Enhancing plant diversity and mitigating BVOC emissions of urban green spaces through the introduction of ornamental tree species

Yuan Ren¹, Ying Ge¹, Danping Ma², Xilu Song², Yan Shi³, Kaixuan Pan³, Zelong Qu³, Peipei Guo⁴, Wenjuan Han⁵, Jie Chang⁶

¹ College of Life Sciences, Zhejiang University, Hangzhou 310058, PR China
² Engineering Experimental Training Center, Zhejiang University of Water Resources and Electric Power, Hangzhou 310018, PR China
³ Capital Construction Department, Shandong University of Science and Technology, Qingdao 266590, PR China
⁴ School of Landscape Architecture, Zhejiang A & F University, Lin'an 311300, PR China
⁵ Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, PR China

ABSTRACT
Promoting the plant diversity of urban green spaces is crucial to increase ecosystem services in urban areas. While introducing ornamental plants can enhance the biodiversity of green spaces it risks environmental impacts such as increasing emissions of biogenic volatile organic compounds (BVOCs) that are harmful to air quality and human health. The present study, taking Qingdao City as a case study, evaluated the plant diversity and BVOC emissions of urban green spaces and tried to find out a solution to increase biodiversity while reducing BVOC emissions. Results showed that: (1) the species diversity and phylogenetic diversity of trees in urban green spaces were 22% and 16% lower than rural forest of this region; (2) urban areas had higher BVOC emission intensity (2.6 g C m⁻² yr⁻¹) than their rural surroundings (2.1 g C m⁻² yr⁻¹); (3) introducing the selected 11 tree species will increase 15% and 11% of species diversity and phylogenetic diversity, respectively; and (4) the BVOC emissions from green spaces will more than triple by 2050, but a moderate introduction of the selected low-emitting ornamental trees species could reduce 34% of these emissions. The scheme of introducing low-emitting ornamental species leads to a win-win situation and also has implications for the sustainable green space management of other cities.

1. Introduction
Urbanization is accelerating worldwide (Ramalho and Hobbs, 2012; Seto et al., 2012). The rapid urban transition and associated land use change drives habitat loss, threatens biodiversity in urban areas (Kowarik, 2011; Palliwoda et al., 2017). As a way of compensation, urban green spaces (exclude ruminant vegetation) are purported to preserve biodiversity and provide a wide range of ecosystem services that are critical for human well-being (Goddard et al., 2010; Pataki et al., 2011; Wolch et al., 2014). Plant diversity and species composition play crucial roles in the functioning of urban ecosystems and the sustainable supply of ecosystem services (Zhang and Jim, 2014). For the purpose of improving human well-being in cities, there is an urgent need to understand, assess and optimize the plant diversity and species composition of urban green spaces.

Ornamental plant species are frequently introduced to green spaces to improve plant diversity and cultural services (e.g. aesthetic, recreational, educational and inspirational) of urban areas (Niinemets and Peñuelas, 2008; Noe et al., 2008). Despite concerns about the ecological risks attributed to introduced species, such as the exacerbation of biological invasion, displacement of native species, and biotic homogenization (Kowarik, 2011; Qian et al., 2016), the process of species introduction in cities never slows down (Niinemets and Peñuelas, 2008). On the one hand, the introduction of ornamental plant species can enhance species diversity directly; on the other hand, the evolutionary distances of introduced ornamental species often differ greatly from the local ones, and thus may increase the phylogenetic diversity of green spaces significantly.

Another important impact of the introduction of ornamental tree species is the changes in emissions of biogenic volatile organic compounds (BVOCs). On a global scale, the source strengths of BVOCs far exceed those of anthropogenic VOCs (AVOCs) (Guenther et al., 2012). BVOCs are essential for plants to cope with various environmental stresses (Peñuelas and Staudt, 2010; Mentel et al., 2013). However, BVOCs emitted by urban trees, together with AVOCs from human activities, are believed to play critical roles in the formation of...
tropospheric ozone and secondary organic aerosols, which have negative effects on air quality and human health in urban areas (Mueller and Mallard, 2011; Calfapietra et al., 2013; Harrison et al., 2013). Thus, from the perspective of improving human well-being, increases in BVOC emissions should be avoided when introducing ornamental tree species to cities (Noe et al., 2008; Tiwary and Kumar, 2014).

BVOC emissions are highly species-specific (Tani and Kawawata, 2008; Aydin et al., 2014), making it possible to mitigate emissions in urban areas by optimizing species composition in green spaces (Simpson and McPherson, 2011; Ren et al., 2014). In many temperate cities of China, urban green spaces are dominated by strong BVOC emitters from the genera Sophora, Platanus, Populus, and Salix (Ghirardo et al., 2016; Zhang et al., 2016), while many ornamental tree species origin from the subtropical zone have relatively lower BVOC emission potentials (Chang et al., 2012; Ren et al., 2014). If these low-emitting ornamental trees are introduced to green spaces of temperate cities, a win–win situation (i.e. reducing BVOC emissions while improving biodiversity) can be achieved.

Numerous efforts have been made worldwide to study the plant diversity of urban green spaces (Knapp et al., 2008; Goddard et al., 2010; Nielsen et al., 2014; Zhang and Jin, 2014). Urban green spaces are found to be locations of low plant diversity and are dominated by non-native species (Alvey, 2006). Several studies also focus on BVOC emissions from urban areas (Chang et al., 2012; Calfapietra et al., 2013; Ghirardo et al., 2016) and reveal that green spaces can emit considerable amount of BVOCs (Chang et al., 2012; Guo et al., 2013). All these previous studies have provided insights into the different aspects of urban green spaces. Nevertheless, plant diversity and BVOC emissions are seldom discussed together. In particular, no previous studies focused on enhancing plant diversity while reducing BVOC emissions through optimizing the species composition of urban green spaces.

In this study, we took Qingdao City, as a case study. Through an urban vegetation survey, we calculated the plant diversity of urban green spaces; using a BVOC estimation model based on vegetation, meteorological and land use data, we estimated BVOC emissions from green spaces in Qingdao. We further discussed the potentials of introducing ornamental tree species to reduce BVOC emissions and to improve the plant diversity of green spaces in Qingdao City. The findings could inform management decisions for urban greening of cities in temperate zones, and compact cities elsewhere facing similar challenges to enhance biodiversity and to control urban BVOC emissions.

2. Material and methods

2.1. Study area

Qingdao City (35°35’–37°09’ N, 119°30’–121°00’ E) is located on the southwestern coast of Shandong Peninsula, bordering on the Yellow Sea in the east and contiguous to the mainland in the west with a land area of 11,282 km² (NBSC, 2015). It is one of the largest coastal cities in China with a population of about 7.8 million (NBSC, 2015). Under the impact of ocean currents and the southeast monsoon, this region is characterized by a temperate monsoon climate and also has characteristics of a maritime climate, with an annual average temperature of 12.7 °C and annual precipitation of around 660 mm. Qingdao has characteristics of a maritime climate, with an annual average temperature of 12.7 °C and annual precipitation of around 660 mm. Qingdao has characteristics of a maritime climate, with an annual average temperature of 12.7 °C and annual precipitation of around 660 mm. Qingdao has characteristics of a maritime climate, with an annual average temperature of 12.7 °C and annual precipitation of around 660 mm. Qingdao has characteristics of a maritime climate, with an annual average temperature of 12.7 °C and annual precipitation of around 660 mm.

2.2. Investigation for urban green spaces

We conducted an urban vegetation survey in the years 2013 and 2015 (Table 1; Table A.1). The survey encompassed six urban districts (Shinan, Shihe, Licang, Laoshan, Chengyang and Huangdao) which form the bulk of the built-up areas of Qingdao. Urban green spaces were divided into four types: street green space, park green space, residential green space, and affiliated green space (in schools and institutional units). A stratified random selection method (Nowak et al., 2008) was applied, and a total of 198 plots (400 m²) were investigated. Within each plot, all trees (DBH > 2.5 cm) were identified and measured for diameter at breast height (DBH) and tree height.

2.3. Introduction trial of ornamental tree species from subtropical regions

The introduction trial was conducted on the Qingdao campus of the Shandong University of Science and Technology. From 2003–2010, we introduced 13 ornamental tree species with relatively low BVOC emissions (Table A.2; Table A.3) to the campus from the southern provinces of Jiangsu and Zhejiang. This included 6 evergreen broad-leaved tree species, 6 deciduous broad-leaved species, and 1 evergreen coniferous species (Table 2). Most of these tree species have been widely used in the urban greening of southern China but were not found in the vegetation survey of Qingdao. Six of these tree species are listed as national key protected wild plants of China (Table 2). Tree health conditions and the annual changes in DBH were regularly detected after they were transplanted to the campus. To make a comparison, many other ordinary tree species that were widely used in the urban green spaces of Qingdao were also transplanted to the campus as ornamental trees.

2.4. Biodiversity calculation and phylogenetic tree reconstruction

Some numerical indices developed in vegetation ecology and commonly applied in urban-forestry research have been adopted in this study. We considered both the species diversity and phylogenetic diversity of urban trees. Species diversity was represented by the Gleason index (D) calculated by (Gleason, 1922):

$$D = S/nA$$

where $S$ was the total number of species, $A$ was the area of the community. The attribute $D$ was analyzed with reference to all of Qingdao and by tree-habitats (i.e. plots).
Table 2
Characteristics of the 13 introduced tree species.

| Tree species                  | Growth form |
|-------------------------------|-------------|
| Cinnamomum camphora<sup>a,b</sup> | ebt         |
| Ilex rubra<sup>a</sup>          | ebt         |
| Ilex latifolia                | ebt         |
| Manglietia insignis<sup>a</sup> | ebt         |
| Michelia chapensis<sup>a,b</sup> | ebt         |
| Michelia maudiae              | ebt         |
| Camptotheca acuminata<sup>a,b</sup> | dbt         |
| Cercidiphyllum japonicum<sup>a</sup> | dbt         |
| Eucommia ulmoides             | dbt         |
| Houpoea officinalis<sup>a,b</sup> | dbt         |
| Triadica sebifera             | dbt         |
| Nyssa sinensis                | dbt         |
| Taxus wallichiana var. mairei<sup>a,b</sup> | ent         |

| Year of introduction | No. of trees | Survival rate (%) | DBH increment (cm yr<sup>−1</sup>) |
|----------------------|--------------|-------------------|-----------------------------------|
| 2003                 | 80           | 90                | 0.51                              |
| 2008                 | 240          | 96                | 0.87                              |
| 2009                 | 18           | 94                | 0.82                              |
| 2009                 | 10           | 90                | 0.65                              |
| 2006                 | 25           | 96                | 0.66                              |
| 2007                 | 30           | 93                | 0.59                              |
| 2007                 | 20           | 95                | 0.56                              |
| 2010                 | 20           | 25                | 0.35                              |
| 2005                 | 28           | 95                | 0.52                              |
| 2006                 | 100          | 98                | 0.56                              |
| 2005                 | 30           | 93                | 0.65                              |
| 2010                 | 30           | 40                | 0.48                              |
| 2009                 | 40           | 95                | 0.62                              |

<sup>a</sup> Tree species that we recommended to be promoted in the urban greening of Qingdao.
<sup>b</sup> species in the list of national key protected wild plants.
<sup>c</sup> growth form: dbt, deciduous broad-leaved tree; ebt, evergreen broad-leaved tree; ent, evergreen needle-leaved tree.

Fig. 1. Phylogenetic tree of urban green spaces in Qingdao City reconstructed using Phylomatic to APGIII. Introduced tree species were marked in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
We used the online software Phylomatic (Webb and Donoghue, 2005) to reconstruct the phylogenetic tree, which is based on Angiosperm Phylogeny Group’s system (APG III, 2009). We used the BLADJ algorithm in Phylocom 4.1 (Webb et al., 2008) and estimates of angiosperm node ages were taken from Wikstrom et al. (2001) to assign branch lengths to the phylogenetic tree. The phylogenetic tree (Fig. 1) was presented using the web tool iTOL (Letunic and Bork, 2006).

We used Faith’s phylogenetic diversity (PD) metric (Faith, 1992) to quantify the phylogenetic diversity. PD was defined as the minimum total length of all the phylogenetic branches required to span a given set of taxa on the phylogenetic tree (Faith, 1992). We used the PD algorithm in Phylocom 4.1 (Webb et al., 2008) to estimate the phylogenetic diversity of urban green spaces and rural forests in Qingdao. The species list of rural forests in Qingdao was obtained from Cao (2015).

2.5. BVOC estimation

BVOCs were divided into three groups: isoprene, monoterpenes, and other VOCs (OVOCs). Isoprene emission was treated as light-dependent (synthesis emission); OVOCs were treated as light-independent (pool emissions); while monoterpenes were assumed to have both synthesis emissions and pool emissions (Ghirardo et al., 2010; Oderbolz et al., 2013; Ghirardo et al., 2016). The basic BVOCs algorithms were derived from Guenther (Guenther et al., 1995; Guenther, 1997) and were revised based on other studies (Staudt et al., 2000; Heald et al., 2009). The synthesis isoprene (EISP) and monoterpane (EMNS) emissions were quantified as:

\[
E_{\text{ISP}} = E_{\text{ISP}} D_I (τI) I_\gamma C_S + T_S
\]

\[
E_{\text{MNS}} = EMNS D_I (τI) I_\gamma S
\]

where \( I_\gamma \) is the basal emission rate (\( \mu g \text{ C} \cdot \text{g}^{-1} \cdot \text{h}^{-1} \)) at standard conditions (i.e. 30 °C leaf temperature and 1000 \( \mu m \text{ol m}^{-2} \text{s}^{-1} \) photosynthetically active radiation (PAR)); \( D_I \) is the peak foliar biomass (g); \( γ_T, γ_P, \) and \( γ_S \) are environmental correction factors accounting for the influence of temperature, light intensity, and seasonal variation on synthesis emissions; and \( C_S \) is the \( \text{CO}_2 \) inhibition on isoprene emission.

The basal emission rates \( \gamma \) of isoprene (Table A.2), monoterpenes (Table A.3), OVOCs (Table A.4), and the light dependent fraction (Table A.5) of monoterpenes were collected from published literatures (e.g. Klinger et al., 2002; Ren et al., 2014) and were assigned to each tree species using a taxonomic approach (Benjamin et al., 1996).

We used allometric equations (Table A.6) related to DBH to calculate the peak leaf biomass \( D \) of each tree species. To calculate the environmental correction factors, hourly air temperature and PAR data obtained from the meteorological data center of the China Meteorological Administration and monthly \( \text{CO}_2 \) concentration data from the Shandianzhi Baseline Observatory were used. As light varies dramatically within a tree canopy resulting in much lower emissions, a simple canopy model was applied to simulate the effects of solar radiation extinction (Geront et al., 1994).

The pool monoterpane (EMNP) and OVOCs (EOVP) emissions were quantified as:

\[
E_{\text{MNP}} = EMNP D_I (τI) I_\gamma S
\]

\[
E_{\text{OVP}} = EOVP D_I (τI) I_\gamma S
\]

where \( D_I, γ_T, \) and \( γ_P \) have the same meaning as those in Eq. (3). The details and calculations of \( D, γ_T, γ_P, γ_S, \) and the canopy model are found in the Appendix. The details and calculations of \( D, γ_T, γ_P, γ_S, \) and the canopy model are found in the Appendix. BVOC emissions from urban areas may also be influenced by some abiotic or biotic stresses (Peñuelas and Staudt, 2010; Ghirardo et al., 2016). Analyzing plant responses and adaptations to multiple stressors, defined as ‘urban plant physiology’ (Calafipietra et al., 2015), could achieve more accurate estimations on urban BVOC emissions. However, due to the lack of knowledge on these “stress-induced” emissions (Oderbolz et al., 2013), this study is limited to stress-free conditions.

We applied a dynamic BVOC estimation model (Ren et al., 2014) to further investigate the temporal trends of BVOC emissions and the role of management strategies in mitigating those emissions. The model included two parts. Part 1 was used to simulate processes like green space expansion, the tree planting/replacement, and tree growth with a temporal resolution of one year (Fig. A.1). The input of part 1 included the areal extent, species composition, tree density and age distribution of urban green spaces, and the peak leaf biomass of individual trees in each age group for each tree species. The output of part 1 was the peak leaf biomass of each tree species in each simulation year. Part 2 used species-specific basal emission rates, hourly meteorological data (temperature, PAR), \( \text{CO}_2 \) concentration data and the output of part 1 as its inputs and used the algorithms outlined above to simulate the hourly BVOC emissions for each tree species in each year (Fig. A.2). The time step and temporal resolution of part 2 was 1 h.

2.6. Scenario analysis

We developed a series of scenarios to explore the effects of tree species introduction on future plant biodiversity and BVOC emissions. In the business-as-usual (BAU) scenario, the annual air temperature of Qingdao in 2050 is projected to be 1.96 °C higher than present under the medium-mitigation emission scenario RCP 4.5 (Sun et al., 2015); the variations of \( \text{CO}_2 \) concentration (+3.5 ppm yr\(^{-1}\)) (Fang et al., 2014) and urban green space expansion (+1250 ha yr\(^{-1}\)) (NBSC, 2016) in Qingdao were assumed to follow current trends. Species composition of urban green spaces was assumed to remain unchanged over time since 2014. The annual increments of DBH (Table A.7) of different tree species were collected to simulate the changes in foliar mass during tree growth.

We then designed three urban green space management scenarios. In this study, we defined a tree species as a high-emitting species if the sum of its isoprene and monoterpane basal emission rates exceeded 10 \( \mu g \text{ C} \cdot \text{g}^{-1} \cdot \text{h}^{-1} \); if the sum is less than 10 \( \mu g \text{ C} \cdot \text{g}^{-1} \cdot \text{h}^{-1} \) and higher than 1 \( \mu g \text{ C} \cdot \text{g}^{-1} \cdot \text{h}^{-1} \), the species was defined as medium-emitting species; otherwise it is a low-emitting species (Ren et al., 2014). In the ‘proactive introduction’ scenario, the species composition of newly planted trees and existing trees was optimized through a moderate introduction of low-emitting ornamental tree species, that is, change the high-emitting species to combinations of the 11 selected ornamental species gradually. By 2050, the target proportion of these introduced species in total number of tree individuals was 15%. Under the ‘local optimization’ scenario, the high-emitting species will be replaced by the low-emitting species that have been used in the urban greening of Qingdao. The same target proportion of 15% was set to make it comparable to the ‘proactive introduction’ scenario. In the “reckless promotion” scenario, urban greening will continue to expand the use of the high-emitting introduced species, while reducing the use of the low-emitting local species. The proportion of the high-emitting introduced species was assumed to increase 15% by 2050.

3. Results

3.1. Species composition and plant diversity of green spaces in Qingdao City

In the urban vegetation survey of Qingdao, a total of 72 tree species were recorded (Table 1; Table A.1). These species belonged to 52 genera and 20 families. Among tree species, there were 60 deciduous species and 12 evergreen species. All deciduous species were broad-leaved trees and accounted for 76.5% of the total number of tree individuals; most evergreen species were conifers, such as pine and cypress, accounting for 22.2% of the total number of tree individuals; only two evergreen broad-leaved tree species, Magnolia grandiflora and Ligustrum lucidum, were founded in the survey. Park green space had the...
3.2. Adaptability of introduced tree species

In the introduction trial, the deciduous broad-leaved species *Houpeoa officinalis* had the highest survival rate (98%), followed by the two evergreen deciduous broad-leaved species *Michelia chapensis* and *Ilex rubra*. Only *Ceridiphyllum japonicum* and *Nyssa sinensis* had survival rates lower than 90% (Table 2). Most tree deaths happened in the year 2015 when there was the coldest winter in the past 30 years. The evergreen broad-leaved species *Ilex rubra* had the highest annual DBH increment of 0.87 cm yr$^{-1}$. For other species, DBH increments ranged from 0.35 to 0.82 cm yr$^{-1}$ (Table 2). Considering their BVOC emissions and adaptability to the urban environment, we recommended 11 of the 13 ornamental tree species to be promoted in the urban greening of Qingdao City (Table 2; Fig. 1). Their average mortality rate was similar to that (94%) of commonly used tree species in Qingdao.

| City               | Key attribute | Gleason | Phylogenetic diversity | Sources                  |
|--------------------|---------------|---------|-------------------------|--------------------------|
| Qingdao (urban)    | Mean          | 0.75    | 42                      | This study               |
| Max                | 1.67          |         |                         |                          |
| Min                | 0.17          |         |                         |                          |
| Overall            | 0.75          |         |                         |                          |
| Qingdao (rural)    | Overall       | 4.82    | 326                     | Cao (2015)               |
| Beijing            | Overall       | 4.17    | 305                     | Ren et al., (2017)       |
| Changchun          | Overall       | 3.49    | NM$^a$                  | Zhang et al. (2016)      |
| Nanjing            | Overall       | 4.58    | NM$^a$                  | Yang (2015)              |
| Hangzhou           | Overall       | 5.06    | 392                     | Chang et al. (2012)      |
| Guangzhou          | Overall       | 12.97   | NM$^a$                  | Jim and Liu (2001)       |

$^a$ The Gleason index was calculated using the species richness reported in the literature and the areal extent of green spaces in the corresponding city.

3.3. BVOC emissions from different tree species

As shown in Fig. 2, many common tree species in the urban green spaces of Qingdao are strong BVOC emitters. Among the primary tree species, *P. tomentosa* possessed the highest individual BVOC emission potential (1313 g C tree$^{-1}$), followed by *Platycladus orientalis* (1047 g C tree$^{-1}$), *Salix babylonica* (472 g C tree$^{-1}$) and *Populus × cannadensis* (417 g C tree$^{-1}$). *P. acerifolia*, *Liquidambar formosana*, *M. grandiiflora* and *S. japonica* also exhibited relatively high emission potentials (Fig. 2).

The total BVOC emissions from urban green spaces in Qingdao were dominated by only a few tree species despite the fact that dozens of tree species were planted. *P. acerifolia*, *P. tomentosa*, *S. japonica*, *P. orientalis* and *P. thunbergii* contributed the most to the total urban BVOC emissions. These 5 tree species accounted for 36% of the total number of tree individuals, while contributing 78% of total urban BVOC emissions. Among the top 20 tree species with the highest individual BVOC emission potentials, 11 species were introduced species (Fig. 2; Table A.1).

3.4. Temporal trends of total BVOC emissions and emission intensity

In 2014, the annual BVOC emission from urban green spaces was 1.27 $\times 10^9$ g C yr$^{-1}$; isoprene, monoterpenes, and OVOCs contributed 65, 17, and 18%, respectively (Fig. 3). The vegetation-based BVOC emission intensity (defined as BVOC emissions per unit land area occupied by vegetation) of Qingdao was 5.8 g C m$^{-2}$ yr$^{-1}$, and the region-based emission intensity (BVOC emissions per unit built-up area) was 2.6 g C m$^{-2}$ yr$^{-1}$.

Along with environmental changes and the further expansion of urban green spaces (BAU scenario), the BVOC emissions from urban green spaces were projected to rise rapidly and will reach 4.1 $\times 10^9$ g C yr$^{-1}$ by 2050 (Fig. 3), increasing by 222% compared with emissions in 2014. This increase mostly resulted from the rapid growth of urban trees and the planting of new trees. As isoprene emissions were light-dependent and inhibited by a high atmospheric CO$_2$ concentration, its emissions increase initially then begin to decrease around 2045. As some monoterpenes and all OVOCs emissions were light-independent, both of their emissions continued increasing year by year (Fig. 3). In 2050, the combined contribution of monoterpenes (29%) and OVOCs (24%) exceed that of isoprene (47%). The vegetation-based and region-based emission intensity will also increase to 11.1 g C m$^{-2}$ yr$^{-1}$ and 4.9 g C m$^{-2}$ yr$^{-1}$ by 2050, respectively.

4. Discussion

4.1. Significance of introduced species to enhance plant diversity of green spaces

Preserving biodiversity should be an important goal of strategic urban green space planning and management, especially in highly urbanized areas where little natural habitat remains (Kenney et al., 2011). Compared with other Chinese cities, the species diversity (Gleason index) of green spaces in Qingdao was comparable to Beijing and Changchun (Zhang et al., 2016) in northern China, while being lower than Nanjing (Yang, 2015), Hangzhou (Chang et al., 2012) and Guangzhou (Jim and Liu, 2001) in southern China (Table 3). In addition, urban species diversity was also 22% lower than the surrounding rural forests of Qingdao (Cao, 2015).

As for phylogenetic diversity (PD), Qingdao had the lowest value compared to other cities and the rural forests surrounding Qingdao (Table 3). The diminished phylogenetic information might decrease the capacity of urban green spaces to respond to environmental changes (Knapp et al., 2008). There is an urgent need to increase the species diversity and phylogenetic diversity of urbanized Qingdao.

Through the introduction of 11 selected ornamental tree species, the plant diversity of green spaces improved significantly. By 2050, the Gleason index of the whole city increased to 4.21, and the phylogenetic diversity increased to 315. These improvements in plant diversity are crucial for urban green spaces to sustain their various ecosystem functioning and sustainably supply the ecosystem services. Plant diversity was often used as a proxy for cultural services (Graves et al., 2017), meaning that the introduction of the ornamental tree species could contribute significantly to the enhancement of cultural services in urban areas. Moreover, since about half of the selected tree species are listed as national key protected wild plants (Table 2), the introduction and promotion is helpful for the *ex situ* conservation of these valuable plant species in cities.
4.2. Significance of introduced species to mitigating urban BVOC emissions

At present, Qingdao had moderate total BVOC emissions and emission intensity compared with other cities (Table 4) (Guo et al., 2013; Ren et al., 2014; Ghirardo et al., 2016). But compared with the background emissions of Shandong Province (2.1 g C m\(^{-2}\) yr\(^{-1}\)) (Fu and Liao, 2012), the built-up areas of Qingdao are hotspots of regional BVOC emissions. BVOCs mainly have local or regional air quality and human health impacts owing to their high chemical reactivity in the atmosphere (Harrison et al., 2013). Considering that more than 68% of Qingdao’s population lives in the built-up areas (QBS, 2015), Qingdao is facing a challenging situation to control its urban BVOC emissions. In China, short-term and long-term measures to mitigate AVOCs have been implemented to reduce ozone and PM\(_{2.5}\) pollutions in urban areas (Wang et al., 2015) but if the high BVOC emissions are not considered, the success of the current efforts to mitigate air pollution will be compromised (Simpson and McPherson, 2011).

By 2050, through a moderate introduction of the 11 selected low-emitting tree species to green spaces (‘proactive introduction’ scenario), the total BVOC emissions could be reduced by 34% compared with the BAU scenario (Fig. 3). These reductions in BVOC emissions will play significant roles in improving human health conditions in Qingdao.

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**Fig. 2.** The average individual BVOC emission potentials of the primary tree species in green spaces of Qingdao in 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Fig. 3.** Time series of annual BVOC emissions from urban green spaces in Qingdao under the BAU scenario and various management scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
ecosystem service costs and benefits of urban green spaces. Though the assumption could result in an underestimation of BVOC emissions (Ghirardo et al., 2016). To evaluate the relative contribution of stress-induced emissions, we conducted a sensitive analysis by using the latest species-specific induced monoterpenes emission rates from Ghirardo et al. (2016) to rerun the model. Results showed that our new estimate of monoterpenes emissions in 2014 was 17% higher than previous estimate after considering stress-induced emissions. We used air temperature instead of leaf temperature to calculate the temperature correction factor as the latter was not available, which would also lead to an underestimation of BVOC emissions, especially for broad-leaved trees (Leuzinger and Koerner, 2007). Moreover, we only considered the biochemical down-regulation of the isoprene synthesis under elevated CO2 concentrations (Heald et al., 2009). While in fact, the inhibition effect can be largely compensated by the stimulated growth of the canopy leaf under higher CO2 concentrations (Sun et al., 2013; Vanzo et al., 2015). Given the many uncertainties related to the empirical models, data sources and the assumptions, the lack of validation is a limitation of this study that should be addressed by future research.

5. Conclusions

In this study, based on detailed investigations of urban green spaces and an urban BVOC estimation model, the trade-off between biodiversity preservation and BVOC emissions of urban green spaces was evaluated for the first time. As a proxy of many ecosystem services, plant diversity in green spaces in Qingdao City was lower than their rural surroundings. However, urban areas have become hotspots of regional BVOC emissions, partly due to the reckless introduction of ornamental tree species. Furthermore, if no effective measures are taken, urban BVOC emissions in Qingdao will more than triple by 2050, which will have significant effects on future urban air quality and ultimately human health. Our study highlights the importance of introducing the appropriate tree species to maximize the net benefits of urban green spaces. Through a moderate (15%) introduction of 11 low-emitting ornamental tree species that have good adaptability to the urban environment of Qingdao, the species diversity and phylogenetic diversity of green spaces will increase by 15% and 11%, respectively. At the same time, one third of BVOC emissions can be reduced by 2050. This is a win–win strategy for urban green space management to increase co-benefits between biodiversity preservation and BVOC reduction, and thus can be applied to landscape planning in other cities. Although uncertainties exist within the present study, we believe our work is an important step to achieving a better understanding and effective management of urban green spaces.

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Appendix A. Supplementary data
Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ufug.2017.08.011.

References

APG III. (Angiosperm Phylogeny Group III), 2009. An update of the Angiosperm Phylogeny Group classification and the orders and families of flowering plants: APG III. Bot. J. Linn. Soc. 161, 105–121.

Aydog, Y.M., Yaman, B., Koca, D., Dademir, O., Kara, M., Alitöz, H., Dumanoglu, Y., Bayram, A., Tolunay, O., Dönden, M., Elbir, T., 2014. Biogenic volatile organic compound (BVOC) emissions from forested areas in Turkey: determination of specific emission rates for thirty-one tree species. Sci. Total Environ. 490, 239–253.

Benjamin, M.T., Sudjic, B., Koch, L., Winer, A.M., 1996. Low-emitting urban forest trees: a taxonomic methodology for assigning isoprene and monoterpenes emission rates. Atmos. Environ. 30 (9), 1437–1452.

Calfapietra, C., Fares, S., Manes, F., Morani, A., Sgrigna, G., Loretto, F., 2013. Role of Biogenic Volatile Organic Compounds (BVOC) emitted by urban trees on ozone concentration in cities: a review. Environ. Pollut. 183, 71–80.

Calfapietra, C., Penuelas, J., Niinemets, U., 2015. Urban plant physiology: adaptation–mitigation strategies under permanent stress. Trends Plant Sci. 20 (2), 72–75.

Cao, Y., 2015. Flora of Qingdao. China Forestry Publishing House, Beijing (in Chinese).

Chang, J., Ren, Y., Shi, Y., Zhu, Y., Ge, Y., Hong, S., Jiao, L., Lin, F., Peng, C., Mo, X., 2012. An inventory of biogenic volatile organic compounds for a subtropical urban-rural complex. Atmos. Environ. 56, 115–125.

Eickhoff, F.J., Kogner, K., Franz, S., Kaja, E.J.E., 2011. Urban forests and pollution mitigation: analyzing ecosystem services and disservices. Environ. Pollut. 159 (8–9), 2078–2087.

Faith, D.P., 1992. Conservation evaluation and phylogenetic diversity. Biol. Conserv. 61 (1–3), 1–10.

Fang, X.S., Zhou, L.X., Tans, P.P., Ciais, P., Steinbacher, M., Xu, L., Luan, T., 2014. In situ measurement of atmospheric CO2 at the four WMO/GAW stations in China. Atmos. Chem. Phys. 14 (5), 2541–2554.

Fu, L., 2012. Simulation of the interannual variations of biogenic emissions of volatile organic compounds in China: impacts on tropospheric ozone and secondary organic aerosol. Atmos. Environ. 59, 170–185.

Germon, C.D., Guenther, A.B., Pierce, T.E., 1994. An improved model for estimating emissions of volatile organic compounds from forests in the eastern United States. J. Geophys. Res.-Atmos. 99 (D6), 12773–12791.

Ghirardo, A., Koch, K., Taipale, R., Zimmer, K., Schnitzler, J.-P., Rinne, J., 2010. Determination of de novo and pool emissions of terpenes from four common boreal/ alpine trees by 13C02 labeling and PTR-MS analysis. Plant Cell Environ. 33 (5), 781–792.

Ghirardo, A., Xie, J.F., Zheng, X.H., Wang, Y.S., Grote, R., Block, K., Wildt, J., Mentel, T., Kienzl-Scharr, A., Hallquist, M., Butterbach-Bahl, K., Schnitzler, J.-P., 2016. Urban stress-induced biogenic VOC emissions and SOA-forming potentials in Beijing. Atmos. Chem. Phys. 16 (5), 2901–2908.

Glein, G.S., Matson, P.A., Dore, J.C., 1994. From photosynthesis to the atmosphere: carbon fluxes and their uncertainty. Annu. Rev. Ecol. Syst. 25 (1), 1–37.

Gleason, H.A., 1922. On the relation between species and area. Ecology 3, 158–167.

Gu, G., Gu, K., Ren, Y., Shi, Y., Chang, J., Tani, A., Ge, Y., 2013. Biogenic volatile organic compound emissions in relation to plant carbon fixation in a subtropical urban-rural complex. Urban Planet. 13, 74–84.

Hansen, P.M., Morrison, T.A., Brovkin, V., Friedlingstein, P., Hurtt, G.C., Pongratz, J., Poulter, B., 2013. Global-scale inventory of woody biomass and its dynamic representation in Earth system models. Biogeosciences 10 (9), 3845–3861.

Heald, C.L., Duhl, T., Emmons, L.K., Riester, D.J., 2008. Evaluation of the MEGAN2.1: an extended and updated framework for modeling biogenic emissions. Atmos. Chem. Phys. 8, 4561–4575.

Heald, C.L., Duhl, T., Emmons, L.K., 2008. Incorporation of ozone feedbacks in the MEGAN biogenic emission model. Atmos. Chem. Phys. 8, 6461–6478.

Heald, C.L., Duhl, T., Emmons, L.K., 2010. Seasonal variation of emissions of biogenic volatile organic compounds from forests in the eastern United States. J. Geophys. Res.-Atmos. 115, D12302.

Hett, D.A., Pyles, D.R., 2016. multiGAP: a new, global forest canopy structure model. J. Geophys. Res.-Biogeosci. 121 (6), 1505–1525.

Hett, D.A., Pyles, D.R., 2017. multiGAP: a new, global forest canopy structure model. J. Geophys. Res.-Biogeosci. 122 (9), 1923–1947.

Hett, D.A., Pyles, D.R., 2018. multiGAP: a new, global forest canopy structure model. J. Geophys. Res.-Biogeosci. 123 (2), 311–336.

Heilman, M., Elgin, B.D., 2016. Biogenic emissions from urban trees: a methodological review and assessment of the multiGAP model. J. Geophys. Res.-Biogeosci. 121 (1), 106–127.

Heilman, M., Elgin, B.D., 2017. Biogenic emissions from urban trees: a methodological review and assessment of the multiGAP model. J. Geophys. Res.-Biogeosci. 122 (9), 1923–1947.

Heilman, M., Elgin, B.D., 2018. Biogenic emissions from urban trees: a methodological review and assessment of the multiGAP model. J. Geophys. Res.-Biogeosci. 123 (2), 311–336.
http://phylodiversity.net/phylocom/.

Wilkinson, N., Savolainen, V., Chase, M.W., 2001. Evolution of the angiosperms: calibrating the family tree. Proc. R. Soc. B-Biol. Sci. 268 (1482), 2211–2220.

Wolch, J.R., Byrne, J., Newell, J.P., 2014. Urban green space, public health, and environmental justice: the challenge of making cities ‘just green enough’. Landsc. Urban Plan. 125, 234–244.

Yang, J., 2015. Study on the Diversity of Woody Plant Communities in Green Spaces of Nanjing City. Master Dissertation. Nanjing Agricultural University, Nanjing, Jiangsu (in Chinese).

Zhang, H., Jin, C.Y., 2014. Species diversity and performance assessment of trees in domestic gardens. Landsc. Urban Plan. 128, 23–34.

Zhang, D., Zheng, H.F., He, X.Y., Ren, Z.B., Zhai, C., Yu, X.Y., Mao, Z.X., Wang, P.J., 2016. Effects of forest type and urbanization on species composition and diversity of urban forest in Changchun, Northeast China. Urban Ecosyst. 19 (1), 455–473.