Opinion

Gardening and urban landscaping: significant players in global change

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Global warming leads to shifts in vegetation types in given temperate environments. The fastest species movement is due to the globalized supply and use of exotic plants in gardening and urban landscaping. These standard practices circumvent dispersal limitations and biological and environmental stresses; they have three major global impacts: (i) the enhancement of biological invasions, (ii) the elevation of volatile organic compound emissions and the resulting increase in photochemical smog formation, and (iii) the enhancement of CO\textsubscript{2} fixation and water use by gardened plants. These global effects, none of which are currently considered in global-change scenarios, are increasingly amplified with further warming and urbanization. We urge for quantitative assessment of the global effects of gardening and urban landscaping.

Gardening accompanying urbanization: neglected global relevance

Changes in atmospheric composition, climate, land use and biodiversity are well-established components of current global change. However, there is another major component of global change that has not received the attention it deserves. Rapid increases in human population and economic development have led to tremendous urbanization and road construction, implying a mosaic of landscapes with most vegetation selected for their ornamental characteristics and resistance to urban conditions. Rapid urbanization has become an area of crucial concern in conservation biology owing to the radical changes in habitat structure and the loss of species as a result of urban and suburban development [1]. However, the accompanying phenomena of gardening and urban landscaping and their global relevance have not yet been given due consideration. Here, we highlight three major global effects of expanded gardening and urban landscaping activities. These activities lead to (i) increased spread of invasive species, (ii) enhanced emission of biogenic volatile organic compounds (BVOCs; see Glossary), particularly enhanced emissions accompanied by elevated formation of photochemical smog (see Glossary) in the winter months and (iii) increased uptake of CO\textsubscript{2} and augmented water use by urbanized areas. We also emphasize that both gardening and urban landscaping itself and most of these effects are favored by global warming [2,3]. Finally, we conclude that an effort by the scientific community to quantify all these global effects of gardening and urban landscaping is warranted to discern their actual role in global and urban ecology.

Enhancement of plant invasions and spread of invasive species

Urban and suburban areas are important foci for the spread of introduced plant species [4–6]. Gardening practices favor the dispersal and establishment of alien species in many ways. In particular, the dispersal of gardened plants is neither limited by climatic requirements for propagule formation and maturation nor by propagule natural dispersal. Furthermore, standard gardening practices result in the reduction of abiotic and biotic stresses that the plants must tolerate (Box 1). As a result, gardening brings together a rich mixture of species of widely varying geographic origin. The florals of public and domestic urban gardens form the greatest source of potentially invasive alien plants [7], and many alien plant species grown in gardens have escaped cultivation and become invasive [6,8–10]. In addition, hybridization with other alien species or local species can increase the stress tolerance and invasibility of gardened species [11]. Human-facilitated introduction of species has contributed to exotic species’ colonization in locations where they would never have naturally dispersed because of large geographic

Glossary

Biogenic volatile organic compounds (BVOC): volatile organic compounds synthesized by organisms, mainly by plants. Volatile isoprenoids (isoprene, monoterpenes) form the most significant class of BVOC. BVOC contribution exceeds anthropogenic volatile compound production by more than an order of magnitude.

Frost hardiness: species potential to tolerate sustained periods with low temperature. Plants not hardy in given climates cannot be cultivated or require special care (winter covers etc.).

Hydrologic drought: limited water availability resulting from lowered water tables that is common in urbanized areas. Urban drought typically results from engineered deep stream channels, excessive consumption of ground water and impervious surface.

Laurophyllization: invasion of deciduous temperate communities by broad-leaved evergreen vegetation. Currently typically occurring in Northern Italy and Southern Switzerland as well as at higher altitudes in mountains of Mediterranean countries.

\( Q_{10} \) value: rate of reaction at temperature \( T+10\degree C \) relative to the rate of reaction at temperature \( T \).

Photochemical smog: formation of particulate matter (secondary aerosols) and ground-level ozone as the result of light-driven chemical reactions in the participation of nitrogen oxides (NO\textsubscript{x}) and volatile organic compounds.

Secondary aerosols: particulate matter formed in the atmosphere as the result of oxidation reactions and condensation of vapours of organic compounds.
Box 1. Facilitation of plant dispersal and survival by gardening

Common gardening practices facilitate establishment, growth and survival of plants by diminishing dispersal limitations, amelioration of environmental and biological stresses and improving winter survival.

Facilitation of species dispersal by gardening
Non-facilitated dispersal of local species or invasive alien species requires the maturation of viable propagules (seeds, vegetative propagules) during the growing season and the successful dispersal of these to potential growth habitats. For plants from warmer climates transferred to cooler environments, the length of the growing season is often not long enough for seed maturation. In addition, flower buds and seeds are significantly less resistant to frost than leaves and vegetative buds (see Ref. [58] for a detailed review). As a consequence, plants hardy enough to grow and survive in cooler climates might not form viable offspring. Furthermore, pollination and seed dispersal of alien species can be curbed by lack of pollinators and specialized seed dispersing animals. By contrast, all these hurdles are easily overcome by alien plants cultivated in gardens. Furthermore, plants are propagated with lower cost in milder climates and container-grown seedlings or saplings are transferred to cooler environments (Figure I). Gardening companies producing plant material in warm climates offer constant supply, and local businesses in northern, cool-temperate climates can introduce novel ornamental species that are not necessarily hardy enough for local climate (i.e. do not exhibit frost hardiness; see Glossary) or are unable to cope with abnormally cold winters, commonly occurring about every ten years [40]. Nevertheless, this constant supply of partly hardy plant material implies that the number of species growing in gardens in any given time and location closely reflects the potential of species frost-resistance limits (see Figure 1 in main text). Therefore, gardening practices respond to global warming essentially immediately [41].

Diminution of environmental stresses
Survival of plants in any given environment is significantly affected by various abiotic stresses. For example, plant survival and growth is often limited by low soil fertility and by episodic low water availability, limiting the number of alien invaders, as well as local species that can colonize a given habitat [59]. The additional supply of resources during the growing season, such as irrigation or fertilization, is part of routine gardening practices, allowing plants that would not survive in natural habitats to succeed.

Protection from and amelioration of biological stresses
A variety of biological stresses, such as pathogen attack, herbivory and competition with neighboring plants, further affects plant survival and growth. The mechanical and chemical control of weeds, the use of a variety of pesticides and fungicides and mechanical shields, such as bark protections against rodents, belong to standard gardening practices. Such measures significantly curb the overall level of biological stress and improve survival and growth of gardens planted.

Facilitation of winter survival
Limited winter survival is the major obstacle for growing many ornamental plants in cooler environments. Winter survival is affected by several factors including tolerance of minimum temperatures (frost hardiness), resistance of snow loads and tolerance of above-ground desiccation stress, as well as enhanced photoinhibition in warmer clear days in spring when the rooting zone is still frozen [58,60,61]. Various types of protective covers are generally employed to avoid dieback resulting from excessively low minimum temperatures and damage due to spring photoinhibition and desiccation stresses. Higher carbohydrate reserves that plants in cultivation with ample supply of water and nutrients and without biotic competition can build further contribute to the enhanced survival in harsh winter conditions and to faster and more complete recovery from winter damage [60]. In cultivation, a given temperate plant species can typically grow in climates with −5 to −10 °C lower minimum temperatures (1–2 USDA hardiness zones) than the same species in wild conditions [62–64].

Figure I. Plants are propagated with lower cost in milder climates and container-grown seedlings or saplings are shipped to cooler environments. In Europe, there is a major export (indicated by red arrows) of gardening plant material from countries with a mild temperate oceanic climate, such as Denmark and the Netherlands, to Scandinavian and Baltic countries with a more continental temperate climate, as well as from countries with a Mediterranean climate, such as Italy and France, to countries with a mild temperate climate, such as Germany, and from semi-arid Northern Africa to Mediterranean Southern Europe.

distances. For instance, in isolated New Zealand, characterized by very low rates of species invasions in the geological past, more than 25,000 exotic species have been introduced during the past 150 years, many of which have become invasive weeds [12]. Recent studies demonstrate that several components of global change, such as enhanced nitrogen depositions and elevated CO₂ concentration, can favor the competitive ability of alien species, and that these drivers have enormously enhanced species invasions globally [13]. Gardening worldwide has contributed—and keeps contributing significantly—to this enhanced invasion, even though the contribution differs between regions. For instance, the contribution of gardening to species invasions is slightly less important in Southern Europe than in Central and Northern Europe owing to water limitations in Southern Europe that constrain the number of species that can potentially grow and become invasive in areas where water is not supplied artificially.

Global warming further amplifies species invasions
Many of the species cultivated in gardens are potentially not invasive at the time of introduction because of lack of natural dispersal mechanisms and because they rely on protective measures for winter survival (Box 1). However, as temperatures are rising globally, many species can escape from the rich species pool present in the gardens. Global warming-driven shifts in vegetation boundaries accompanied by enhanced species richness have occurred many times in the Earth’s geological past [14–16]. Because of the moderate rate of temperature increase and the long life-span of woody vegetation, such invasions of species
from warmer habitats have progressed at a relatively slow rate. In recent decades, warming has occurred significantly faster, probably faster than any other time during past 1300 years [2]. The average land surface temperature in the Northern hemisphere has increased by a rate of 0.29–0.34 °C per decade between 1979 and 2005 [2], and the average land surface temperature is predicted to increase by 2.5–5 °C by 2099 [3]. Furthermore, winter temperatures have risen much faster, particularly in Northern Europe and the northern part of North America (0.7–1.3 °C per decade); this fast change is visible in altered species distributions [17,18]. Moreover, the winter minimum land surface temperature is predicted to increase further by 5–8 °C and by more in Boreal Europe and North America by 2099 [3]. Besides, the urban-heat-island effect increases the temperature in urbanized areas even more than in natural areas and agricultural plantations (for example, see Ref. [19]).

In temperate environments exhibiting winters with freezing temperatures, an increase in minimum winter temperature by 5 °C is expected to increase the number of species able to grow in any given location by 7–20% (Figure 1). A 10 °C increase in minimum winter temperature is even predicted to increase the potential species pool by 10–40% (based on the data and fits in Figure 1). Detailed simulations of the responses of potential plant species richness to climate change in Fennoscandian ecosystems predict on average a 26% increase in species richness by the end of this century [20].

Gardening companies operating in a globalized world generally produce at lower cost in countries with a warmer climate planting material that will be sold and planted in gardens of cooler climates. Although the worldwide distribution of gardened species is also somewhat limited by biogeographically defined anthropogenic and historical factors [21], there is more and more evidence of gardened species transfer across the continents [21,22], further increasing the potential gardened species pool.

In addition to plants that are fully hardy in cooler climates, barely hardy plants are often offered and planted in cooler locations. The consistent supply of semi-hardy plants implies that the actual increase in species number in urban habitats keeps close track with the global warming-driven potential species number (Box 1). There is ample evidence demonstrating that the species number in urban vegetation has followed the climatic warming in the past [23]. Thus, gardening in a warming world strongly facilitates species movement to higher latitudes, and cultivated species numbers respond to global warming almost instantly. This is in contrast to the long-term changes in natural vegetation boundaries, the speed of which is limited by the lifespan of dominating woody species and competition by established and invading species. The current alien flora of cities in temperate climates is very species-rich compared with surrounding native vegetation [7,24], which confirms that gardening is an effective way to enhance species richness and to take advantage rapidly of warmer climate.

The enhanced pool of exotic species further increases the number of species that can potentially escape cultivation and become invasive [6]. For instance, a series of Mediterranean broad-leaved evergreen species has escaped gardens and become an important forest component in several Central European and Western European countries, leading to a ‘laurophyllization’ (see Glossary) of typical evergreen needle-leaved or broad-leaved deciduous forests [11,25].

Amplification of volatile organic compound emissions by altered species composition and planting design of urban habitats

An important implication of gardening practices from a global change perspective is that many ornamental plants are strong emitters of BVOCs, such as isoprene and monoterpenes [26]. For instance, most broad-leaved species from genera Eucalyptus, Liquidambar, Liriodendron, Populus, Quercus and, essentially, all conifers are important emitters of volatile isoprenoids; a list that is being constantly complemented with new entries (see, for example, Refs [27,28] and Centritto et al., unpublished*). Such plant-generated emissions strongly contribute towards ozone formation in the atmosphere, as well as to the formation of secondary aerosols (see Glossary), collectively leading to the creation of photochemical smog in urban atmospheres [29–31].

Most of the current emission inventories are for local native species, and the emission scenarios for urban atmospheres have been developed on the basis of these native species checklists [32,33], which are not necessarily valid for urbanized environments. A completely different set of
species generally dominates urban environments [7], and many of these species have significantly higher BVOC emission potentials than local native species. For instance, many species introduced from Mediterranean Europe to Western and Central Europe have strongly fragrant foliage with large monoterpane reservoirs in the leaves and large constitutive monoterpane emission potentials, whereas the typical dominants of late-successional broad-leaved deciduous forests in Europe have low-to-moderate isoprene emission potentials [34].

Furthermore, plants growing in urban habitats are generally spaced far apart, thus most of the plants’ foliage is exposed to high light. This is relevant as the emission of many plant volatiles is much larger in leaves intercepting high-light intensities than in shaded leaves [35]. Although the total area of urban vegetation can be relatively small, the contribution to BVOC emissions can be disproportionately large. Volatile-isoprenoid emissions also respond very strongly to temperature with reaction rate increasing 3–6-fold for a 10 °C increase in temperature (Q10 value; see Glossary). This temperature response is significantly stronger than that of typical biochemical reactions such as photosynthesis (Q10 = 2–3) [36]. Thus, plant-generated BVOC emissions, in particular emissions from gardened plants, are expected to increase strongly with globally rising temperatures [37]. Furthermore, ozone is also a strong greenhouse gas, and plant-mediated ozone production might be partly responsible for the warming in boreal to arctic latitudes [38].

Enhancement of winter emissions
As evergreen vegetation stays ornamental throughout the year, there is particular interest in planting evergreens in cool-temperate and temperate gardens and roadsides. Strong isoprenoid-emitting shade-intolerant ornamental conifers and emitting broad-leaved evergreens are currently relatively rarely planted in Boreal and Temperate European cities because there are only 3–5 native species with few ornamental cultivars. Among introduced North American conifers, there are several cold-tolerant species from the genera *Picea* and *Thuja* planted in gardens; however, owing to dense, strongly shading conical crowns, these species are not favored in strongly urbanized space-limited areas. Currently, major ornamental, urban conifer genera, such as sparse-foliated *Araucaria* and *Cedrus* or narrow-crowned *Cupressus*, which dominate maritime temperate and Mediterranean cities, do not tolerate cool temperate climates.

Global warming in temperate and boreal environments not only means warmer average and warmer winter temperatures, but also implies wetter winters with enhanced snow depth during the frost period and extended growing season [39]. The length of the growing season currently increases ca. two days per decade, and this increase is expected to accelerate in future climates [2,3]. Enhanced snow depth during periods with freezing temperatures improves the winter survival of evergreen broad-leaved shrubs and young trees, whereas extended growing season length generally favors warm-temperate and Mediterranean evergreen broad-leaved vegetation [25]. Furthermore, gardening of evergreen exotic vegetation can be limited by exceptionally cold winters. As more than 300 years of gardening experience in Russia demonstrates, such severe winters typically occur every 10 years [40,41]. With global warming, it is predicted that the frequency of exceptional cold air outbreaks in the northern hemisphere will decrease by 50–100% [3,42]. All these modified climatic factors potentially increase the contribution of evergreen vegetation in temperate to cool-temperate gardens.

Apart from temperature, the variety of frost-tolerant species along major roads in temperate and boreal climates is further significantly constrained by the use of high amounts of chloride salts for de-icing of roads in winter. None of the native conifers growing in temperate and boreal forests have foliage and roots that are salt stress tolerant, and many strong deciduous BVOC emitters, such as *Populus* and *Quercus*, do not tolerate root-zone salt stress either [43]. Therefore, current roadside vegetation in temperate and boreal climates primarily consists of deciduous species with low emitting potential, such as *Acer* and *Tilia*. As the need for de-icing salts is expected to decrease owing to enhanced periods with non-freezing temperatures [44,45], the potential pool of strong BVOC-emitting species, such as *Populus* and *Quercus*, is further enhanced by global warming. Moreover, extensive research is currently being carried out to find de-icing chemicals with lower environmental impact, (de-icing chemicals that decay faster, chemicals with lower ecotoxicity [46,47]). The use of environmentally ‘friendly’ de-icing chemicals would also allow roadside cultivation of evergreens that are already hardy in the current climates.

Because they emit volatiles throughout the year, the increased planting of ornamental coniferous evergreen species and emitting broad-leaved evergreen species in urban areas can strongly enhance BVOC emissions in cities. Although the biogenic emissions strongly depend on temperature and are generally at low levels during winter, emission bursts can be observed on sunny days in which the temperature of evergreen foliage rises 8–10 °C above the ambient temperature. Such emission bursts currently play a decisive role in the formation of winter smog in Mediterranean and mid-latitude temperate cities and are projected to become more and more significant in northern temperate and boreal cities as well. Currently, there is only a limited formation of spring or winter smog in the northern habitats, but the conditions might be right to produce them in the future if gardening continues its current rapid growth.

Increased CO2 uptake and water use
A further important effect of gardening is that species introduction and landscape disassembly to mosaic also affect the carbon balance of the Earth. In particular, the species introduced in the framework of common gardening practices generally grow faster at the beginning of their introduction owing to the lack of natural parasites and enemies, as well as human-mediated alleviation of environmental stresses (Box 1). Furthermore, plants in gardens and roadsides are generally widely spaced and, consequently, are exposed to high light. Together with
irrigation and fertilization practices common in gardening, plants grown in gardens achieve much higher rates of photosynthesis than non-gardened native plants grown under a plethora of biological and environmental stresses in natural environments. Furthermore, plants in urban ecosystems are exposed to higher temperatures, CO₂ and nitrogen deposition than plants in rural areas. These factors usually have a beneficial influence on plant photosynthesis and growth. In certain situations, these urban plants can even be submitted to lower cumulative urban ozone (O₃) exposures and adverse effects, amidst a background of higher regional exposures beyond the urban core [48]. In fact, the managed green spaces (e.g. parks, gardens and golf courses) often have elevated local plant productivity relative to the surrounding wild land, and the productivity of such green spaces can reach the higher end of the maximum productivities observed in given environments [49,50].

This reasoning and the evidence outlined suggest that although the total area of urban vegetation can be relatively limited, its contribution to the Earth's carbon balance might be disproportionately large. Altered rates of net primary productivity (NPP) in urban green spaces can partially mitigate losses in productivity caused by extensive impervious urban surface cover [49,50]. An analysis of NPP for the USA found elevated total NPP in urban areas relative to nearby wildland, despite increased impervious surface cover, in two general cases: (i) cities in arid environments and (ii) cities with lower-density development [49]. Direct measures of NPP in the arid grasslands of Colorado corroborate this finding. Urban lawns exhibited four to five times the aboveground NPP relative to native grasslands [50]. Analogously, in three Korean cities, although the mean annual carbon uptake by woody plants ranged from 1.60 to 3.91 t ha⁻¹ yr⁻¹ for natural forest patches within the cities and 0.53–0.80 t ha⁻¹ yr⁻¹ for urbanized area, woody plant coverage was almost an order or magnitude less in urbanized locations, demonstrating considerably higher carbon fixation at given woody species coverage in urban areas [51].

Urban and road gardening increases NPP, but because it increases water consumption, it can also generate ‘hydrologic drought’ (see Glossary) by lowering water tables, which can be particularly significant in drier climates by altering soil, vegetation and microbial processes [52]. As drinking water is often used for irrigation of plants in the gardens, gardening can globally contribute to the overall shortage of drinking water [53]. For instance, studies demonstrate that the use of drinking water for irrigation of lawns and gardened woody vegetation has increased by more than 400% between the mid-1970s to the mid-1990s in some European countries [54].

Conclusions and perspectives

With globally changing temperatures, the number of plant species that can potentially grow in northern temperate and boreal environments is rapidly increasing. This increase is particularly enhanced if the limitations on species dispersal are removed and if abiotic and biotic stresses are alleviated by gardening practices. Many of the species facilitated by gardening practices are invasive species or can become invasive in a globally changing environment. Many of these species are also strong emitters of volatile organic compounds. This is particularly significant for emissions during the winter months because future gardening practices will probably favor evergreens in current temperate and boreal climates; currently, the urban vegetation under these climates is commonly deciduous. Typical gardening practices can further lead to higher photosynthetic rates (and water use) in gardened plants (in particular in semi-arid and arid lands). We advocate that the modifications of florals, amplification of world-scale biogenic volatile compound emissions and enhanced CO₂ uptake that result from changes in species distribution and diversity as a result of gardening practices constitute a significant component of global change.

Until now, urban ecology has mostly focused on the effects of urban greening on energy budget and carbon uptake of urban environments. We suggest that the outlined potential effects of increasing gardening and urban landscaping call for their introduction in the agenda of urban ecology, and altogether warrant an effort by the scientific community to assess those effects quantitatively.

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