated by *A. altissima*, contrary to formerly cited observations. This can be explained if it is taken into account that the whole community structure was changed, with species inhabiting native *Quercus* vegetation being less frequent, while the observed high diversity was in the largest part accomplished by synanthropic and opportunistic species, characteristic for disturbed habitats. Overall, the highest abundance of *A. altissima* trees was found in urban habitats, especially in abandoned areas, road edges, and alleys, up to 100 m in altitude. In non-urban areas, most highly populated were agricultural fields, road edges, and wetlands, where it was observed also in association with *Platanus orientalis* and *Salix alba* (Fotiadis et al. 2011).

In forests and riverbanks, it has also been reported along the Danube (Drescher and Lieβ 2006) and rivers and streams in Switzerland, France, the Mediterranean, and North America (Rio Grande, California, the Eastern seaboard) (Kowarik and Säumel 2007). The impact of *A. altissima* on vegetation structure was also assessed in Fontainebleau forest near Paris with oceanic, continental, nordic, and mediterranean climatic influences (Motard et al. 2011). It was found that the species richness in the understory vegetation was significantly lower under *A. altissima* trees in comparison to native tree species (168–193 species); species composition was different, with common plant species being more frequent and the number of root suckers was negatively correlated with species richness. Weber and Gut (2004) made a risk assessment for *A. altissima* in Central Europe and determined it was a species with a high risk of invasion for this area. In Bulgaria, several studies have observed different impacts of *A. altissima* on the environment, such as the replacement of natural pastures and grassland by bushes and dense low forests of *A. altissima*, leading to the elimination of grassland flora. This most often occurs by replacement of grasslands with agricultural lands, and their subsequent abandonment, creating the ideal environment for the spread of *A. altissima* which later prevents the recolonization of native flora (Kožuharova et al. 2014). Such effect of *A. altissima* colonization presents the highest risk for endemic, endangered, and rare species of these habitats and is also observed to occur in natural reserves (Grozeva 2005; Vladimirov 2013; Uzunov et al. 2012). Additionally, the deterioration of native grassland flora negatively impacts the associated species, especially herbivorous insects such as butterflies (Abadjiev and Beshkov 2007). Other habitats endangered by *A. altissima* (and other ruderal and invasive species) in Bulgaria are loess cliffs and soils, specific substrates inhabited by specific mosses, which have been observed to structurally deteriorate under the presence of such disturbance.

In North America *A. altissima* is reported in hemlock, oak-hickory, and maple-birch forests, affected by anthropogenic disturbances (Miller 1990) causing gap openings, thus enabling its colonization. Gap openings may also be of natural origin, such as storms or herbivory on native species (Kowarik and Säumel 2007). In North American temperate forests, the presence of *A. altissima* and *Acer platanoides* is also shown to affect soil properties and processes by increasing nutrient availability and cycling rates. It is proposed that their presence may in such a way change the community structures in forests by favoring the species more competitive on fertile soil (Gómez-Aparicio and Canham 2008).

Data on the effect of *A. altissima* colonization on the faunal communities are scarce, although the displacement of native vegetation and changes in the physicochemical parameters of soil should induce a change in species composition of associated groups. Several studies have shown that plant cover influences the soil community of microorganisms, mycorrhizal fungi, and invertebrates, such as nematodes, arthropods, and earthworms (Das and Joy 2009; Cesarz et al. 2007; Jonsson et al. 2006). The decreased diversity of Collembola was observed in exotic forests in Portugal compared to the native ones (Arbea and Jordana 1988; Sousa et al. 1997), while these changes were attributed to altered physicochemical properties of litter, and consequentially soil (Pinto et al. 1997).

The effect of *A. altissima* on riparian forests soil microarthropod community was performed on Henares river bank (Madrid, Spain). The study showed the preference of some groups to soil under *A. altissima*, in comparison to native *Populus nigra*. The arthropod community was changed by an increased abundance of Actinedida mites under *A. altissima*, and decreased abundance of some groups of springtails, mites, spiders, pseudoscorpionidas, isopods, and insects (Gutiérrez-López et al. 2014).

Ecosystem changes induced by the spread of *A. altissima* are also accomplished by aiding other invasive species such as planthopper *Metcalfa pruinosa* and butterfly *Hyphantria cunea* native to North America. They were introduced in Europe and rapidly spread and today are classified as pests in many European countries (CABI 2014). *A. altissima* serves as one of their hosts for eggs deposition and food source, in both species in the top 10 most frequent hosts (Kožuharova et al. 2014).

Although it possesses many features giving it a competitive advantage over other plant species, outside of the Mediterranean, *A. altissima* is mostly confined to urban areas. Here, where most of the native species are eliminated by the pollution and lack of growable surface, *A. altissima* thrives due to its low environmental requirements and a tolerance to air and soil pollution. Although built-up areas are of low conservational value, a high abundance of individuals in cities can create problems by obstructing the view of drivers, breaking asphalt surfaces, entering walls and sewers, and damaging archeological remains with its wide extending roots.

It can also have effects on human health, causing allergic reactions, dermatitis, and in a few cases myocarditis (Kowarik and Säumel 2007). In a study conducted in Sardinia, out of 54 patients with allergy symptoms, 10 were found to have been caused by *A. altissima* pollen. It is reported to significantly attribute to allergic reactions due to production of pollen in large quantities (Ballero et al. 2003). In some cases, contact with sap can cause dermatitis (Derrick and Darley 1994), while there are rare reports of myocarditis in cases of sap entering the body through cuts or abrasions (Bisognano et al. 2005). The latter two effects may occur during close contact with tree tissues such as during cutting or felling the tree.

The eradication methods of cutting the trees are often not efficient due to its high regenerative capacity and extremely fast stump shoot growth, increasing maintenance requirements and costs. Even repeated cutting showed no significant reduction in the resprouting rate (Constán-Nava et al. 2010). Other eradication methods include chemical control, biocontrol, burning, and grazing (Kowarik and Säumel 2007). Burning and grazing could be applied to areas outside of cities, although this method can only be used for controlling the population to some extent. Biocontrol by natural pests is one of the most promising control measures of alien invasive plants both from the efficiency and economic points of view, but are currently under-funded (van Wilgen and De Lange 2011). The only way to effectively control *A. altissima* is the application of herbicides after mechanical treatment, as has been shown in several studies (Constán-Nava et al. 2010; Badalamenti and LaMantia 2013). Badalamenti and LaMantia (2013) showed that the application of herbicide glyphosate in a drilled hole in the trunk has killed 90 % of treated trees within 1 month. Similar results were achieved in Constán-Nava et al. (2010), where the application of glyphosate on cut stump surface significantly reduced resprouting. The growth reduction was sufficient to allow the initiation of natural vegetation recovery, which was observed 5 years later.

Conclusions

It has been well documented that invasion by non-native species represents one of the greatest threats to biodiversity worldwide. Biotic invasions can cause an ecosystem to become homogenized and can decrease regional diversity (Fotiadis et al. 2011). Ecosystems everywhere are subject to disturbance, fragmentation, and invasion by alien species that are driving them outside of their historical ranges of variability and thus they become 'novel ecosystems.' Nowadays, it is very difficult to prevent biological material from traveling and also to stop already present non-native species from spreading. This means that we must cope with the consequences of new components in ecosystems, find models to re-establish the ecological balance, and the positive aspects of invasive trees for some ecosystem services have to be weighed against the loss of other ecosystem services.

There are dichotomous views of whether, when, and how invasive tree species should be removed or used. This review shows how complex is the interaction between possible use of *Ailanthus altissima* and its products, and the negative effects on the environment and human well-being. Invasive tree *A. altissima,* due to its environmental comparative advantages, compromises biodiversity in natural habitats but on the other hand provides a number of human-related services. Habitat-specific studies are needed in order to adopt goal-specific measures for the use and management of *A. altissima*. In environments altered by human activities, *A. altissima* does not present any major threat and its invasive properties are outweighed by its potential services, while in natural ecosystems, protected and isolated areas such as islands, it compromises ecological stability, and it must be removed or at least kept under control by management measures. Considering the number of its potential uses and services, the applications of *A. altissima* would be possible if some precautionary measures could be applied to reduce the risk for its dispersal in the surrounding environments. This review showed several limitations of the tree, such as an inability for its establishment in areas with cold climates and a sensitivity to shade, which could be used in the prevention of its dispersal. The utilization of the tree should be thus restricted to areas unsuitable for its natural establishment and kept outside high risk environments and climate zones.

Despite the gaps in knowledge on *A. altissima*, enough is known to indicate the need for

- Systematic acquisition of datasets on distribution estimates according to internationally agreed methodology as well as the development of techniques to estimate the rate at which *A. altissima* will spread;
- Urgent collective action in the form of the establishment of the European countries' national databases on *A. altissima*;
- Considering its multiple use of ailanthone containing derivate (medicinal, herbicidal, insecticidal), more studies should be performed on the practical application protocols and industrial production of ecological products;
- Considering its high ecological tolerance, a possible use in environmental rehabilitation must be studied thoroughly; and
- Finally, a thorough economic assessment of *A. altissima* impact in countries where it is present must be done in order to adopt sustainable management practices.

The high ecological tolerance and adaptability of *A. altissima* is a subject of many studies on all continents but up to now it has not been applied successfully to develop ecosystem resources. New systematic researches are needed in order to balance its invasive (negative) properties and possible uses in boosting ecosystem services.

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