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Ecophysiological and micromorphological characterization of green roof vegetation for urban mitigation

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ABSTRACT

Urban greening helps to improve environment quality and human health thanks to the ability of plants to absorb greenhouse gases and remove significant amounts of air pollutants. Green roofs, providing vegetated surfaces in dense cities, can help to mitigate the negative effects of urban pollution. The present study aimed to evaluate the potential ability of fifteen green roof species (*Lonicera pileata*, *Satureja repandens*, *Hypericum moserianum, Erigeron karvinskianus*, *Solidago praecox*, *Rudbeckia sullivantii 'Goldsturm'*, *Filipendula purpurea*, *Filipendula vulgaris 'Kahome'*, *Gaura lindheimeri*, *Campanula persicifolia*, *Veronica longifolia*, *Sedum spectabile*, *Origanum vulgare*, *Salvia nemorosa*, and *Achillea millefolium*) to mitigate carbon dioxide (CO_2) and urban pollutant concentration analysing the leaf physiological traits (gas exchange) and morphological structures (stomata, trichomes, epicuticular waxes and cuticular ornamentation) involved in pollutant removal. Furthermore, considering the important role of biogenic volatile organic compounds (BVOC) on the photochemical reactivity of the atmosphere, their species-specific emission was also assessed together with the derived ozone forming potential (OFP). Our results suggested that the potential mitigation capacity based on the investigated traits of the shrubs and herbaceous species was species-specific. The very low potential of all the tested species to form ozone indicated their suitability for urban planning programs.

1. Introduction

About half of the world population is currently living in cities with a predicted rise up to 60% by 2030 (Martine and Marshall, 2007), making the cities more congested and polluted due to high traffic density, conditioning and heating (Blanco et al., 2009). The rising concentrations of carbon dioxide (CO_2), one of the main greenhouse gases trapping heat in the atmosphere, and of air pollutants such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3) and airborne particulate matter (PM), are causing adverse effects on human health (WHO, 2006; McDonald et al., 2007). The atmospheric particles, especially those with an aerodynamic diameter $\leq 10\,\mu m$ (PM_{10} and $PM_{2.5}$) that are considered the most hazardous (WHO, 2005; EEA, 2007), pose a long-term threat to human respiratory functions, finally increasing mortality rate (Powe and Willis, 2004; Birmili and Hoffman, 2006; Tchepel and Dias, 2011).

Decreasing anthropogenic pollution from vehicular and industrial sources is generally challenging and it becomes vital to explore all alternatives to lower pollution concentrations in urban areas. Because of its low environmental impact, cost effectiveness and positive response from the urban community (Escobedo et al., 2008), vegetation is often considered as an effective and feasible remediation strategy for the reduction of pollutant concentration and, consequently, for health protection (Villeneuve et al., 2012; Gascon et al., 2016). In the last decades green roofs, implying the conversion of impervious surfaces into a multifunctional land cover (Mogbel and Salim, 2017), have become popular in city planning (Baik et al., 2012). As roofs can form up to the 35%-50% of the urban land area (Dunnet and Kingsbury, 2004; Nowak et al., 2013), the use of these usually neglected surfaces could be an effective strategy to mitigate the negative impacts of urbanization (Moghbel and Salim, 2017). Green roofs may be intensive or extensive (Agra et al., 2017). Extensive green roofs consist of only herbaceous perennial or annual plants, with shallow media depths (less than 15 cm), and require minimal maintenance; intensive roofs, including shrubs and trees as well, have deeper media and are similar to landscaping found at natural ground level (Agra et al., 2017). Due to building weight restrictions and costs, extensive green roofs are far more common (Getter et al., 2009). Green roofs provide many ecosystem services such as regulation of building temperatures, reducing urban heat-island effects, adsorbing noise, dust and smog, and reducing

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stormwater runoff (Baik et al., 2012; Li and Babcock, 2014); they also increase urban biodiversity and provide a more aesthetically pleasing environment (Getter et al., 2009). Green roofs could reduce the high levels of CO_2 concentrations in big cities by directly sequestering substantial amounts of carbon in plants and soils through biological processes, while indirectly reducing carbon emissions from power plants and furnaces due to energy savings in heating and cooling (Li and Babcock, 2014; Agra et al., 2017). Green roofs act as passive filters of airborne particulate matter, especially if adjacent to strong sources, and if characterized by plants with high near-surface roughness (Speak et al., 2012). Finally, there is already some evidence for the potential benefits of green roof vegetation in air pollution control (Clark et al., 2005; Yang et al., 2008; Rowe, 2011; Li and Babcock, 2014; Jayasooriya et al., 2017). Green roofs are thus increasingly being recognized as investments that can help address many of the challenges facing urban residents; however, further research on aspects such as plant selection, development of improved growing substrates, and water quality of runoff are needed (Rowe, 2011; Li and Babcock, 2014).The potential of vegetation to reduce greenhouse gases and urban pollution is influenced by the differences in the ability to sequester carbon due to species diversity, ecosystem age, plant density, species composition, and climate and plant morphology (Whittinghill et al., 2014). Plants can also intercept and capture pollutants, both gaseous and particulate (Grote et al., 2016). According to their chemical structure, gaseous pollutants (e.g. O_3, NO_x and SO_2) can enter leaves through the stomata following the CO_2 diffusion pathway by absorption (Omasa et al., 2012), or can interact with the cuticle and epidermis wax layer by adsorption (Omasa et al., 2002a, 2002b; Singh and Verma, 2007). Differently, particles are removed from the air by dry deposition onto leaves and branches (Omasa et al., 2012) and can be transferred to the ground during rain (Chen et al., 2016; Yan et al., 2016). Previous studies assessed the deposition rate at which particles are taken up by the plants (Freer-Smith et al., 2005; Litschke and Kuttler, 2008; Peachey et al., 2009). Each plant species is characterized by a different capacity of capturing particulate and several factors are involved in the mitigation process (Baraldi et al., 2010; Sæbø et al., 2013). Based on these assumptions, the species potential capacity of environmental mitigation is determined by structural and functional eco-physiological traits. Indeed, plants have species-specific functions such as photosynthetic efficiency, leaf micromorphology, leaf traits, crown geometry, foliar distribution and air-flow (Baraldi et al., 2010; Sæbø et al., 2013; Grote et al., 2016). In particular, through specific leaf micromorphology characteristics such as stomata density, cuticular ornamentation, wax coating, and trichomes, it is possible to estimate the potential of plants to adsorb particles (McPherson, 1994; Jamil et al., 2009; Blanusa et al., 2015). Through leaf ecophysiological traits, like stomatal conductance, gas metabolic rates in leaf tissue (Omasa et al., 2012) and stomatal density (Drake et al., 2013) it is feasible to determine the foliar gas absorption of CO_2, SO_2, O_3, NO_2, peroxyacetyl nitrate (PAN) and hydrogen fluoride (HF). Besides, the epicuticular waxy layers play a role in absorbing aromatic hydrocarbons such as benzene and toluene (Holoubek et al., 2000; Omasa et al., 2002a, 2002b). Finally, the complexity of leaf structure determined by leaf micro-roughness allows particles deposition (Beckett et al., 2000; Lei et al., 2006; Sæbø et al., 2012) and plays a role in preventing adsorbed particulate removal by wind or rain (Beckett et al., 2000; Prajapati and Tripathi, 2008; Hwang et al., 2011; Mori et al., 2015).

When planning an urban “plantscape” it is also necessary to consider the species-specific capacity of plants to emit biogenic volatile organic compounds (BVOC), including isoprenoid compounds as isoprene and monoterpenes, which are generally released for communication, defense and/or protection under biotic and abiotic stresses (Peñuelas and Llusià 2004; Rosenstiel et al., 2004; Loreto et al., 2014; Carriero et al., 2016). The importance of BVOC in urban areas is related to the high reactivity of some of these compounds that can affect the atmospheric chemistry (Fehsenfeld et al., 1992; Chameides et al., 1992). For instance, when moderate or high levels of NO_x are present in urban environment, isoprene breakdown leads to tropospheric O_3 formation (Hewitt et al., 2011), while in NO_x-limited conditions BVOC can reduce O_3 (Curci et al., 2009; Calfapietra et al., 2013). Furthermore, monoterpenes can contribute to the formation of secondary organic aerosols and particles (Grote et al., 2016).

Since quality and quantity of pollutants absorbed and BVOC emissions vary depending on species and environmental conditions, plant biodiversity can significantly affect photochemical reactivity in urban environment. Hence, it is crucial to select the most suitable species in planning urban green areas for pollution mitigation. A list of tree species apt for urban landscape planning is already available (Baraldi et al., 2010; Sæbø et al., 2013; Grote et al., 2016), but very little is known on the most suitable shrubs and herbaceous species for air pollution control (Currie and Bass, 2008) though they could contribute to reduce urban emissions in areas where ground planting is not always feasible due to the already established structures (i.e. paving and buildings).

Aim of this study was to investigate the potential ability of 15 shrubs and herbaceous species, commonly used as vegetation growing on rooftops, to mitigate greenhouse gases emissions and urban pollutants by analysing functional and structural leaf species-specific properties, namely CO_2 absorption, BVOC emission and leaf micromorphology. The specific contribution of BVOC on ozone-forming potential (OFP) was also estimated. Our results could provide useful information on the type and composition of green roof vegetation for enhancing the benefits on overall environmental quality using an ecophysiological and micromorphological approach.

2. Materials and methods

2.1. Plant material

For this study fifteen species were selected among shrubs, perennial herbaceous and aromatic plants generally used as green roof vegetation (Wolf and Lundholm, 2008; Dunnett et al., 2008; Getter et al., 2009; Rowe, 2011; Speak et al., 2012; Whittinghill et al., 2014). These species belong to nine different families: the low ground covering evergreen shrub *Lonicera pileata* Oliv. (Caprifoliaceae), the evergreen shrub *Satureja repandens* L., (Lamiaceae), the semi-evergreen shrub *Hypericum moserianum* L. (Clusiaceae), the perennial herbaceous plants *Erigeron karvinskianus* DC, *Solidago praecox* Moench, *Rudbeckia sullivantii 'Goldsturm'* Aiton (Asteraceae), *Filipendula purpurea* Mill., *Filipendula vulgaris 'Kahome'* Moench (Rosaceae), *Gaura lindheimeri* Engelm. & A. Gray (Onagraceae), *Campanula persicifolia* L. (Campanulaceae), *Veronica longifolia* L. (Plantaginaceae), *Sedum spectabile* Boreau (Crassulaceae), and the perennial aromatic herbs *Origanum vulgare* L. (Lamiaceae), *Salvia nemorosa* L. (Lamiaceae) and *Achillea millefolium* L. (Asteraceae). To compare the different plant species performance under the same environmental conditions, two-year old healthy plants of each species were grown in pots at well-watered conditions in the nursery of the Institute of Biometeorology in Bologna. The gas exchange measurements of carbon assimilation (A), stomatal conductance, (g_s) transpiration (E) and BVOC emission were taken from three healthy leaves of three plants for each species. For micro-morphological analyses three further leaves were harvested from the same plants.

2.2. Gas exchange and BVOC emission

Carbon assimilation, stomatal conductance and transpiration were evaluated using the LI-COR 6400 Photosynthesis System (LI-COR, Inc., USA) by placing a fully developed leaf in a 6 cm^2 cuvette. Measurements were performed at reference CO_2 (400 $\mu mol\ mol^{-1}$), flow rate (500 $\mu mol\ min^{-1}$), photosynthetic active radiation (PAR) (1000 $\mu mol\ m^{-2}\ s^{-1}$), and at a temperature of 30 °C with 30–50% of relative humidity. Carbon assimilation was measured for approximately 2–4 min, until the photosynthetic intensity was stabilized. For the