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Tree Species as Tools for Biomonitoring and Phytoremediation in Urban Environments: A Review with Special Regard to Heavy Metals

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Abstract. Trees play an important role for the improvement of environmental quality in urban areas. The improvement of microclimate, runoff mitigation, carbon storage and sequestration, noise reduction, air purification through removal and fixation of pollutants in leaves, stems, and roots are ecosystem services provided by urban greening. Additionally, the capacity of certain tree species as bioindicator or to take up contaminants has to be taken into account. Presented here is a review that focuses on 9 ornamental tree species commonly planted along urban streets in Central Europe. Their potential role for bioindication and phytoremediation was assessed. Due to physiological and morphological characteristics and to the intrinsic tolerance to several stress factors, some species seem particularly promising as an indicator for the state of the urban environment or to decrease the amount of specific pollutants. It must be pointed out that intrinsic species properties (e.g., tolerance and/or bioindication capacity for a specific contaminant) can help planners create an effective monitoring net in strategic areas of a city or to detect single contaminants representative of a specific human impact. In particular, *Betula pendula* and *Robinia pseudoacacia* can be considered ideal, low-cost candidates for phytoremediation. Due to their high hardiness, pollution tolerance, and their characteristic as pioneer species, both species might additionally be taken into account as biomonitors, or for their foliar trapping capacity. *Tilia cordata* is also suitable for phytoremediation in urban environments due to its foliar trapping capacity that can provide valuable information on airborne pollutants.
Key Words. *Betula pendula*; Bioindicators; Monitoring; Phytoremediation; *Robinia pseudoacacia*; Traffic Emission; Urban Planning; Volatile Organic Compounds.

Urban greening can potentially provide various ecosystem services, like microclimate improvement, runoff mitigation, carbon storage and sequestration, and noise reduction, as well as air purification through removal and fixation of pollutants in leaves, stems, and roots (Yang et al. 2005; Nowak et al. 2006; Buccolieri et al. 2011; Dobbs et al. 2011; Escobedo et al. 2011; Roy et al. 2012; Gómez-Baggethun and Barton 2013; Konijnendijk et al. 2013, Russo et al. 2014; Russo et al. 2016). In particular, trees can reduce air pollutants, both directly, by absorbing gaseous compounds, such as SO_x, NO_x, and O_3 through leaf stomata, as well as indirectly, by decreasing air temperature and lowering the activity of chemical reactions, which produce secondary air pollutants in urban areas (Yang et al. 2005; Georgi and Dimitriou 2010). Furthermore, leaves, bark, and the root system of trees, which are continuously exposed to atmospheric pollutants, such as wet and dry deposition, can trap or uptake, as passive accumulators, contaminants bound both to airborne particulate matter and/or to the soil, therefore becoming suitable for a long-term monitoring (Kardel et al. 2011).

Vehicle traffic mainly contributes to air pollution in urban areas, generating gaseous pollutants, such as nitrogen oxides (NO_x), carbon monoxide (CO), methane (CH_4), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO_2), ammonia (NH_3), and particulate matter (Bell et al. 2011). Particulate matter contains organic compounds, hydrocarbons, acid aerosols, and metals attached or adsorbed to a carbonaceous core (de Kok et al. 2006; Bell et al.

2011). Key pollutants are the so-called traffic-related elements (TREs)—i.e. Cd, Mn, Cu, Mo, As, Sb, Zn, together with Pd, Pt, and Rh, which are regarded as emerging contaminants (Duong and Lee 2011; Fujiwara et al. 2011). Table 1 summarizes the main inorganic marker elements associated with various emission sources or processes (Duong and Lee 2011; Fujiwara et al. 2011; Calvo et al. 2013). TREs can precipitate directly on ground surfaces, or first accumulate in the atmosphere and then deposit on ground surfaces through rainwater transport (Gunawardena et al. 2013). For this reason, the presence of TREs not only in airborne particulate matter, but also in road dust, soils, vegetation, river sediments, and other related matrices, represent a risk factor for human health (Fujiwara et al. 2011 and references therein; Sawidis et al. 2011). The importance of this phenomenon needs to be viewed against the background of a general growth of large cities throughout the world and coupled with increasing vehicular traffic (Amato et al. 2009; Gunawardena et al. 2013).

In such complex environments like urban-industrial areas, it is essential to identify plant species that can be used to assess the status and trends related to human health (Burger 2006) and are also potentially suitable for environmental quality improvement. Bioindication and phytoremediation are applied aspects of the uptake of chemical elements from soil to plants. According to Markert (2008) and Pellegrini et al. (2014), a bioindicator is an organism that contains information on the quality of the environment. In urban and industrial areas, vascular plants have been studied as bioindicators and bioaccumulators of trace elements. Evergreen species were used as a passive sampler and as indicators for airborne trace element in anthropogenic and remote sites. Also, the foliage of common deciduous trees was used for long–term monitoring of trace metal concentrations (Pellegrini et al. 2014 and references therein).

Phytoremediation has emerged as a potential tool to rehabilitate contaminated lands by removing pollutants from the environment or rendering them harmless (Pulford and Watson 2003). It is a "soft" remediation treatment that makes use of the ability of some plant species to accumulate certain elements, including TREs, in amounts exceeding the nutrient requirements of plants (Baker et al. 2000; Gupta et al. 2000). Ornamental tree and shrub species can also provide this ecosystem service in urban-industrial environments. Accordingly, urban planners could prioritize their potential in environmental quality improvement and maintenance, together with their stress tolerance, when selecting trees for urban-industrial areas or heavy-traffic roads. This strategy needs species-specific information, including their bioindication and phytoremediation potential, their biological characteristics, and any potential ecosystem disservices (Pataki et al. 2008; Lyytimäki and Sipilä 2009; Lyytimäki 2014); the latter, for example, might include the reduction of air flow by street trees (Vos et al. 2013; Nowak et al. 2014) or the production of pollen and its interaction with air pollutants (Traidl-Hoffmann et al. 2003).

Therefore, researchers carried out a literature review by focusing on the following information:

1) The general potential of trees for bioindication and phytoremediation in urban environments;

2) the tolerance of selected urban tree species against stress (as a continuous negative impact by biotic or abiotic factors on the plant, which causes damage and/or loss of productivity); and

3) recommendations for urban planners with regard to urban forestry.

The general bioindication and/or phytoremediation potential with regard to heavy metals are outlined first. Secondly, the review focuses on nine tree species that are commonly planted along streets in cities of central Europe, and provide comprehensive information on their role and potential for bioindication and phytoremediation. With this review, researchers provide a comprehensive basis for urban planning and urban forest management, also with regard to the potential role of those tree species in environmental quality improvement.

Phytoremediation with Regard to Heavy Metals: Strategies and Application

The dramatic increase of land surfaces and soils affected by pollution, salinization, and non-sustainable land use (Daily 1995) has led to the study and implementation of various technologies for cleaning contaminated sites. However, conven-

Table 1. Inorganic marker elements associated with various emission sources or processes (modified according to Duong and Lee 2011; Fujiwara et al. 2011; Calvo et al. 2013).

	SO_4^{2-}	NO_3^-	NH^{4+}	Cl^-	Br-	Li	Na	K	Mg	Ca	Sr	Ba	Al	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Mo	Rh	Pd	Cd	Sn	Sb	Pt	Pb
Aerosols/Sea salt	x	x	x	x	x		x		x																						
Crustal/Geological tracers						x	x	x		x	x	x	x					x													
Steel and metal industries													x			x	x			x	x	x	x	x			x	x	x		x
Heavy industries														x	x	x			x	x		x	x						x		
Oil burning	x														x	x	x	x		x			x								
Coal burning													x	x					x				x						x		x
Biomass burning					x			x																							
Waste incineration								x														x							x		x
Automobile gasoline	x	x																												x	
Automobile diesel	x	x																													
Vehicle tailpipe																						x		x	x	x				x	
Tire wear abrasion												x										x									
Brake wear abrasion												x									x								x		

tional technologies, such as isolation and containment, mechanical/pyrometallurgical separation, or chemical treatment (Mulligan et al. 2001) are usually expensive, labor intensive, and soil disturbing (Gardea-Torresdey et al. 2005). Therefore, phytoremediation as plant-mediated decontamination/detoxification processes has emerged as a methodology to remove, reduce, degrade, or immobilize environmental pollutants from air, soil, and water, thus restoring contaminated sites toward a clean, non-toxic environment (Pulford and Watson 2003; Pilon-Smits and Freeman 2006; Rajkumar et al. 2012 and references therein). The following specific techniques are considered for the phytoremediation of polluted sites, in particular concerning heavy metals:

a) phytoextraction—i.e., metal-accumulating plants (hyperaccumulator) remove metals from soil by concentrating them in harvestable parts of the plant. After a certain period of growth, the plants are harvested and disposed or incinerated (Raskin et al. 1997; Salt et al. 1998); and

b) phytostabilization—i.e., metal-tolerant plants immobilize and inactivate metals through *in situ* rhizospheric processes, thus preventing the risk of further environmental degradation by leaching into groundwater or by airborne spread. Metals are thereby precipitated or sequestered by complexation and sorption mechanisms within the soils. Metal availability to plants is minimized and metal leaching into groundwater is reduced (Salt et al. 1995).

Since Bauman (1885), the capacity of plants to take up trace elements has been well-known. Areas with deposits of minerals often support a characteristic flora, rich in endemic species (e.g., *Viola calaminaria* Lej.) that through constitutive or adaptive mechanisms are able to tolerate or accumulate high metal concentrations in their tissues (Sheroan 2009; Monaci et al. 2011). Based on field surveys in nickeliferous soils (related to ultrabasic rocks), Brooks et al. (1977) defined those plants as "hyperaccumulators," which contain more than 1 mg Ni g^{-1} dry weight (Rascio and Navari-Izzo 2011). Accumulators are able to quickly translocate trace elements with a concentration of 100–1,000 fold higher than those found in non-accumulator species to the shoots and to the leaves, in particular, to the shoots and leaves (Baker 1981; Salt et al. 1998).

Consequently, effective phytoremediation depends on the plant's ability 1) to grow fast in nutrient-poor soils, 2) to develop a dense and/or deep root system, and 3) to show metal-tolerance traits (Baker et al. 1994; Brooks et al. 1994; Rascio and Navari-Izzo 2011; Sarma 2011). Furthermore, accumulators are genetically adapted and often strictly bound to their natural habitats and selective for specific metals. Urban trees, in particular, are considered efficient in pollutant removal thanks to their root systems, their large total leaf area, and their high transpiration (Pulford and Watson 2003; Rosselli et al. 2003; Meers et al. 2007; Unterbrunner et al. 2007; Brunner et al. 2008; Domínguez et al. 2008; Papa et al. 2012; Ugolini et al. 2013). Experiments have shown that tolerance against heavy metals can be induced by gradual acclimatization to metal stress (Dickinson et al. 1991; Turner and Dickinson 1993; Punshon and Dickinson 1997; Dickinson et al. 2002; Pulford and Watson 2003). Trees have the potential to enhance the remediation of brownfields, landfills, and other contaminated sites by absorbing, transforming, and accumulating a number of contaminants (Nowak and Dwyer 2007).

REVIEW METHODOLOGY

This review focuses on trees in urban areas, considering their capacity to withstand stress by heavy metals. Species-specific information on the phytoremediation potential and/or phytoremediation techniques will be identified. In particular, researchers consider the suitability for bioindication and heavy-metal stress tolerance and hardiness for a selection of tree species. Additionally to the specific phytoremediation suitability of species, information was compiled with regard to their origin and morphological characteristics (e.g., maximum height, root development, or life span). Ecosystem services related to environmental quality improvement as well as potential disservices were assessed with special regard to volatile organic compounds (VOCs) and ozone emission.

In total, more than 134 literature sources, including books and manuals on dendrology, tree identification, and tree biology, as well as scientific papers, were reviewed, all extracted from the Scopus® and ScienceDirect® citation/journal databases. For the current study, key words searched included "heavy metals" and the respective species name, as well as "urban areas" and/or "cities" together with "heavy metals." Figure 1 quantifies the revised literature sources differentiated into research topics.

The selected species were *Acer pseudoplatanus* L., *Ailanthus altissima* P. Mill., *Betula pendula* Roth, *Carpinus betulus* L., *Ginkgo biloba* L., *Platanus* × *hispanica* Mill. Ex Muenchh. "Acerifolia", *Quercus robur* L., *Robinia pseudoacacia* L., and *Tilia cordata* Miller (for biological and phytogeographical characteristics, see Table 2).

These species are frequently found in several medium-large cities in northern and northeastern Italy (Paludan-Müller et al. 2002; Comune di Padova 2006; Paoletti 2009; Comune di Bolzano, 2010; Semenzato et al. 2011; Comune di Merano 2012; Città di Torino 2013; Marziliano et al. 2013). Moreover, they are commonly planted in urban areas and along streets and highways throughout central and northwestern European cities (Pauleit et al. 2002; Pauleit et al. 2005; Sæbø et al. 2012; Sajdak and Velazquez-Marti 2012). *Betula pendula*, for example, occurs up to arctic (Sjöman et al. 2012) and near-arctic regions of Europe (Rosenvald et al. 2011; McBride and Douhonikoff 2012). Researchers did not consider trees with invasive root systems that are not suitable for streets, such as *Populus* and *Salix* species (Trees for Cities 2014). Some species listed in Table 2 (e.g., *Robinia pseudoacacia* and *Betula pendula*), while not specifically indicated for phytoremediation purposes, are considered

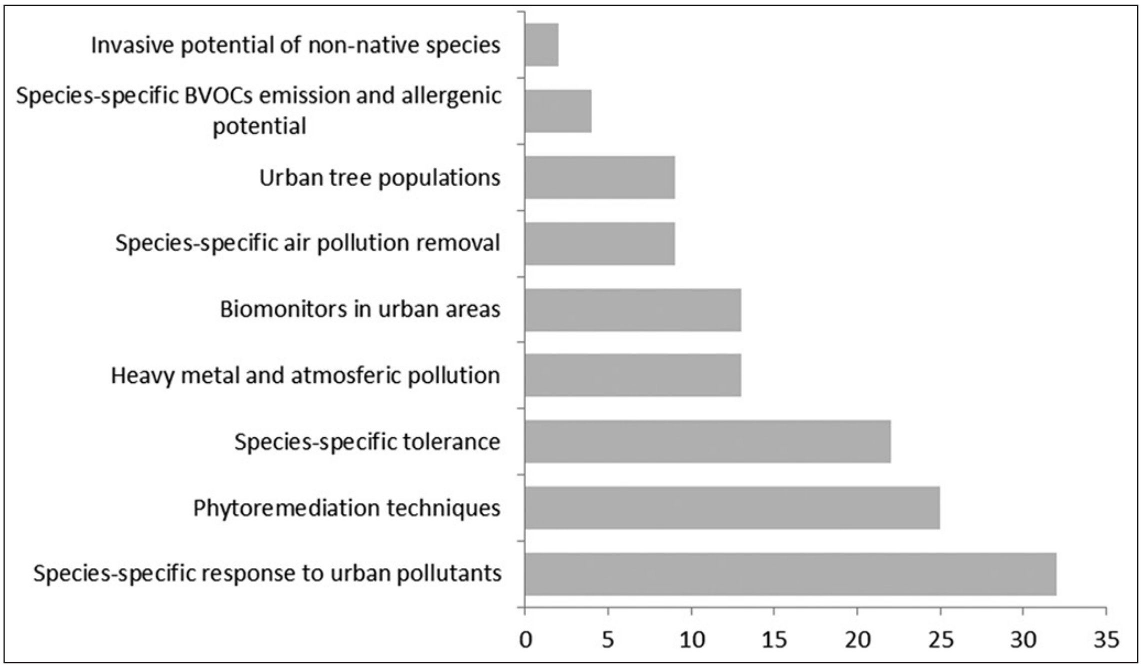

Figure 1. Research papers out of a total 134 reviewed papers with different aspects on phytoremediation in the urban environment.

Table 2. Biological and phytogeographical characteristics of the selected tree species (1–6 literature sources; life span refers to urban areas). Asterisk (*) indicates hybrid.

Species	Family	Indigenous (I); non-native (N)	Native range	Maximum height (m)	Average growth rate per year (cm)	Root system	Life span (years)
Acer pseudoplatanus L.	Aceraceae	I	Europe and Caucasus/ Asia	15–30[z]	0.63[y]	Fasciculate shallow[x]	40–70[w]
Ailanthus altissima P. Mill.	Simaroubaceae	N	China–North Vietnam	20–30[z]	0.63[y]	Taproots[v]	30–50 [v]
Betula pendula Roth	Betulaceae	I	Northern Europe	30[z]	0.77[y]	Fasciculate shallow[x]	80
Carpinus betulus L.	Betulaceae	I	Central and eastern Europe	20[z]	0.71[u]–0.77[y]	Fasciculate deep[x]	50–70[w]
Gingko biloba L.	Gingkoaceae	N	China, Japan	20–30[z]	0.80[y]	Fasciculate deep[x]	>250
Platanus × hispanica Mill.	Platanaceae	N*	Europe	30[z]	0.89[y]	Fasciculate deep[x]	100–120[w]
Quercus robur L.	Fagaceae	I	Central and northern Europe	30–40[z]	0.70[u]–0.77[y]	Taproots[x]	80-100[w]
Robinia pseudoacacia L.	Fabaceae	N	Northeastern United States	20–25[z]	0.65[u]–0.74[y]	Fasciculate deep[x]	40–50[w]
Tilia cordata Miller	Tiliaceae	I	England/Wales, central and western Europe	25[z]	0.61[u]–0.62[y]	Fasciculate deep[x]	80–100[w]

[z] von Malek and Wawrik (1985)
[y] Strobach et al. (2012)
[x] Odone (1992)
[w] Ferrari and Medici (1998)
[v] Russo et al. (2014)
[u] USDA (2012)

heavy-metals accumulators and potential biomarkers for the urban environment (Baycu et al. 2006; Tomašević et al. 2011). As an invasive species in Europe, *Ailanthus altissima* was also selected because it has become popular as a roadside tree in many European cities (Carinanos and Casares-Porcel 2011). In addition, experimental data show the tolerance of *A. altissima* to multiple heavy metals and suggest that this species can be tested for reforestation or phytoremediation of areas polluted with heavy metals (Gatti 2008).

RESULTS AND DISCUSSION

Fast-growing tree species, such as *Betula pendula* and *Robinia pseudoacacia,* can be considered ideal low-cost candidates for phytoremediation applications, due to their high transpiration rates, fast growth rate after transplanting, and high biomass production. Moreover, *Betula pendula* has a high potential for phytoremediation, as it is able to mobilize trace elements in the soil and concentrate them at the root level, thus minimizing their translocation to leaves, wood, and bark (Evangelou et al. 2012). This has been shown, for example, for aluminum by Baker et al. (1981), and Rosselli et al. (2003). As Table 3 shows, all selected tree species are characterized by promising tolerance traits and show a high hardiness that render them suitable for a wide range of urban environments. Several studies have revealed that salt-tolerant plants may also tolerate other stresses, including heavy metals and xenobiotics, offering greater potential for phytoremediation research (Manousaki and Kalogerakis 2011). Additionally, the high tolerance to pests and diseases defines the ability of some deciduous trees for phytoremediation (Peuke and Rennenberg 2005; Lohmus et al. 2007; Rosenvald et al. 2011).

The potential/suitability for each species for phytoremediation and biomonitoring is shown in Table 4. Consequently, some of those species may provide information on the quality and quantity of trace elements. *Betula pendula* or *Robinia pseudoacacia* appear suitable for several applications related to phytoremediation. Furthermore, *Betula pendula* can grow on older heavy-metal soils by utilizing ectomycorrhizal fungi (Bothe 2011). *Tilia cordata* might be also suitable for phytoremediation due to its foliar trapping capacity and it can provide valuable information on airborne pollutants (Anicic et al. 2011; Tomaševic et al. 2011). There is a lack of information about the capacity of *Carpinus betulus* on heavy metals removal. Table 4 also shows the foliar trapping capacity of the tree species. In general, leaves with hairy, resinous, scaly, and coarse surfaces have the highest potential to intercept contaminants and particulate matter in comparison to smooth leaves (Beckett et al. 1998; Beckett et al. 2000; Yang et al. 2005).

Table 5 shows the allergenicity potential and the VOCs emission capacity of the selected urban tree species. Trees with high BVOC (biogenic volatile organic compounds) and pollen emissions should be avoided in urban areas. The air pollution due to BVOC emissions is related to their reactivity with some of the compounds released from anthropogenic sources, especially nitrogen oxides (NO_x). Ozone, peroxyacyl nitrates, aldehydes and ketones, hydrogen peroxide, secondary

Table 3. Tree species' main tolerance traits; h = highly suitable with regard to stress, m = moderately, l = low.

Species	Pollution resistance	Salt stress resistance	Drought resistance	Hardiness[z]
Acer pseudoplatanus	l[y]	h[x, w]	l[z, v]	h
Ailanthus altissima	h[u, t]	h[s, x]	h[z, t, r]	m
Betula pendula	h[q, p]	m[x]	m[z]	h
Carpinus betulus	h[u]	l[x, o]	m[z]	h
Ginkgo biloba	h[u]	m[n]	h[z]	m
Platanus × hispanica	h[m]	l[l]	h[z]	m
Quercus robur	l[x, y, k, j]	l[o, i]	l[z]	h
Robinia pseudoacacia	h[x, u, h]	h[h]	h[z]	h
Tilia cordata	l[g]	h[h, g]	l[x]	h

[z] Roloff et al. (2009)
[Y] Aasamaa et al. (2002)
[x] Dirr (1976)
[w] Turner et al. (1993)
[v] Sjöman et al. (2015)
[u] Chiusoli (2004)
[t] Kowarik (2011)
[s] Karlik and Pittenger (2012)
[r] Constán-Nava et al. (2010)
[q] Hartikainena et al. (2012)
[P] Seco et al. (2007)
[o] Antonellini and Mollema (2010)
[n,] Takahashi et al. (2005)
[m] De La Torre (2001)
[L] Rose and Webber (2011)
[k] Allen et al. (2010)
[j] Wisniewski and Dickinson (2003)
[i] Sehmer et al. (1995)
[h] Sjöman and Busse Nielsen (2010)
[g] Paludan-Müller et al. (2002)

Table 4. Tree species' potential and/or suitability in various phytoremediation techniques; h = high, l = low, n.k. = unknown.

Species	Bioindicator	Pb	Cd	Cu	Zn	Phytostabilization	Phytomanagement	Foliar trapping capacity
Acer pseudoplatanus	l[z, y, x, w, v]	n.k.	l[u]	l[u] h[v]	h[v, u]	h[t]	(pioneer species)[s]	h[u, r]
Ailanthus altissima	h[q, p]	l[q]	l[q]	n.k.	l[q, p]	n.k.	n.k.	h[p]
Betula pendula	h[z, x, w, o, n, m, l]	l[k] h[z, n, l]	l[m, l, k] h[z, n, j]	l[n, l]	h[w, n, l, j]	l[l]	(pioneer species)[l]	h[z, r, l, i]
Carpinus betulus	l[y, m]	n.k.	n.k.	n.k.	n.k.	n.k.	n.k.	h[y, r, l]
Ginkgo biloba	l[s, i]	l[h]	n.k.	l[h]	l[h]	n.k.	n.k.	l[s, h]
Platanus × hispanica	l[l]	l[l]	n.k.	l[l]	n.k.	n.k.	n.k.	l[g] h[l]
Quercus robur	h[z, y, x, f lo, w, e]	l[e]	l[e]	l[e]	l[e] h[l]	l[x]	n.k.	h[r, l]
Robinia pseudoacacia	h[z ,y, w, q, l, d, c, b, a,*]	l[q, a, *] h[d, c]	l[q, d, c, a, *]	h[d, c, *] l[a]	l[q, a] h[d, c, *]	h[l, f]	(pioneer species)[l]	l[s, r]
Tilia cordata	l[y, o, m, k]	l[o, k, **]	l[k]	l[o] h[k]	l[o]	n.k.	n.k.	h[y, g, r, i]

[z] Dmuchowski et al. (2011)
[y] Kardel et al. (2011)
[x] Kardel et al. (2012)
[w] Pourrut et al. (2011)
[v] Sawidis et al. (2011)
[u] Simon et al. (2011)
[t] André et al. (2006)
[s] Neinhuis and Barthlott (1998)
[r] Sæbø et al. (2012)
[q] Baycu et al. (2006)
[p] Wang et al. (2006)
[o] Aničić et al. (2011)
[n] Evangelou et al. (2012)
[m.] Khavanin Zadeh et al. (2012)
[l] Van Nevel et al. (2011)
[k] Tomašević et al. (2011)
[j] Unterbrunner et al. (2007)
[i] Murakami et al. (2012)
[h] Xiao and McPherson (2011)
[g] Dzierżanowski et al. (2012)
[f] Wisniewski and Dickinson (2003)
[e] Aboal et al. (2004)
[d] Çelik et al. (2005)
[c] Cicek and Koparal (2004)
[b] Ji et al. (2012)
[a] Samecka-Cymerman et al. (2009)
[*] Serbula et al. (2012)
[**] Tomašević et al. (2013)

organic aerosol, and particulate matter can be formed by the photochemically driven reaction between NO_x and VOCs (Fehsenfeld et al. 1992; Fuentes et al. 2001; Calfapietra et al. 2013).

The choice of an emitting or non-emitting species might be important for the improvement of the air quality in urban environments. Abiotic stresses (e.g., mechanical injuries or drought) may induce a change of constitutive BVOCs, either stimulating or quenching the emissions, or may induce *de novo* synthesis and emission. Induced emissions may occur in a systemic way—i.e., away from the site of damage (Loreto and Schnitzler 2010). The emission of BVOCs is biosynthetically controlled by abiotic factors, such as light and/or temperature, atmospheric CO_2 concentration, or nutrition. Trees in urban environments can be either particularly subjected to stresses related to temperature variations, drought and salt, herbivore or pathogen attack, alone, or in combination (Loreto and Schnitzler 2010). Emission of volatile isoprenoids is a metabolic cost for plants, but benefits involve an improvement of thermotolerance and higher antioxidant capacity (Loreto and Schnitzler 2010; Tattini et al. 2015). Indeed, plants may use volatile isoprenoids as a fast response mechanism to cope with environmental constraints (Loreto et al. 2014). However, in the choice of the tree species in urban areas, it is important to consider that a species can emit VOCs, but that this disservice can be counterbalanced by the services it provides.

Table 5. Tree allergenicity and VOCs emission capacity; h = high, l = low.

Species	Allergenicity	VOCs emission
Acer pseudoplatanus	h[z]	l[y]
Ailanthus altissima	h[z, x, †]	l[w]
Betula pendula	h[z, x]	l[w]
Carpinus betulus	h[z, x]	l[w]
Ginkgo biloba	h[z, x, †]	l[w, v]
Platanus × hispanica	h[x]	l[w] h[w]
Quercus robur	h[z, x]	h[w, v]
Robinia pseudoacacia	h[z]	h[w, v]
Tilia cordata	h[z]	l[y]

[z] Ogren (2000)
[y] Karl et al. (2009)
[x] Carinanos and Casares-Porcell (2011)
[w] Loreto et al. (2014)
[w] Kesselmeier and Staudt (1999)
[v] Benjamin and Winer (1998)
[†] Female

CONCLUSIONS

This review has provided a comprehensive assessment of tree species suitable for phytoremediation in the urban environment. Due to physiological and morphological characteristics and to the intrinsic tolerance to several stress factors, some species seem particularly promising as an indicator of the environmental state of an urban environment and to lower the amount of specific pollutants. It must also be pointed out that intrinsic species properties (e.g., tolerance and/or bioindication capacity for a specific contaminant) can help planners to create an effective monitoring net in strategic points of a city, or to detect single contaminants representative of a specific anthropogenic impact. Actually, only implementing larger-scale projects will help determine whether green infrastructure will have measurable effects on climate, air and water quality, and human health at a municipal scale (Pataki et al. 2011). Furthermore, those trees can be also used for ecosystem restoration (see Zerbe and Wiegleb 2009). The selection of species and the management practices with regard to phytoremediation should promote a sustainable urban development to mitigate pollution in order to achieve a healthier urban environment.

There are several successful examples of phytoremediation projects in cities, as stated by Felson and Pickett (2005), Kirkwood (2011), Sousa (2003), and Wilschut et al. (2013). For example, a field of birch trees was used to remediate the soil on the site of the former blast furnaces of Duisburg-Nord Park in Germany (Felson and Pickett 2005). However, only limited information is available about project performance and timeframes for project completion (Oh et al. 2014).

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Résumé. Les arbres jouent un rôle important pour l'amélioration de la qualité de l'environnement des milieux urbains. L'amélioration du microclimat, l'atténuation des eaux de ruissellement, le stockage et la séquestration du carbone, la réduction du bruit, l'épuration de l'air par l'intermédiaire de l'élimination et de la fixation des polluants par les feuilles, les tiges et les racines sont des services écosystémiques générés par le verdissement urbain. De plus, la capacité de certaines espèces d'arbres à se signaler en tant que bio-indicateur ou pour l'absorption de contaminants doit être prise en compte. Voici donc une analyse mettant l'accent sur dix (10) espèces d'arbres ornementaux couramment plantées en bordure des rues urbaines en Europe centrale. Il s'agissait d'évaluer leur rôle potentiel pour la bio-indication et la phytoremédiation. En raison de caractéristiques physiologiques et morphologiques et de la tolérance intrinsèque à plusieurs facteurs de stress, certaines espèces apparaissent particulièrement prometteuses à titre d'indicateur de l'état de l'environnement urbain ou aux fins de réduction de la quantité de polluants spécifiques. Il faut souligner que certaines propriétés des espèces intrinsèques (par exemple, la capacité de tolérance et/ou de bio-indication d'un contaminant spécifique) peuvent aider les urbanistes à créer un réseau de surveillance efficace dans les zones stratégiques d'une ville ou à détecter la présence d'un contaminant découlant d'un impact humain spécifique. De manière particulière, le *Betula pendula* et le *Robinia pseudoacacia* peuvent être considérées comme d'excellents sujets, peu onéreux pour la phytoremédiation. En raison de leur grande rusticité, de leur tolérance à la pollution et de leurs caractéristiques en tant qu'espèces pionnières, ces deux espèces peuvent en outre être considérées comme des indicateurs biologiques ou pour leur capacité de rétention foliaire de contaminants. Le *Tilia cordata* est également un bon spécimen pour la phytoremédiation en milieu urbain en raison de sa capacité de rétention foliaire pouvant fournir de précieuses informations sur les polluants atmosphériques.

Zusammenfassung. Trees play an important role for the improvement of environmental quality in urban areas. The Bäume spielen eine wichtige Rolle bei der Verbesserung der Umweltqualität in den urbanen Regionen. Die Verbesserung von Mikroklima, Ablaufwasserbewegung, Kohlenstoffspeicherung und –bindung, Lärmreduzierung, Luftreinigung durch die Entfernung und Fixierung von Kontaminationen in Blättern, Stämmen und Wurzeln sind ökologische Leistungen, die von urbanem Grün geliefert werden. Zusätzlich muss man die Kapazität von bestimmten Baumarten als Bioindikator oder zur Aufnahme von Kontaminationen berücksichtigen. Hier wird ein Rückblick präsentiert, der sich auf zehn ornamentale Baumarten fokussiert, die häufig in Zentraleuropa entlang von Straßen gepflanzt werden. Ihre potentielle Rolle bei Bioindikation und Phytomediation werden hier untersucht. Einige Arten scheinen aufgrund ihrer physiologischen und morphologischen Charakteristika und ihrer spezifischen Toleranz gegenüber einigen Stressfaktoren sehr vielversprechend als Indikator für den Zustand der urbanen Umwelt oder bei der Reduzierung von der Menge spezifischer Kontaminationen. Es muss darauf hingewiesen werden, dass die spezifischen Eigenschaften einiger Arten (z.B. Toleranz und/oder Bioindikationsfähigkeit für einen bestimmten Schadstoff) den Planern helfen können, ein effektives Überwachungsnetz in strategisch wichtigen Bereichen einer Stadt zu etablieren oder bestimmte Schadstoffe, die repräsentativ für eine spezifischen menschlichen Einfluss sind, aufzuspüren. Besonders *Betula pendula* und *Robinia pseudoacacia* werden als kostengünstige Arten für Phytomediation erachtet. Wegen ihrer hohen Anpassung, Toleranz gegenüber Schadstoffen und ihrer Charakteristika als Pioniergehölz, könnten beide Baumarten auch als Biomonitor in Betracht kommen, oder für ihre Fähigkeit, Schadstoffe auf ihren Blättern zu binden. *Tilia cordata* ist wegen ihrer Fähigkeit, Schadstoffe auf ihren Blättern zu binden auch geeignet für Phytomonitoring in urbanen Umgebungen, da so wertvolle Informationen über luftübertragene Schadstoffe gesammelt werden können.

Resumen. Los árboles juegan un papel importante para la mejora de la calidad ambiental en las zonas urbanas. La mejora del microclima, la mitigación de la escorrentía, el almacenamiento y secuestro de carbono, la reducción del ruido, la purificación del aire mediante la eliminación y la fijación de contaminantes en las hojas, tallos y raíces son servicios ecosistémicos proporcionados por la ecología urbana. Además, debe tenerse en cuenta la capacidad de ciertas especies arbóreas como bioindicador o para absorber contaminantes. Se presenta aquí una revisión que se centra en 10 especies de árboles ornamentales comúnmente plantadas a lo largo de las calles urbanas de Europa Central. Su papel potencial para la bioindicación y la fitorremediación fueron evaluados. Debido a las características fisiológicas y morfológicas, y a la tolerancia intrínseca a varios factores de estrés, algunas especies parecen particularmente prometedoras como indicador del estado del medio ambiente urbano o para disminuir la cantidad de contaminantes específicos. Cabe señalar que las propiedades intrínsecas de las especies (por ejemplo, la capacidad de tolerancia y / o bioindicación de un contaminante específico) pueden ayudar a los planificadores a crear una red de monitoreo eficaz en áreas estratégicas de una ciudad o a detectar contaminantes únicos representativos de un impacto humano específico. En particular, *Betula pendula* y *Robinia pseudoacacia* pueden considerarse candidatos ideales y de bajo costo para la fitorremediación. Debido a su alta resistencia, tolerancia a la contaminación y sus características como especies pioneras, ambas especies podrían ser consideradas como biomonitores, o por su capacidad de captura foliar. *Tilia cordata* también es adecuada para la fitorremediación en entornos urbanos debido a su capacidad de captura foliar que puede proporcionar información valiosa sobre contaminantes aerotransportados.