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Natural Selection? Picking the Right Trees for Urban Greening

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Abstract

Fast-track programs to plant millions of trees in cities around the world aim at the reduction of summer temperatures, increase carbon storage, storm water control, provision of space for recreation, as well as poverty alleviation. Although these multiple benefits speak positively for urban greening programs, the programs do not take into account the drastic differences between urban and natural systems. Elevated temperatures together with anthropogenic emissions of air and water pollutants distinguish the urban system. Although the potential for emissions of volatile organic compounds from urban vegetation combined with anthropogenic emissions to produce ozone has long been recognized, the municipalities actively enlarging their green spaces still generally either overlook or ignore this fact. Here we assess the scientific evidence of biogenic induction of ground-level ozone concentrations in urban and sub-urban areas and argue that it is feasible and beneficial to implement measures necessary to limit biogenic contributions to air pollution. With the example of biogenic induction of ground level ozone concentrations we demonstrate that interactions between plants and urban ambient conditions have to be taken into account in all efforts of creating "naturopolises". We explore the mechanisms behind these interactions and propose a pathway to improve our understanding of these interactions.

1. Introduction

To improve the livelihoods of the largest part of the world's populations in the years to come, many cities are actively increasing green space area or planting trees (Knuth, 2006; Young, 2011). Chinese cities have even reported a consistent increasing trend in the urban green cover over the past two decades, from 17.0% in 1989 to 37.3% in 2009 (Zhao et al., 2013). Various national and international programs exist to promote urban greening efforts. National programs target the expansion of forests and green space in general, implementing international agreements and conventions which have broader goals such as mitigation of climate change or desertification (Knuth, 2006). The Agenda 21 (United Nations, 1993) refers to "urban forestry in the context of the achievement of the objective to promote greening on urban and peri-urban human settlements". The Billion Tree Campaign launched by UNEP in 2006 and later handed over to "Plant for the Planet" (Plant for the Planet) planted 12.5 million trees in urban and rural areas in the first five years. The Earth Day Network developed a Canopy Project (Earth Day Network) in partnership with the Billion Tree Campaign. The accomplishments of this project include 1.5 million trees planted in 18 countries over three years. In the United States, projects to expand urban canopies have been undertaken in New York City, San Francisco, Los Angeles, St. Louis, Atlanta, Baltimore, Cleveland, Flint, and Chicago. With a few exceptions (Pincetl et al., 2013; Young, 2011) there has been little analysis of the historical, cultural, political, or institutional origins of such programs, or the efficiency of their design and implementation. The only existing review of urban greening programs in eight major cities and one metropolitan county in the United States (Young, 2011) shows that most analyzed urban greening programs are small, individual projects rather than integrated, community–wide efforts. Cities employ a spectrum of planning strategies to advance such programs, ranging from highly institutionalized initiatives to decentralized, grassroots efforts. Although cities use various strategies to support and implement urban greening initiatives, they pursue very similar goals.

Fast-track programs to plant millions of trees in cities around the world aim at the reduction of summer temperatures, increase carbon storage, storm water control, provision of space for recreation, as well as poverty alleviation. Urban and suburban forests and green spaces can become a source of bio-energy (de Richter et al., 2009) or be used for food production, both of which are vital for poor urban communities. Although these multiple benefits speak positively for urban greening programs, the programs do not take into account the potential of several popular urban tree species and associated management practices to contribute to the production of secondary air pollutants, in particular ground-level ozone. Annually ozone has been associated with an estimated 0.7 ± 0.3 million respiratory mortalities (Anenberg et al., 2010) and causes tens of billions of dollars of crop production losses globally (Van Dingenen et al., 2009). Although the potential for emissions from urban vegetation combined with anthropogenic emissions to produce ozone (Calfapietra et al., 2013; Chameides et al., 1988) has long been recognized, many municipalities actively enlarging their green spaces still either overlook or ignore this message. Here we assess the scientific evidence of biogenic induction of ground-level ozone concentrations in urban and sub-urban areas and argue that it is feasible and beneficial to implement measures necessary to limit biogenic contributions to air pollution.

2. Emissions of BVOC and NO_x

Nearly all plants emit biogenic volatile organic compounds (BVOC) during reproduction, growth, and defense. The BVOCs are emitted by leaves, flowers, and fruits of plants. BVOC are used as a communication media between plants, on one hand, and between plants and insects, on the other hand (Laothawornkitkul et al., 2009). While trees emit mostly isoprene and monoterpenes, grasses produce oxygenated BVOCs and some monoterpenes. Generally

BVOC emissions increase with temperature and light, but the production and/or release of BVOCs also increase when the plants are exposed to severe drought, air pollution, or when plant tissue is damaged (Holopainen and Gershenzon, 2010). Several factors may lead to increases in BVOC emissions in urban areas: planting species with high BVOCs emissions, mowing of lawns, insect outbreaks, and generally rising air temperatures, with the last two predicted to intensify in cities under climate change (Tubby and Webber, 2010). Emissions of isoprene, one of the most abundant BVOC, exponentially increase with temperature, reach their maximum at the leaf temperature of about 40°C, and rapidly decline thereafter (Guenther et al., 1993). Recent observations of holm oak BVOC emissions over different seasons in a forest near Barcelona, Spain indicated a one order of magnitude increase in isoprenoid VOCs in summer as a result of the vegetation physiological activity enhanced by the high temperatures and solar radiation (Seco et al., 2011).

Oxides of nitrogen (NO_x) are a family of highly reactive gases including nitric oxide (NO) and nitrogen dioxide (NO_2), which are produced during combustion. The sources of atmospheric NO_x are natural (e.g., lightning) as well as anthropogenic. Sources of anthropogenic NO_x include automobiles, trucks and various non-road vehicles (e.g., construction equipment, boats, airplanes, etc.) as well as power plants, industrial boilers, cement kilns, and turbines.

BVOC emissions are relatively harmless if released in remote areas, where concentrations of NO_x are relatively low. The first study showing that urban BVOC emissions together with anthropogenic emissions of NO_x, mostly from automobile traffic, can substantially affect ground ozone levels dates back to late 1980s (Chameides et al., 1988). Since vegetative emissions are about three times more reactive than VOCs from anthropogenic sources, i.e., motor vehicles (Karlik and Pittenger, 2012), plant VOC emissions lead to more rapid formation of ozone. Recent studies confirm a strong influence of BVOC emissions on urban air quality in Asia (Kim et al., 2013; Situ et al., 2013; Wang et al., 2013; Wang et al., 2012), Europe (Duane et al., 2002; Hellén et al., 2012), and North America (Diem, 2000; Papiez et al., 2009). The emissions of BVOC and their impact on the ozone production change over the seasons and reach the maximum during warm and hot seasons in tropical regions. Isoprene emissions in summer in the subtropical city of Taipei, Taiwan, were the highest among isoprene emissions measured in many other urban and suburban areas in temperate zones (Wang et al., 2013). Observed emissions were predominantly attributed to vegetation and had a large substantial potential to influence formation of ozone. Situ et al. (2013) showed that the modeled impact of BVOC emissions on the ozone peak increase was ~ 10 ppb on average with a maximum increment of 34 ppb over the Pearl River delta in China in summer. Wang et al. (2012) attributed the three longest ozone pollution episodes in May and early June of 2008 in Xi'an, China to the high BVOC emissions from the vegetation of the Qinling Mountains. On those three days hourly ozone concentrations exceeded the Chinese National Ambient Air Quality Standard Grade 2 of 102 ppbv for more than four hours. Qinling Mountains have forests, which are especially lush in spring, summer, and early autumn. In Insubria, Northern Italy, during the growing season isoprene exhibited a distinct diurnal variation with maximum concentrations late in the afternoon attributed to strong emissions from the abundant vegetation of broad-leaf deciduous trees in this area (Duane et al., 2002). The subsequent calculations showed that isoprene's contribution to the local ozone formation was as high as 50–75% in summer. Papiez et al. (2009) suggested that under certain conditions even modest BVOC emissions from palm trees and ashes could have a significant impact on air quality. Biogenic terpenes increased time-dependent ozone production rates by a factor of 50 in a suburban location near Las Vegas, the United States, that was downwind of the urban core (high NO_x; low anthropogenic VOC). A positive feedback loop between BVOC emissions, air pollutants, and climate (Pinto et al., 2010) can be formed, because high ground-level ozone concentrations and elevated air temperatures typical for the cities increase BVOC emissions even further. This feedback loop is however still poorly documented and needs further research.

There is very little literature about the impact of tree age on BVOC emissions of trees. Kim (2001) found that seven year old saplings of slash pine emitted seven-fold the monoterpene amount that four year old saplings. Funk et al. (2006) found the opposite for a different tree species, an approximately 10-25 % decline of isoprene emission potential of eucalypt trees between two and six year of age. Leaf longevity can also affect emissions. Both Alves et al. and Bracho-Nunez et al. (Alves et al., 2014; Bracho-Nunez et al., 2011) suggested that BVOC emissions mostly decrease with leaf age.

The increasing understanding of the basic chemistry responsible for ground-level ozone production through emissions of NO_x and VOC has led to the implementation of stringent controls on anthropogenic emissions in much of the developed world. In Europe, for example, non-methane VOC emissions have been reduced by 55% in the period 1990-2009, while NO_x emissions have been reduced by 45% (EEA, 2013). These reductions in ozone precursor emissions have coincided with decreases in the frequency of ozone threshold exceedances, although quantifying the role of the emission reductions is difficult, due to other influencing factors such as variability in meteorological conditions.

Increases in BVOC emissions from urban greening efforts with plant species releasing large amounts of BVOC have the potential to reverse the gains made in controlling anthropogenic emissions of VOC such as declined exceedances of ozone threshold in urban areas. Such urban greening efforts can contribute to increased ozone formation with concomitant negative impacts on health and agriculture in urban and suburban areas.

3. Urban greening programs

The last abovementioned message has not taken hold in municipalities yet, although municipalities are the major players in the design and implementation of international, national, or local programs of urban greening. In the countries of West and Central Asia several governmental agencies are responsible for urban greening policies and strategies, with municipalities responsible for planning and management of green areas within cities (Knuth, 2006). In the United States many of these projects are implemented as public-private partnerships, in which local government agencies partner with non-profit organizations and community groups to plant and maintain the trees (Pincetl et al., 2013; Young, 2011). These partnerships also encourage residents to provide basic care and maintenance to trees such as watering, even though most residents see tree care as the responsibility of the city's government (Moskell and Allred, 2013). Cities actively develop their own programs for the creation of new green spaces, planting trees, or roof gardens. For instance, Los Angeles's mayor initiated the Million Trees Los Angeles program, which aimed to make Los Angeles the greenest large city in the United States. This program has been implemented by city nonprofit organizations in collaboration with regular city departments. Despite the program's ambitions to have a long-term impact on climate and life quality in the city, there were no environmental criteria such as trees' water use or canopy size to guide tree selection (Pincetl et al., 2013). Ecosystem services provided by different tree species are however well documented in the literature (Donovan et al., 2005). Although air pollution is a problem in many cities, none of the urban greening programs provided explicit guidance on which plant species should be preferred or avoided for large scale plantings so as to prevent air pollution increase.

Common considerations guiding the selection of species encompass, but are not limited to, their representativeness of pre-settlement vegetation, decorativeness, salt tolerance, ability to uptake soil contaminants, and growth performance. For example poplars (*Populus*) and willows (*Salix*), species that are among the highest isoprene emitters (Figure 1), are actively planted on the brownfields around Liverpool, UK (French et al., 2006). The goal of the Liverpool project is to understand whether tree planting provides an effective long-term solution to soil contamination issues either through extraction or immobilisation of contaminants. The choice of trees was mostly based on the UK Forestry Commission guidance (Tabbush and Parfitt, 1999). The short-rotation coppice willow clones were chosen for their ability to clean-up cadmium contamination of soil (Dickinson and Pulford, 2005). As a pilot project, a poplar plantation has been recently established in Berlin. The goal of the Berlin project is to test the viability of urban forest plantations as a source of bio-fuel (Berlin Senat, 2012). In New York the share of high emitting trees such as Tulip tree *(Liriodendron tulipifera*) and Blackgum (*Nyssa sylvatica*) was low before the New York tree planting campaign started (Nowak et al., 2007). Despite their high BVOC emissions, these species are still on the list of trees being planted within the framework of the MillionTreesNYC project running since 2007 (Million Trees NYC).

4. Recommendations

While there is no doubt that greening of cities brings multiple benefits to their dwellers, as long as cities remain strong emitters of NO_x, caution should be exercised while making urban greening plans. The growing popularity of a “return to nature” in urban areas will actually be a transition to a new “urban nature”, which will be quite different from the nature which was left behind. The urban system is characterized by anthropogenic emissions of air and water pollutants, which do not exist in undisturbed ecosystems. In addition, air temperatures are higher in urban than in rural areas and provide an additional stress factor on urban vegetation. Interactions between plants and urban ambient conditions have to be taken into account in all efforts of creating “naturopolises”. Shifting the focus of urban greening programs from the restoration of a historical ecological system to the creation of a coupled natural-human ecosystem will lay the ground work for sustaining the quality of life on the Earth (Palmer et al., 2004).

Policies targeting reduction of ground-level ozone in urban and suburban areas must consider a massive reduction of the NO_x levels. Limiting emissions of VOC from both plants and anthropogenic sources should be contemplated until NO_x concentrations in cities and sub-urban areas are diminished. Certain tree species known to be high BVOC emitters (Figure 1) should possibly be banned from being planted in large quantities in urban and suburban areas. Also, a reduction of turf grass area in cites may be considered as a measure towards air quality improvement. Turf grasses cover an appreciable area in some countries (Milesi et al., 2005) and are mowed at least once per week during warm seasons. The oxygenated BVOC are emitted from freshly cut grass as part of wound defense mechanism and can also lead to the production of ozone (Brilli et al., 2012; Kirstine et al.).

Public awareness of BVOC and NO_x emissions should be raised, which is especially important in the context of tree-planting campaigns and community-driven efforts of city greening. Here, recommendations about which tree species to plant are particular important and can be provided at the level of campaign or community coordinators or financial donors.

We suggest that further investigations are urgently needed to determine which plant species should be favored, and others possibly banned from large-scale planting in urban and suburban settings until NO_x concentrations are drastically reduced. The feedback loop between BVOC emissions, air pollutants, and air temperature should be further investigated to identify environmental conditions under which it can form.

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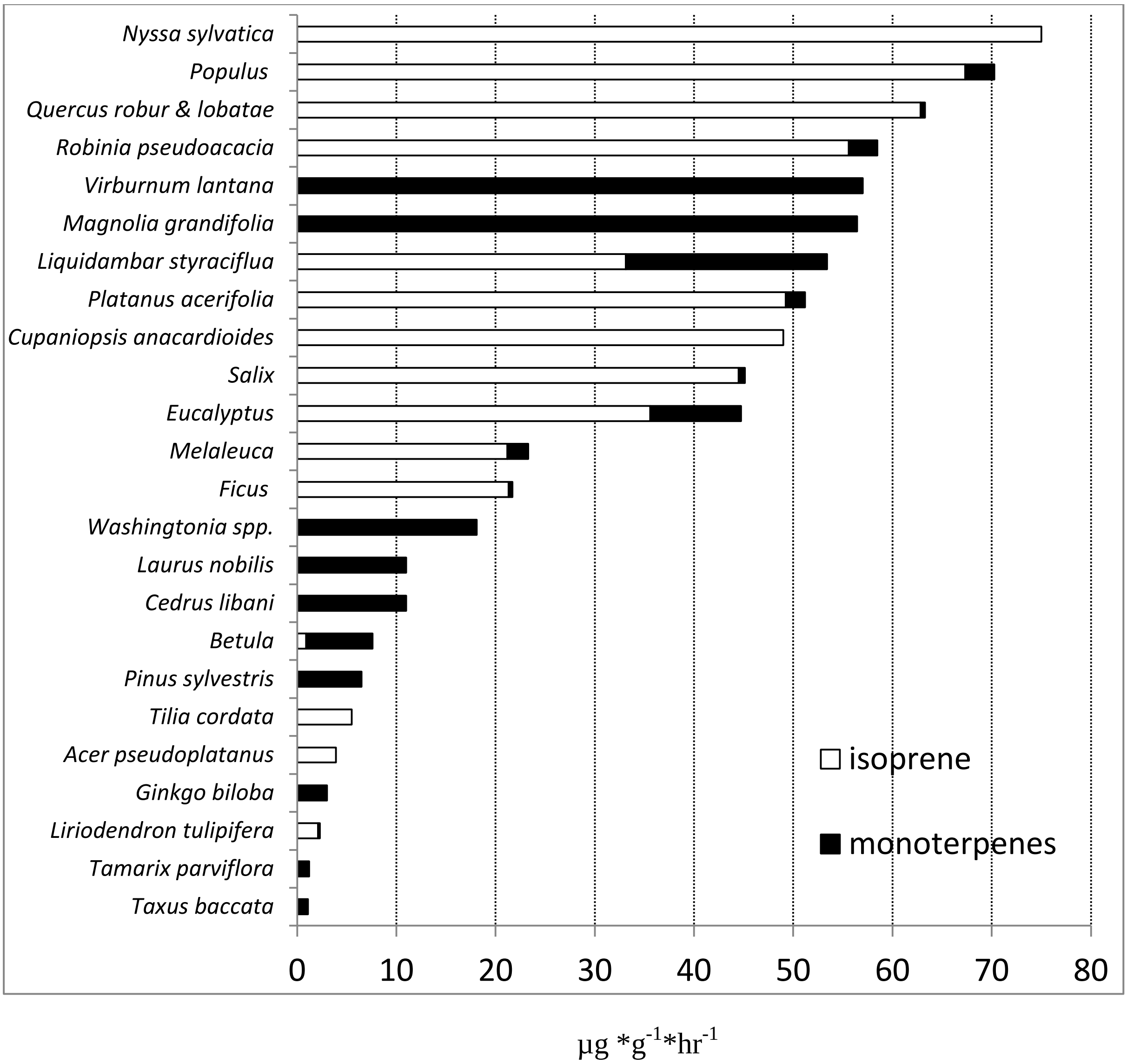

Fig 1. Popular urban plants species with high, medium, and low BVOC emissions rates (in micrograms of isoprene or monoterpenes per gram of leaf mass per hour). Average emission rates (see Table 1 in Supplementary Materials for details) are reported under standard conditions of temperature and light: 30° C and photosynthetically active solar radiation of 1000 mol*m^{-2} *sec^{-1}. One can find a recent compilation of studies estimated BVOC emissions from other plants in Guenther (2013).