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Estimation of the potential BVOC emissions by the different tree species in Malmö

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Abstract

BVOC emissions from trees contribute to ozone and secondary aerosol formation and therefore have an impact on air quality. The two most abundant BVOCs emitted from trees are isoprene and monoterpenes. In urban areas, air pollution levels are already elevated and high rates of isoprene and monoterpene emissions from trees will potentially contribute to even higher levels of ozone and aerosols in the atmosphere. In Malmö, trees are planted along streets, in parks and in private gardens. In this study, aerial images were used to determine the overall tree cover, the species composition and their potential contribution to BVOC levels in the atmosphere, with the help of literature sources for standardized emission rates. The results showed that 14% of the study area were covered by trees, and for a smaller section of the study area, it was determined that 62% of that tree cover resulted from unknown and unregistered trees. For the whole study area, *Tilia* (linden) trees proved to be the dominant genus, making up over 44% of the known tree cover. The second most abundant tree genus is *Aesculus* (horse chestnut) with 8.2% of the tree cover and *Platanus* (plane tree) with 8.1% of the tree cover. The emission potential was calculated for each species using literature values and multiplying them with the area that each tree covered. The results showed that *Quercus robur (European oak)*, *Platanus x hispanica* (London plane) and *Quercus rubra* (northern red oak) have the highest isoprene emission impact on atmospheric chemistry by having standardized emission rates of around 19 to 67 μgC gdw^{-1} h^{-1} and therefore falling into the categories of moderate to highest emitters of the emission categories used in this study. The tree species with the highest monoterpene emission impact levels are *Aesculus hippocastanum* (horse chestnut), *Fagus sylvatica* (European beech) and *Platanus x hispanica* (London plane) with standardized emission rates of around 4 to 12 μgC gdw^{-1} h^{-1} and being in the categories of high and highest emitters. The most abundant genus, *Tilia*, is a low emitter and therefore does not have the highest emission contribution, despite its high occurrence. The methodology proved to be appropriate to give an estimate of emission impact for a large area but came with many limitations and uncertainties and would not be appropriate to calculate the emission impact on an individual tree level.

Keywords: BVOC emissions, isoprene, monoterpene, air quality, Malmö.

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1. Introduction

The human population is growing, and with this, cities and urban settlements increase in size and density with a worldwide annual growth rate of around 2% in 2017 (The World Bank Group 2018b). Along with the growing population comes an increasing amount of air pollution. In cities, motorized traffic, households, industrial processes, energy production, and fires are the main sources of air pollution, as stated by the European Environment Agency (EEA 2018). The main pollutants are carbon monoxide (CO), sulphur oxides (SO_x), non-methane volatile organic compounds (NMVOCs), fine particulate matter (PM10 and PM2.5), nitrogen oxides (NO_x), ozone (O_3) and ammonia (NH_3), which are used as the main indicators in air quality control (EEA 2018).

These compounds are a threat to the environment as well as to human health. Every year, 3.3 million people die prematurely due to exposition to high levels of air pollution (Lelieveld et al. 2015). Not only are these pollutants a threat to human health, but the emitted particulate matter are also primary aerosols in the lower atmosphere. In addition to scattering and absorbing light, aerosols can serve as cloud condensation nuclei (CCN). An increased amount of CCN impacts the reflectance, height and precipitation rates of clouds and therefore plays a role in altering the amount of incoming radiation that reaches the surface of the Earth. Globally, it means that the energy budget of the Earth can be altered (Penuelas and Staudt 2010; Boucher et al. 2013). The gaseous NMVOCs, as well as sulphate, nitrate and ammonium, play a role in forming secondary organic aerosols (SOAs), which in turn can also act as CCN (Boucher et al. 2013). Furthermore, high levels of lower atmosphere ozone and other pollutants can cause destruction of vegetation, increase their biogenic volatile organic compound (BVOC) emissions and lead to lower rates of photosynthesis caused for example by stomatal or leaf damage (Seyyednejad et al. 2011; Bolsoni et al. 2018).

To reduce air pollution in urban settlements, different strategies can be applied, with planting trees being one of them. Trees are known to take up CO_2, the soil around them provides a surface for water infiltration, they mitigate the urban heat island effect through evapotranspiration, provide surfaces for PM10 and PM2,5 deposition, and provide a recreational value to urban areas. Therefore, they are great candidates for mitigating air pollution and improving the urban climate. Nevertheless, there are great differences between tree species in terms of CO_2 uptake, PM10 removal and BVOC emissions. Therefore, they differ greatly in how much they can contribute to air quality.

Focusing on BVOC emissions from trees, these emitted compounds play a role in ozone formation and therefore have a negative impact on air quality. Separate from that, they can contribute to secondary aerosol formation and growth. The emission rates are dependent on the tree species and different environmental factors; therefore, it is important to consider the tree species that are being planted during urban tree planting campaigns and park creations. The compounds with the highest emission rates are isoprene (C_5H_8) and monoterpene ($C_{10}H_{16}$), which play a role for example in protecting the trees from periods of excess temperatures, high levels of ozone and predators (Penuelas and Staudt 2010).

In Sweden, 87% of the population live in urban settlements (The World Bank Group 2018a) and around 340,000 of the inhabitants live in the third largest city, Malmö. It also happens to be the fastest growing city in Sweden (Malmö Stad 2019). In Malmö, successful actions have been taken to reduce air pollution by investing in public transport, reducing the allowed driving speed and building bike paths (Miljöförvaltningen 2018). Nevertheless, no studies have been performed on the potential impact trees have on air quality.

1.1 Aim of study

This study aims to estimate the magnitude of potential BVOC emissions by the different tree species in Malmö, based on ground surface area covered by the tree canopy and the isoprene and monoterpene emission potential of the different tree species. The research questions on which this study focuses on are:

- Which tree species are present in the study area and how much ground surface area does their canopy cover?
- Does the most abundant tree species have the highest potential emission contribution, or does it come from less abundant but very highly emitting tree species?

2. Background

2.1 Definition and occurrence of BVOCs in the environment

Biogenic volatile organic compounds (BVOCs) are chemicals emitted by vegetation, which play a role in the metabolism of the plants, their ability to grow, to defend themselves against predators and abiotic stress factors, as well as their ability to reproduce (Penuelas and Staudt 2010). They are reactive trace gases that influence atmospheric chemistry and play a major role in the formation of ozone and secondary organic aerosols (SOAs) (Kesselmeier and Staudt 1999). BVOCs are emitted from a wide range of sources such as vegetation or soil microbial activity but the majority are emitted by trees in forest ecosystems (Guenther et al. 1995; Zemankova and Brechler 2010). In total, there are over 1700 BVOCs that have been identified as being emitted by plants (Knudsen et al. 2006). The group of compounds with the highest occurrence and emission rates are the terpenoids, which include isoprene, monoterpene and sesquiterpenes (Acosta Navarro et al. 2014). Isoprene emissions are commonly highest in deciduous trees, whereas conifers are higher emitters of monoterpenes but there are exceptions to this rule. For example, the *Abies* species which are coniferous, can emit both isoprene and monoterpenes (Calfapietra et al. 2013). A deciduous tree genus that emits monoterpenes would be the *Magnoli*a genus (Noe et al. 2008). Moreover, emissions even vary within species and individuals (Bäck et al. 2012).

2.2 Light and temperature dependence of isoprene and monoterpene emission rates

Isoprene and monoterpene emissions respond to a variety of different environmental factors but show a high dependency on light intensity (photosynthetically active radiation (PAR)) and leaf temperature. Monoterpenes, emitted from storage pools, however, are mainly temperature dependent (Kuhn et al. 2002; Dindorf et al. 2006). Figure 1 illustrates that isoprene emissions increase rapidly with increasing light intensity with the emission rate closely following the shape of a rectangular hyperbola, similar to the photosynthesis rate curve. The response to increasing temperature is nearly exponential up to a temperature of 40°C and declines rapidly after that. (Laothawornkitkul et al. 2009). Furthermore, isoprene is often emitted directly after production and responds immediately to environmental changes or stress, while monoterpene emissions can be emitted directly as well as from storage pools in plant organs and therefore show short and long-term responses to environmental changes (Tang et al. 2016). Some studies have even shown that new monoterpene and monoterpene stored in plant organs can be emitted at the same time (Kesselmeier and Staudt 1999; Ghirardo et al. 2010).

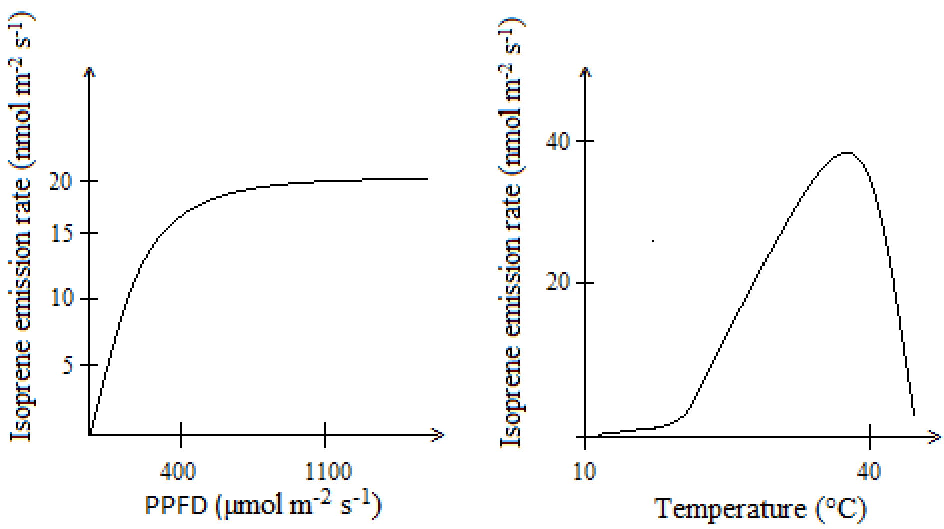


Figure 1: General behavior of isoprene emission rates in response to increasing photosynthetic photon flux density (PPFD) and temperature. PPFD, a measure of the amount of photosynthetically active radiation that reaches the plant, is given in µmol m^{-2} s^{-1} and temperature is given in °C. Based on Zimmer et al. 2001.

2.3 Effect of environmental stress on BVOC emission rates

In contrast to the immediate impact light and temperature have on emission rates, the response to environmental stress through herbivory, pathogens or disease can show an increase in emissions over longer periods of time, which was studied by Berg et al. (2013). The study analyzed the effect of an attack of mountain pine beetle on a *Lodgepole pine* (*Pinus contorta*) and *Engelmann spruce* (*Picea engelmannii*) forest, with the result that these coniferous trees showed higher emissions for weeks and months after being attacked by beetles, with the emission rates only decreasing when the trees started dying. Trees that survived the attack were not studied. The increased monoterpene flow from the storage pools has the function to remove the beetles, to emit compounds that are toxic to beetles and cause their death, as well as to attract beetle predators. Other environmental factors that impact BVOC emission rates are water stress, elevated levels of ozone, CO_2, high temperatures and other air pollutants (Penuelas and Staudt 2010). When exposed to water stress, according to Laothawornkitkul (2009), isoprene and monoterpene both play a role in protecting vegetation from damage by periods of drought and excess temperatures. One proposed mechanism is that isoprene strengthens membranes and proteins, which prevents the photosynthesis rate from decreasing due to leaking membranes. Another function of isoprene is to protect the plant from high levels of ozone, which is provided through its function as an antioxidant in the leaves and protecting them from oxidative stress during photosynthesis (Laothawornkitkul et al. 2009; Lahr et al. 2015).

2.4 Ozone formation

BVOCs play a big role in protecting vegetation from environmental stress like herbivores or drought, but once they are released into the atmosphere, they also impact atmospheric chemistry due to their high reactivity with hydroxyl radicals (OH), which are abundant during the day in urban areas (Laothawornkitkul et al. 2009). One impact is the indirect contribution to ozone formation, which can be explained with the chemical reactions in equations (1) through (5) (Kirkwood and Longley 2012; Simon et al. 2019). In an atmosphere free of BVOCs, ozone is formed through the light dependent reaction of atomic oxygen with molecular oxygen and an absorbing agent M, as seen in equation (1) and (2) and it is depleted through the reaction in equation (3). These reactions create a balance of nitrogen oxides (NO_X) with the ratio of nitrogen dioxide (NO_2) and nitrogen monoxide (NO) being in equilibrium. In contrast, when BVOCs are present, especially isoprene (C_5H_8), they act as catalysators in ozone formation, since they are highly reactive with free hydroxyl radicals, for example OH. In equation (4) it can be seen that the reaction of isoprene with hydroxyl radical leads to the formation of peroxyl radicals RO_2, which in turn react with NO to form NO_2 in equation (5). This shifts the balance of NO and NO_2 towards NO_2 which is then available in larger quantities to form ozone, starting again at equation (1). These reactions show that, when the NO_x concentration in the troposphere is elevated, BVOCs lead to an accelerated formation of ozone. This would be the case during daytime in urban areas where NO_x levels are high due to the combustion of fossil fuels.

Equations:

(1) $NO_2 + hv\ (\lambda < 400\ nm) \rightarrow NO + O$	Ozone formation
(2) $O + O_2 + M \rightarrow O_3 + M$	
(3) $O_3 + NO \rightarrow NO_2 + O_2$	Ozone depletion
(4) $C_5H_8 + OH \rightarrow RO_2 + O_2$	Accelerated ozone formation
(5) $RO_2 + NO \rightarrow NO_2 + HO_2 + x$	

2.5 SOA and cloud condensation nuclei formation

In addition to forming ozone, BVOCs can contribute to secondary organic aerosol formation and growth, by oxidizing into less mobile compounds after being emitted into the atmosphere. These slower compounds can then able to condensate onto aerosols that are already present in the air and therefore increase their size and abundance (Cahill et al. 2006). Isoprene and monoterpene are the most abundant compounds of all BVOCs that contribute to SOA formation. The so formed aerosols absorb and scatter light and act as condensation nuclei for cloud droplets. These enhance cloud formation by providing a surface for condensation and increase their reflectance. Therefore, the energy balance of the Earth can be altered through scattering and the reflection of incoming solar radiation (Penuelas and Staudt 2010; Boucher et al. 2013).

3. Methods

This study aims to determine the magnitude of the emission potential for the different tree species of an urban area in Malmö, southern Sweden. This was achieved by estimating the ground surface area covered by the tree canopy of each species, by digitizing aerial images, and multiplying the ground surface area covered by the canopy with the emission rates of the species, found in literature sources. This gave an insight into which species contribute most to BVOC emissions in the given study area.

3.1 Material and data sources

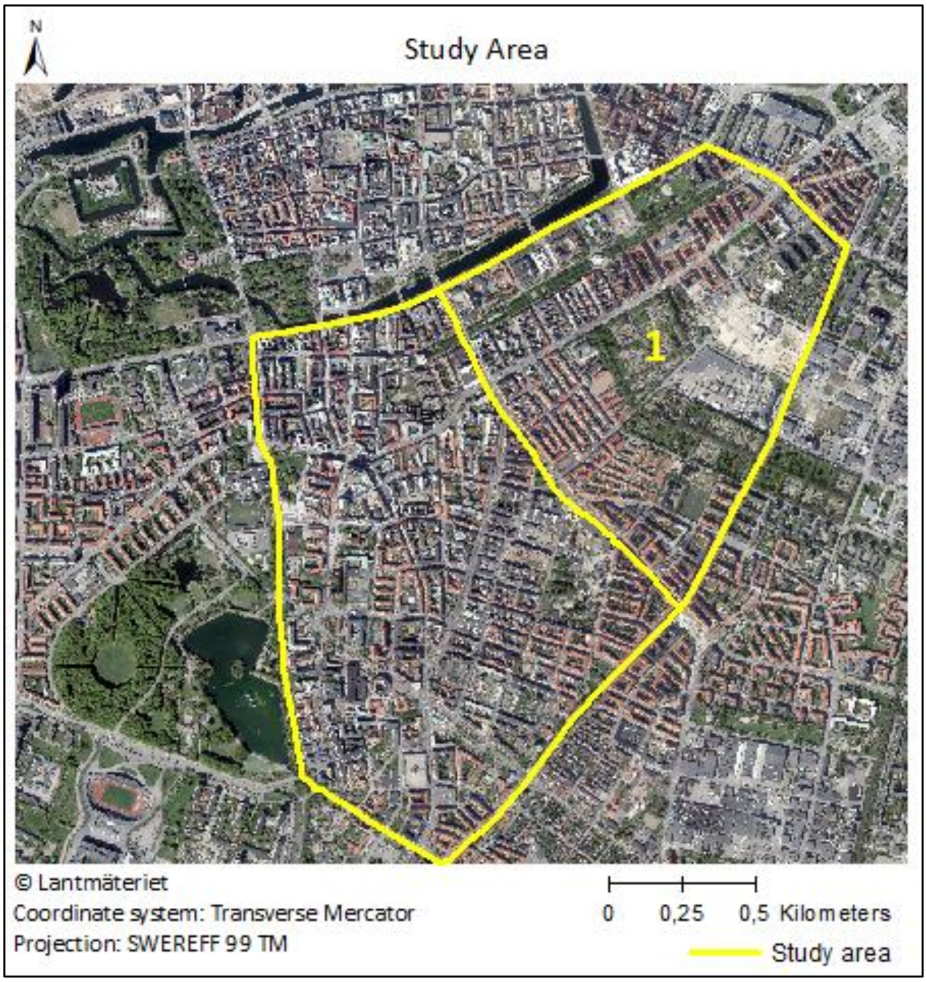
To digitize the location and canopy area of the trees, two aerial orthoimages were obtained from Lantmäteriet. One of the images was an infrared image (IR) (Lantmäteriet 2016a) and one was in color (RGB) (Lantmäteriet 2016b). Both were taken in May 2016 and came with a 0.25m resolution in the Transverse Mercator coordinate system and Swereff 99 TM projection. In addition, a layer with buildings and a road layer were obtained from Lantmäteriet. The building layer was published in January 2018 (Lantmäteriet 2018) and the road layer was created in September 2015 (Lantmäteriet 2015). Both were only used for orientation, as there have been some changes in buildings and in road locations, which made it not seem very accurate as some roads were passing through houses. All images and layers extended from 6,161,616m to 6,164,287m North and from 372,914m to 375,964m East. The images and layers were loaded into the computer software ArcGIS Desktop version 10.5.1 by Esri, which was the program used for the digitization and canopy cover measurements. To identify the species of the digitized trees, the website Curio XYZ (Breadboard Labs 2019) was used. This website provided the species name, and if documented, also the trunk diameter, tree age and vitality status of the trees documented in the tree database of Malmö City. This tree database was unfortunately not accessible to the public, which is why Malmö City provided the link to the Curio XYZ website. To assign the emission rates to each species and to perform the potential emission calculations, Excel for Microsoft Office 365 ProPlus version 1904 was used. The standardized isoprene and monoterpene emission rates of the different species were obtained from different literature sources, presented in the following section.

3.2 Literature sources

To obtain isoprene and monoterpene emission rates for all the species in the study area, twelve different literature sources were used. The sources that provided most of the values were Karl et al. 2009, Kesselmeier and Staudt 1999, and Owen et al. 2003, as they provided inventories of common European tree species and a study on BVOC emissions from the urban trees in the West Midlands in the United Kingdom. A complete list of the used literature sources can be found under Table 6 in the appendix.

3.3 Study area

The study area is located in Malmö, southern Sweden, in the central and urban area, located south of the old town. To be precise, Regmentsgatan and Drottninggatan are building the northern border and it extends from the southern tip of Kungsparken in the north-west, to Dalaplan in the south-west, up to the crossing of Nobelvägen and Sallerupsvägen in the East, with Nobelvägen building the southern border of the study area. The area was chosen because it represents the urban built up of Malmö, with some of the main streets with the highest air pollution levels and traffic, Nobelvägen, Amiralgatan, Bergsgatan and Värnhemstorget (Miljöförvaltningen 2018) being in the study area. In total, the study area extends over an area of 3km^2. This total area was used to determine the species distribution and their emission potential. Due to limited time to work on this project, the area percentage that is covered by trees that are not registered or are of unknown species was only determined for a section of the total study area. This area is on the eastern side of the study area and is noted with a 1 on Map 1. In Map 1, you can see the location of the total study area, as well as the border line to the smaller study area. The study area 1 in the East extends over 1.2km^2 and the area in the West over 1.8km^2.



Map 1: Location of the study area in Malmö and the division line to study area 1. Background image: GSD-Ortofoto in color, 0.25m resolution © Lantmäteriet (2016b)

3.3 Data analysis

All images were loaded into ArcMap 10.5.1 and all trees in the eastern study area were digitized from orthofotos. To identify the species, the Curio XYZ website was used. The tree species were then noted in the attribute table of the tree polygon layer. If the tree was not registered on the Curio XYZ website, the species was noted as "unknown" in the attribute table. For the second half of the study area, only known trees were digitized from the aerial images, along with their species. Once the digitization process was completed, the area covered by each species was noted in Excel, as well as the total area covered by trees in the study area. The species area was obtained using the "select by attribute" and "statistics" functions in ArcMap. From this information, the percentage area that each species covered was calculated, as well as the percentage area that is covered by unknown trees in study area 1.

3.4 Calculation of potential BVOC emissions

In order to determine the potential impact on atmospheric chemistry that each species has through their emission potential, emission rates of isoprene and monoterpene were taken from literature sources. When provided, the emission rates were noted on a species level, and when no data was found for individual species, genus or family averages where taken. When available, different sources for each species were looked at, to see if different authors obtained similar results when measuring emission rates of the same species in different locations, but this was not possible for all species. When different authors got results in a similar order of magnitude, the average rate of those results was calculated. When the standardized emission rates would fall into different emission categories, it was attempted to find more research papers who measured the BVOCs of this species. This was done to get an idea of which one of the values is the outlier in order to use the values with a similar order of magnitude for further calculations. If no other research paper was found, then the average of the differing values was taken. When all the species of the same genus showed the same emission rates, those species were then grouped into one field. One example for this is the genus *Prunus*, where *Prunus avium*, *padus* and *serotina* all have an isoprene emission rate of 0 μgC gdw^{-1} h^{-1} and a monoterpene emission rate of 0.1 μgC gdw^{-1} h^{-1}, according to Karl et al. 2009. Therefore, all the *Prunus* species, even the ones where no data was found, were summarized in t0he group *Prunus*. For genera that cover species with a large variability in emission rates, for example *Quercus* (oak), the emission rates were kept at species level.

For simplification purposes, the trees were categorized into emission rate categories, depending on their isoprene and monoterpene emissions (Table 1). These categories were taken from Li et al. (2017). Only the monoterpene category of highest emitter was adapted to this study, because the study by Li et al. did not have a category for emission rates between 4.0 and 10.0 μgC gdw^{-1} h^{-1}, as there were no trees representing that category in their study. To rank the species or genera in terms of the magnitude of their potential BVOC emissions, the ground surface area that the canopy of each species or genus covered was multiplied with their emission rate. The resulting value is referred to as 'impact' value. This was done separately for isoprene and monoterpene, as they have different effects on atmospheric chemistry, and a table ranking the species and genera by potential BVOC emissions was created in Excel.

Table 1: Isoprene and monoterpene emission rate categories, based on the study by Li et al. (2017) and adapted to this study.

Isoprene emission category	**Isoprene emission rate in μgC gdw^{-1} h^{-1}**	**Monoterpene emission category**	**Monoterpene emission rate in μgC gdw^{-1} h^{-1}**
Lowest	0.0-0.5	Lowest	0.0-0.1.
Lower	0.5-3.0	Lower	0.1-0.3
Low	3.0-9.0	Low	0.3-0.9
Moderate	9.0-20.0	Moderate	0.9-2.0
High	20.0-50.0	High	2.0-4.0
Higher	50.0-90.0	Higher	4.0-10.0
Highest	90.0-200.0	Highest	> 10.0

4. Results

The ground area covered by the species' canopies, the percentage of the total tree cover, potential emission rates, impact values and data sources are given for each species in Table 6 in the appendix.

4.1 Tree species occurrence by canopy area

Table 2 shows the tree genera that are most abundant in the study area and that cover more than one percent of the ground surface area covered by the canopy of registered trees. The isoprene and monoterpene impact levels are also given. It shows that *Tilia* (linden) trees are by far the most planted trees, with more than 44% being *Tilia* trees, including Tilia *cordata*, *Tilia platphyllos* and *Tilia x europaea*. These three species are all low isoprene emitters and show no monoterpene emissions. The second most abundant genus is *Aesculus* (horse chestnut), which includes the species *Aesculus carnea* and *Aesculus hippocastanum*, with the latter one being more abundant and taking up 7.8% of the tree cover (see Table 6 in appendix). *Aesculus* species are high monoterpene emitters. *Platanus* (plane tree) trees make up over 8% of the tree cover as well. The only *Platanus* species that is present in the study area is *Platanus x hispanica*, also known as *Platanus x acerifolia*, and which contributes significantly to the isoprene and monoterpene emissions. Next is the *Acer* (maple) genus, which includes *Acer campestre*, *Acer platanoides*, *Acer pseudoplatanus*, *Acer saccharinum* and *Acer x freemanii*, which are low isoprene and low monoterpene emitters. The genus taking up over 6% of the registered tree cover is the *Quercus* (oak) genus, which summarizes species which can be high isoprene or high monoterpene emitters, as well as a combination of both. In this study area, *Quercus robur, rubra*, *petraea* and *coccinea* are significant isoprene emitters, as well as emitters of lower rates of monoterpene, while *Quercus cerris* is a high monoterpene emitter only. The *Fagus* (beech) genus combines *Fagus sylvatica* and *Fagus orientalis*, where *Fagus orientalis* does not emit isoprene or monoterpene at all, whereas *Fagus sylvatica* is a high monoterpene emitter and is responsible for the monoterpene impact of this genus. The *Prunus* (prunus) genus is a generally low emitter and does not have a large contribution to BVOC emissions. The only tree belonging to the *Carpinus* (hornbeam) genus in this study area is *Carpinus betulus*, which is low monoterpene emitter. The *Robinia* genus, represented by *Robinia pseudoacacia* is an isoprene and monoterpene emitter. Next, the *Fraxinus* (ash) genus, represented by *Fraxinus angustifolia*, *exselsior* and *ornus*, which cover 1.3% of the area covered by registered trees, are non-emitting trees. The *Malus* and *Sorbus* genera are also very low emitters of isoprene and monoterpene and make up around 1% of the tree cover each.

Table 2: Tree genera that cover more than 1% of the ground surface area covered by registered trees in the whole study area, along with their assigned isoprene and monoterpene impact values. The impact value is obtained by multiplying ground surface area covered by the canopy times the potential emission rate found in literature.

Rank #	**Genus**	**Common name**	**Ground surface area (%)**	**Isoprene impact (m^2 µgC gdw^{-1} h^{-1})**	**Monoterpene impact (m^2 µgC gdw^{-1} h^{-1})**
1	*Tilia*	Linden	44	25,000	0
2	*Aesculus*	Horse chestnut	8.2	0	150,000
3	*Platanus*	Plane tree	8.1	220,000	47,000
4	*Acer*	Maple	7.8	14,000	6,500
5	*Quercus*	Oak	6.6	410,000	9,700
6	*Fagus*	Beech	5.1	0	78,000
7	*Prunus*	Prunus	3.0	230	450
8	*Carpinus*	Hornbeam	2.3	0	860
9	*Robinia*	Robinia	1.4	19,000	5,200
10	*Fraxinus*	Ash	1.3	0	0
11	*Malus*	Malus	1.3	470	570
12	*Sorbus*	Sorbus	1.0	390	1,200

4.2 Trees with the highest isoprene impact

Table 3 shows the ten tree species with the highest isoprene emission contributions, given by the impact values. The *Quercus*, *Platanus*, *Populus* (populus) and *Salix* (willow) trees are all high emitters and have very high isoprene contribution factors, even though they cover only 0.4 to 8.1% of the surface area covered by registered trees in the whole study area. *Tilia* trees and *Acer pseudoplatanus* trees are lower emitter trees, but due to their high occurrence, they contribute greatly to the total potential emissions.

Table 3: Tree ranking on species level by isoprene emission impact.

Top 10	**Species name**	**Common name**	**Ground surface area (%)**	**Isoprene Impact (m^2 µgC gdw^{-1} h^{-1})**	**Emitter category**
1	*Quercus robur*	European oak	3.0	300,000	Higher
2	*Platanus x hispanica*	London plane tree	8.1	220,000	Moderate
3	*Quercus rubra*	Northern red oak	2.0	110,000	High
4	*Populus genus (unknown sp.)*	Populus	0.4	41,000	Higher

5	*Salix x pendulina*	Weeping willow	0.2	34,000	Highest
6	*Populus x canadensis "Robusta"*	Canadian poplar	0.4	29,000	High
7	*Tilia sp.*	Linden	44	25,000	Lower
8	*Robinia pseudoacacia*	Black locust	1.4	19,000	Low
9	*Salix alba*	White willow	0.4	18,000	High
10	*Acer pseudoplatanus*	Sycamore maple	4.4	13,000	Lower
Sum			**65**	**810,00**	

4.3 Trees with the highest monoterpene impact

Table 4 lists the ten highest monoterpene emission contributors, with *Aesculus hippocastanum* being the highest contributor with an impact value of 140,000 m^2 µgC gdw^{-1} h^{-1} followed by *Fagus sylvatica* and *Platanus x hispanica*. All trees in this ranking are very high emitters, except for *Acer pseudoplatanus* and the *Quercus* trees, which are moderate and low emitters but contribute greatly due to their abundant occurrence in the study area.

Table 4: Ranking on species level by monoterpene emission impact, along with the percentage of ground surface area covered by tree canopies in the whole study area and the emission categories of the species.

Top 10	Species	Common name	Ground surface area (%)	Monoterpene Impact (m^2 µgC gdw^{-1} h^{-1})	Emitter category
1	*Aesculus hippocastanum*	Horse chestnut	7.8	140,000	Highest
2	*Fagus sylvatica*	European beech	4.8	78,000	Highest
3	*Platanus x hispanica*	London plane tree	8.1	47,000	High
4	*Aesculus carnea*	Red horse-chestnut	0.4	7,000	Highest
5	*Robinia pseudoacacia*	Black locust	1.4	5,200	High
6	*Quercus cerris*	Turkey oak	1.5	4,000	Moderate
7	*Acer pseudoplatanus*	Sycamore maple	4.4	3,300	Low
8	*Magnolia sp.*	Magnolia	0.1	3,100	Highest
9	*Ginko biloba*	Maidenhair tree	0.6	2,800	High

10	*Quercus rubra*	Northern red oak	2.0	2,800	Moderate
Sum			**31**	**290,000**	

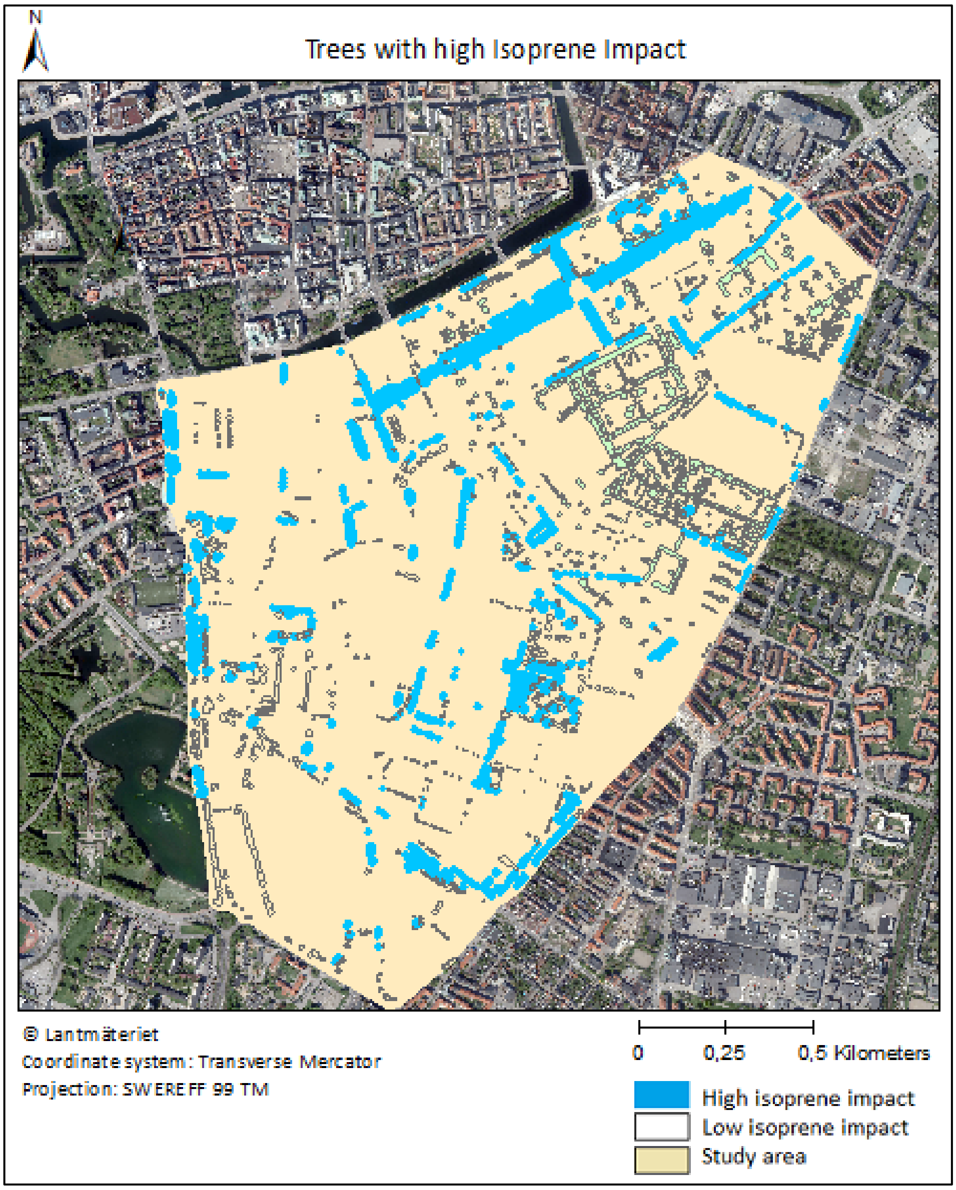
4.4 Determination of how much of the tree cover is unknown

Table 5 shows the results from the analysis in area 1, where all the trees were digitized from aerial images, to calculate the amount of tree cover that were not registered by the Curio XYZ website. It shows that this area has a tree cover of 14% and that 62% of the tree cover area is covered by unidentified trees.

Table 5: Distribution of known and unknown trees in study area 1

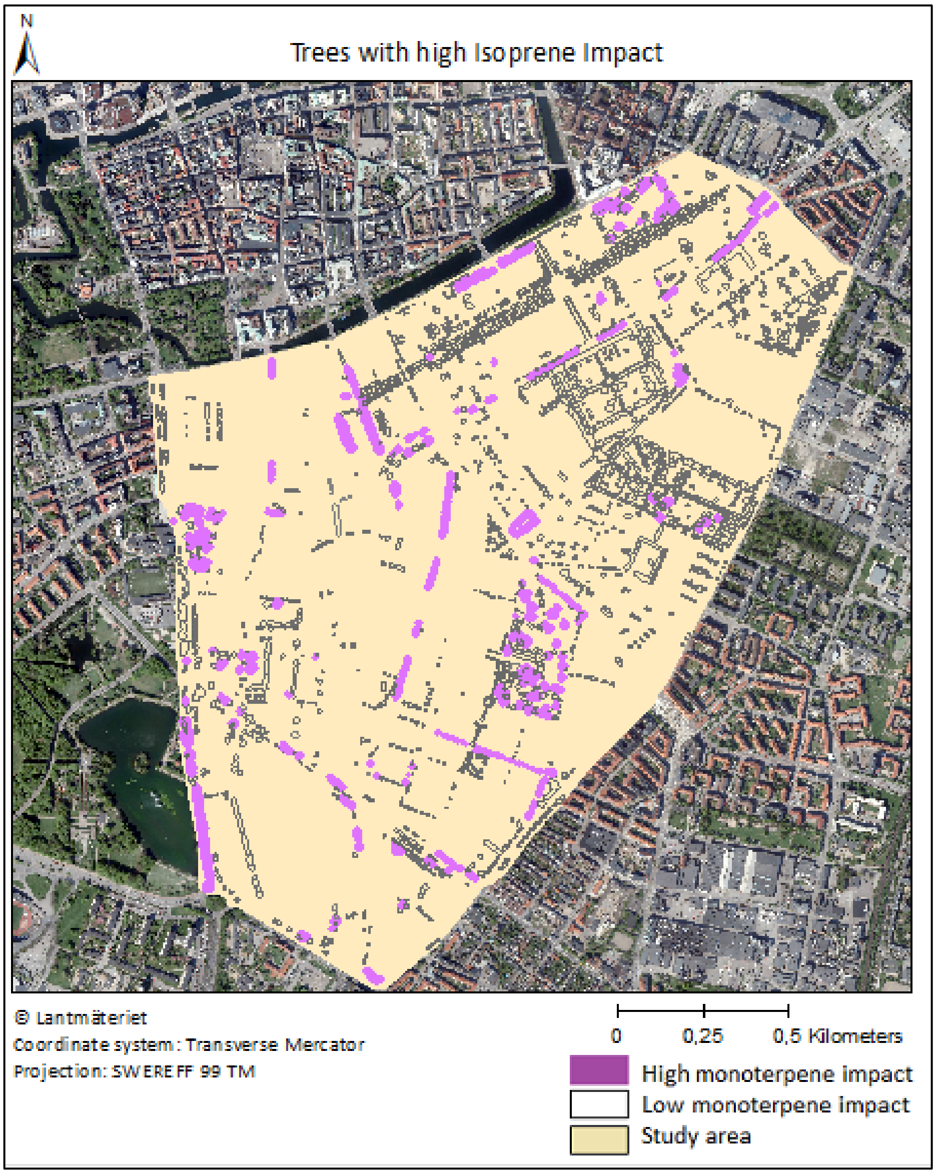
Area 1 (m^2)	**Area covered by trees (%)**	**Known trees (%)**	**Unknown trees (%)**
1,200,000	14	38	62

Map 2 shows the location of the high isoprene contributors, which is mainly in the urban park in the north of the study area as well as along the western border of the study area and along roads in general.



Map 2: Location of trees with the top ten isoprene impacts, shown in blue. Background image: GSD-Ortofoto in color, 0.25m resolution © Lantmäteriet (2016b)

Map 3 shows the location of the highest monoterpene emission contributors, which are also located along roads, but also occur in urban parks, for example on the western border of the study area and in the lower center of the study area.



Map 3: Location of the top ten tree species with the highest monoterpene impact, shown in purple. Background image: GSD-Ortofoto in color, 0.25m resolution © Lantmäteriet (2016b)

5. Discussion

5.1 Tree species distribution

The results show that *Tilia* trees are the dominant tree genus planted in Malmö, making up over 44% of the tree cover that is registered in Curio XYZ, followed by *Aesculus* and *Platanus* trees, which make up less than 10% each. The species that contribute most to the isoprene emissions are *Quercus robur*, *Platanus x hispanica* and *Quercus rubra* and the trees contributing most to monoterpene emissions are *Aesculus hippocastanum*, *Fagus sylvatica* and *Platanus x hispanica* as well. They each cover between 4.8 and 8.1% of the tree cover area and are very high emitters. Overall it can be said, that the highly dominant genus, *Tilia*, is a low emitter and is a good choice to plant when the goal is to keep the BVOC emissions low. Nevertheless, other species with less area coverage fall in the category of highest emitters and are responsible for most of the isoprene and monoterpene emissions. In this study, the results show only the order of magnitude of the emission potential of the different tree species, as the emission rates were taken from different literature sources, which comes with a variety of uncertainties.

5.2 Amount of unknown trees

The results given in Table 4 show that unknown and unregistered trees make up 62% of the tree cover in study area 1. This is due to the two large cemeteries that are in the study area, S:t Pauli Norra kyrkogård and S:t Pauli Mellersta kyrkogård, where very few or no trees at all are identified. These two cemeteries are not the only two in Malmö that are not registered. In fact, several other cemeteries like Gamla kyrkogården in the old town, parts of Slottsträdgården, all Östra kyrkogården and its surroundings, as well as many street and garden trees are not registered. This further demonstrates how high the uncertainty in the isoprene and monoterpene emission impact is, when more than half of the tree cover is unknown and cannot be analyzed with literature values.

5.3 Literature source uncertainties

5.3.1 Variation in emission rates of the same species

Firstly, the emission rates were taken from different sources, which are studies performed in different parts of the world with different environmental conditions, as well as emission inventories which assemble even more different sources. All the measured emission rates are standardized to a PAR value of 1000 µmol m^{-2} s^{-1} and a temperature of 30°C using the Guenther et al. algorithm (Guenther et al. 1993), but different growing conditions like soil moisture, air pollution and eventual undetected diseases can influence the measured rates significantly (Laothawornkitkul et al. 2009; Bäck et al. 2012). Furthermore, the age of the measured trees and even the leaves or needles on the branch play a major role, as younger leaves and needles show higher emission rates than older ones (Wang et al. 2017).

Secondly, some of the species found in the study area are not native to Europe and were only analyzed by studies performed in their native environment, where the growing conditions might be different. An example of this is *Populus simonii*, which is a native tree in northern China (FAO 2002) and was analyzed in Yunmeng Mountain, Beijing in a study by Li et al. (2017), where the growing conditions are different from the conditions in the urban area of Malmö. The climate differs between the two locations, because the average temperature on Yunmeng mountain is 25°C in July and -7 in January (Zhang and Shao 2015), while Malmö has an average temperature of 17°C in July and 0°C in January (Climate-data.org 2019). Furthermore, Yunmeng Mountian is affected by a summer monsoon from June to September, with most of the precipitation falling in this time period, while Malmö experiences precipitation evenly over the whole year. Both sites receive around 600-700mm of rain each year, but the difference in distribution will have an impact on soil moisture throughout the year (Zhang and Shao 2015; Climate-data.org 2019). As mentioned in the section 2.3, water stress and temperature can affect BVOC emission rates.

Thirdly, another factor that influences the accuracy of the results is that some species were assigned a high variation of emission rates by different literature sources. An example for this is the species *Quercus petraea*, where the isoprene emission rates varies between 0.6 and 45 μgC gdw^{-1} h^{-1}, depending on the source. Another example of a varying isoprene emission rate is the *Tilia* genus, where Karl et al. (2009) state that *Tilia* species emit 0 μgC gdw^{-1} h^{-1}, whereas Owen et al. (2003) measured 5.5 μgC gdw^{-1} h^{-1}. Since it is the most common species in Malmö, this rate difference would make a large difference in the resulting overall emission. The same phenomenon occurred for literature values of monoterpene emissions. One example is *Fagus sylvatica*. Here, the literature values range from 0.5 to 21.1 μgC gdw^{-1} h^{-1}, which is a huge range from low to highest emitter, considering that this species makes up almost 5% of the tree cover. For the impact calculations, averages were taken for all the species with varying values, in order to account for the extreme range of values. Therefore, just from looking at the literature values, the uncertainty in the accuracy of the results is already important.

5.3.2 Seasonal variations of emission rates

Another factor that impacts the accuracy of these results is stated by Benjamin et al. (1997), who compiled an inventory of isoprene and monoterpene emission rates of trees and shrubs found in the California South Coast Air Basin, and combined the hourly emission rates with daily light intensity and temperature data to calculate daily emission rates. He found out that the hourly emission rates given in most studies and inventories are an overestimation, since they are usually measured around noon on a summer day, when emission rates are at their peak. Through the standardization, diurnal variations in emission rates are taken into account, but seasonal variations are left out. Therefore, they do not consider that emission rates might be much lower during winter, when deciduous trees do not have leaves. Another seasonal impact that affects emission rates is flowering, which was an outcome of the study conducted by Baghi et al. (2012), which measured the BVOC emissions of different tree species during spring and summer to determine if there are differences in emission rates during and after flowering. For the species *Aesculus hippocastanum*, the results showed that the species had a monoterpene emission rate of 9.1 μgC gdw^{-1} h^{-1} during flowering and a rate of 12 μgC gdw^{-1} h^{-1} after flowering. Isoprene compounds were not found. This shows that is makes a big difference when the measurements are taken. For other sources, no information was given on whether the measured trees were flowering or not. For this study, the after-flowering value was taken, since it would be valid for a longer period as the species is in bloom for around 2.5 weeks in mid-May only. Most trees bloom in spring. Nevertheless, the majority of the literature sources collected their data in the time period of June to October ((Benjamin and Winer 1997; Isebrands et al. 1999; Curtis et al. 2014; Li et al. 2017). Only the study by Owen et al (2003) took averages over the whole year and the other literature sources did not provide the dates of their field data collection. Not only do these uncertainties and ranges in values influence the results, but also not finding any reliable sources of BVOC emission for a species influences the total emissions. This was the case for four species, *Parrotia persica*, which is native in northern Iran, *Phellodendron amurense*, native in north-east Asia and Japan, *Pterocarya fraxinifolia,* which is endemic in northern Turkey, Caucasus and northern Iran, and lastly *Quercus macranthera,* which also comes from Caucasus and northern Iran (SKUD 2019).

5.4 Limitations of methodology: digitization

Not only do the literature sources affect the results, the methodology applied to calculate the tree cover also comes with sources of error. In this study, the trees were digitized from orthophotos and not regular aerial images. This had the result that some trees might not have been visible due to being obstructed by buildings. This lowered the accuracy of digitizing the actual tree cover when the tree was not visible but was indicated to be there by Curio XYZ. For registered trees, this was accounted for by digitizing an estimation of where the tree would be, but for unregistered trees, this led to an underestimation of tree cover. Furthermore, for the unregistered tree cover, the orthoimages in RGB and IR with a resolution of 0.25m were not always clear enough to determine if the vegetation was a tree or a small bush when there were no shadows indicating its height. In addition, due to the large number of trees and the low resolution, and many deciduous trees not having leaves at the time of when the orthophotos were taken, the shape of the crown could not always be drawn with high accuracy. Another factor that is not considered when only taking into account canopy cover to determine the emission potential, is that tree species can have a large variety of canopy shapes. For example, the *Aesculus hippocastanum* species grows a very wide round crown, whereas the *Poplar* species grow high narrow crowns. Therefore, trees with wide and shallow crowns are overestimated and trees with deep and narrow crowns are underestimated in this study and it would have been necessary to look at leaf area indices of each species to correct for that. In addition, this study did not look at tree age or tree health, which are both factors that affect emission rates greatly (Wang et al. 2017). From the Curio XYZ website, it was apparent that a lot of young trees were present in the study area, including high emitting species, that do not contribute much to the tree cover area now, but are likely to do so in the future and probably led to an underestimation of the emission impact by the tree cover, since younger trees often have higher emission rates (Wang et al. 2017).

5.5 Strength of methodology: time efficiency

The methodology used in this study comes with many sources of errors and uncertainties, but it is highly time efficient to determine the order of magnitude of the BVOC emission potential of the urban trees in Malmö. The study area included 100 different species and it took around 16h of intense work to digitize the 3150 small polygons and to assign them their species. In comparison, the height and diameter of 24 *Aesculus hippocastanum* trees were measured on Södra Promenaden in Malmö, as well as 100 trees of differing species in Kungsgården and around the old town, to calculate their leaf biomass with the use of allometric equations. These equations use regression models between different parameters like tree height and diameter in order to calculate the biomass of the tree. From the leaf biomass values and the standardized

BVOC emission rates found in literature, the total emissions of the trees can be obtained. Just the tree measurements of those 124 trees took 48h of field work. This project was not finished, due to the lack of allometric equations for each species, but it shows that the methodology used in this study can cover a much larger area by using aerial images to determine canopy size and area coverage by the different tree species, instead of measuring every single tree in the study area.

5.6 Effect of BVOC lifetime in the atmosphere and local weather

This study determined the potential isoprene and monoterpene emissions impact on air quality by the trees in the study area, but isoprene has a chemical lifetime of 50min to 1.5h, depending on which chemical it reacts with in the atmosphere, and monoterpene has a lifetime of 5min to 5h, depending on the compound (Benjamin and Winer 1997). This means that the study did not account for any BVOC emissions coming from the vegetation surrounding the study area and this can be a major factor, since Pildammsparken is right on the western border of the study area. Furthermore, the prevailing wind direction in Malmö is from the West, South-West, with a wind speed of around 4.5m/s (Miljöförvaltningen 2018), so that the BVOC emissions from Pildammsparken are very likely to enter the study area. Nevertheless, the ozone forming reaction is slower than the emission rate, therefore the highest ozone levels are usually found downwind of urban areas, in this case East of Malmö (Calfapietra et al. 2013). This is not only an error source in this study, but it should also be considered by urban planners when they are planning to plant trees in areas with higher air pollution.

5.7 Other effect of trees on urban areas: ecosystem services

Trees are not only known to contribute to aerosol and ozone formation, they also provide a variety of positive aspects to the urban ecosystem. Some of these ecosystem services are for example the removal of fine particulate matter (PM10 and PM2.5), the provision of surfaces for water infiltration, the reduction of the urban heat island effect through evapotranspiration, CO_2 uptake, provision of shade and the provision of recreational value (Manes et al. 2016). All of those are not taken into consideration and this study but would have to be included in order to make a scientific and objective decision on the suitability of different tree species for the urban environment.

5.8 Future studies

If this study could be repeated, then more variables would be taken into consideration when calculating the emission impact that each specie has on the cities air quality. That would include tree species' leaf area index and tree age, and if possible, also tree health. If more time would be available, then the extent of the study could be elaborated, and emission rates could be measured in Malmö itself and then be compared to literature values.

6. Conclusion

In conclusion, the aim was achieved by

- Estimating the surface area that each tree species covers in the study area and by multiplying that area with the standardized emission rates found in literature
- To answer the first research question on which species are present in the study area, the study revealed that there are 100 different species in the study area and the most common genus is *Tilia*, with 44% of the area covered by trees being covered by *Tilia* trees. The Tilia genus is followed by the Aesculus and Platanus genera, with a coverage of 8.2% and 8.1% of the tree cover area respectively.
- The second research question on which species contribute most to potential BVOC emission can be answered by stating that it is not the most abundant species, the *Tilia* species, but species that are less abundant but have higher potential emission rates. The highest potential isoprene impact comes from *Quercus robur* with an impact value of 300,000 m^2 μgC gdw^{-1} h^{-1}. The highest monoterpene impact comes from Aesculus hippocastanum with an impact value of 140,000 m^2 μgC gdw^{-1} h^{-1}. In comparison, *Tilia* trees are low emitters of isoprene and non-emitters of monoterpene and therefore have a low contribution to BVOC emissions in Malmö, with an isoprene impact value of 25,000 m^2 μgC gdw^{-1} h^{-1}.
- This study also revealed that there is a large discrepancy in literature emission rates for the same species, which affected the accuracy and potentially also the magnitude of the emission impact that the trees of the study area have on air quality. Due to the large number of uncertainties, this study was not able to provide actual values of isoprene and monoterpene emissions in the study area, but it provides an idea of the composition of species and their estimated emission potential, which can be useful for urban planning purposes.

7. Appendix

Table 6: List of the species occurring in the study area, along with their canopy area, standardized isoprene and monoterpene emission rates and their impact values

Species	Ground surface area (m^2)	Percentage of total tree cover area (%)	Isoprene emission rate (µgC gdw^{-1} h^{-1})	Monoterpene emission rate (µgC gdw^{-1} h^{-1})	Avg. ISP (µgC gdw^{-1} h^{-1})	Avg. MT (µgC gdw^{-1} h^{-1})	Impact ISP (m^2 µgC gdw^{-1} h^{-1})	Impact MT (m^2 µgC gdw^{-1} h^{-1})
Acer campestre	3,143	2.10	0.1[c]	0.5[c]	0.1	0.5	314	1,571
Acer platanoides	1,398	0.93	0.1[c]; 0.4[a]	0.5[c]; na[a]	0.25	0.5	350	699
Acer pseudoplatanus	6,547	4.38	0.1[c]; 3.9[f]	0.5[c]	2	0.5	13,094	3,273
Acer saccharinum	463	0.31	N/A[a]; 0.1[c]	2.2/3.5[a]; 0.5[c]	0.1	2.1	46	957
Acer x freemanii	27	0.02	0.1[c]	0.5[c]	0.1	0.5	3	13
Aesculus carnea	586	0.39	0[d]	12[d]	0	12	0	7,031
Aesculus hippocastanum	11,679	7.81	0[d]	12[d]	0	12	0	140,151
Ailanthus altissima	555	0.37	0.1[g]	1.6[g]	0.1	1.6	56	888
Alnus cordata	296	0.20	0[c]	1.5[c]	0	1.5	0	444
Alnus glutinosa	36	0.02	0[c]	1.5[c]	0	1.5	0	54
Alnus incana	605	0.40	0[c]	1.5[c]	0	1.5	0	908
Amelanchier lamarckii	11	0.01	0[g, h]	0[g, h]	0	0	0	0
Araucaria araucana	64	0.04	0.1[g]	1.5[g]	0.1	1.5	6	96
Betula dalecarlica e	83	0.06	0[c]	3[c]	0	3	0	249
Betula pendula	908	0.61	0[a]; 0[c]; 0.05[f]	0.19/5.4[a]; 3[c]; 2.63[f]	0.02	2.8	15	2,547
Betula pubescens	188	0.13	0[c]	3[c]	0	3	0	564
Buxus sempervirens	150	0.10	10[c]	0.2[c]	10	0.2	1505	30
Carpinus betulus	3,447	2.30	0[a]; 0[c]	0.4[a]; 0.1[c]	0	0.25	0	862
Castanea sativa	257	0.17	0[c]	10[c]	0	10	0	2,574
Catalpa bignonioides	33	0.02	0[a]	0[a]	0	0	0	0
Catalpa sp.	105	0.07	0[a]	0[a]	0	0	0	0
Cedrus deodara	17	0.01	0[c]	1[c]	0	1	0	17
Celtis occidentalis	40	0.03	0.1[g]	0.2[g]	0.1	0.2	4	8
Cercidiphyllum japonicum	158	0.11	39.4[g]	1.6[g]	39.4	1.6	6238	253
Cornus mas	278	0.19	0.1[g]	1.6[g]	0.1	1.6	28	446
Corylus colurna	67	0.04	0[c]	0[c]	0	0	0	0
Crataegus intricata	515.39	0.34	0[g]	0[g]	0	0	0	0
Crataegus laevigata	13	0.01	0[g]	0[g]	0	0	0	0
Crataegus monogyna	469	0.31	0.03[f]	0.88[f]	0.03	0.88	14	413
Crataegus punctata	133	0.09	0[g]	0[g]	0	0	0	0
Crataegus rhipidophylla	42	0.03	0[g]	0[g]	0	0	0	0
Crataegus x lavallei	89	0.06	0[g]	0[g]	0	0	0	0
Fagus orientalis	371	0.25	0[c]	0[c]	0	0	0	0
Fagus sylvatica	7,224	4.83	0[a, c]	0.5[a]; 21.1[c]	0	10.8	0	78,023 0
Fraxinus angustifolia	460	0.31	0[c]	0[c]	0	0	0	0

Fraxinus excelsior	1,456	0.97	0[c, f]	0[c, f]	0	0	0	0
Fraxinus ornus	59	0.04	0[c]	0[c]	0	0	0	0
Ginkgo biloba	931	0.62	0[a]	3[a]	0	3	0	2,793
Gleditsia triacanthos	828	0.55	0.1[g]	1.2[d]; 0.2[g]	0.1	0.7	83	579
Juglans regia	202	0.14	0[c]	1[c]	0	1	0	202
Juniperus sp.	75	0.05	0[c]	0[c]	0	0	0	0
Koelreuteria paniculata	244	0.16	44.9[g]	0[g]	44.9	0	10,953	0
Laburnum x watereri ''Vossii''	45	0.03	0.1[g]	0.2[g]	0.1	0.2	5	9
Larix decidua	156	0.10	0[c]	5[c]	0	5	0	781
Liquidambar styraciflua	143	0.10	34/63-99[a]	3.5/ N/A[a]	57.5	3.5	8,246	502
Liriodendron tulipifera	65	0.04	4.1[a]	N/A[a]	4.1		266	0
Magnolia	79	0.05	Na[a, h]; 0.1[g]	5.9[a]; 3[g]; 107[h]	0.1	39	8	3,058
Magnolia x soulangeana	66	0.04	Na[a, h]; 0.1[g]	5.9[a]; 3[g]; 107[h]	0.1	39	7	2557
Malus sp.	853	0.57	0[c]; 0.5[f]	0[c]; 0.6[f]	0.25	0.3	213	256
Malus baccata	308	0.21	0[c]; 0.5[f]	0[c]; 0.6[f]	0.25	0.3	77	92
Malus domestica	75	0.05	0[c]; 0.5[f]	0[c]; 0.6[f]	0.25	0.3	19	23
Malus floribunda	537	0.36	0[c]; 0.5[f]	0[c]; 0.6[f]	0.25	0.3	134	161
Malus x purpurea	113	0.08	0[c]; 0.5[f]	0[c]; 0.6[f]	0.25	0.3	28	34
Metasequoia glyptostroboides	367	0.25	0[g]	3[g]	0.25	0.3	92	110
Morus alba	31	0.02	0.1[g]	0.2[g]	0.1	0.2	3	6
Parrotia persic	46	0.03	N/A	N/A			0	0
Phellodendron amurense	197	0.13	N/A	N/A			0	0
Pinus heldreichii	32	0.02	0[c]	3[c]	0	3	0	95
Pinus nigra	165	0.11	0[c]	3[c]	0	3	0	495
Platanus x hispanica	12,113	8.10	18.5[c]	0.1[c]; 3.9[h]	18.5	3.9	22,4095	47,242
Populus simonii	252	0.17	46.9[j]	0[3]; N/A[j]	46.9	0	11,827	0
Populus sp.	588	0.39	51-100[a]; 60/70[c]; 70[g]	0-4.5[a]; 0[c]; 0.1[g]	70	1.15	41,289	677
Populus tremula	30	0.02	51[a]	4.6[a]	51	4.6	1,521	137
Populus x canadensis ''Robusta''	639	0.43	N/A[c]; 46[i]	0[c]; N/A[i]	46	0	29,383	
Prunus	1,199	0.80	0[c]; 0.1[f]	0.1[c]; 0.13[f]	0.05	0.1	60	0
Prunus avium	1,549	1.04	0[c]; 0.1[f]	0.1[c]; 0.13[f]	0.05	0.1	77	120
Prunus cerasifera	563	0.38	0[c]; 0.1[f]	0.1[c]; 0.13[f]	0.05	0.1	28	155
Prunus padus	255	0.17	0[c]; 0.1[f]	0.1[c]; 0.13[f]	0.05	0.1	13	56
Prunus sargentii	617	0.41	0[c]; 0.1[f]	0.1[c]; 0.13[f]	0.05	0.1	31	25
Prunus serrula	206	0.14	0[c]; 0.1[f]	0.1[c]; 0.13[f]	0.05	0.1	10	62
Prunus virginiana ''Shubert''	26	0.02	0[c]; 0.1[f]	0.1[c]; 0.13[f]	0.05	0.1	1	21
Prunus x persicoides	93	0.06	0[c]; 0.1[f]	0.1[c]; 0.13[f]	0.05	0.1	5	3
Pterocarya fraxinifolia	813	0.54	N/A	N/A	N/A	N/A	N/A	9
Pyrus calleryana	95	0.06	0[c, e]	0[c, e]	0	0	0	
Pyrus communis	78	0.05	0[c]	0[c]	0	0	0	N/A
Quercus cerris	2,183	1.46	0[a, c]	3.1[a]; 0.6[c]	0	1.85	0	0
Quercus coccinea	220	0.15	20.1[a]	3.2[a]	20.1	3.2	4419	0

Quercus macranthera	103	0.07	N/A	N/A	N/A	N/A	N/A	4,038
Quercus petraea	13	0.01	0.61[k]; 45[c]	0.12[k]; 0.3[c]	22.805	0.21	303	704
Quercus robur	4,442	2.97	76.6[a]; 45-61[a]; 70[c]	0[a]; 1[c]	67	0.5	295,554	N/A
Quercus rubra	2,920	1.95	14.8[a]; 45-61[a]; 35[c]	1.8[a]; 0.1[c]	39	0.95	113,894	3
Rhamnus cathartica	19	0.01	36.9[g]	0[g]	36.9	0	691	2,221
Robinia pseudoacacia	2,111	1.41	1.10[a]; 13.5[a]; 12[c]; N/A[h]	0[a]; 4.7[a]; 0.1[c]; 5.1[h]	8.9	2.5	18,719	2,774
Salix	29	0.02	22.7[f]	1[f]	22.7	1	661	0
Salix alba	591	0.40	37.2[c]; 22.7[f]	1.1[c]; 1[f]	30	1	17,708	5,225
Salix x pendulina	300	0.20	115[a*]	N/A[a*]	115	N/A	34,486	29
Salix x sepulcralis	296	0.20	28[c]	0.8[c]	28	0.8	8,283	591
Sambucus nigra	47	0.03	0[e]	0[e]	0	0	0	0
Sorbus	14	0.01	0[c]; 0.5[f]	0[c]; 1.5[f]	0.25	0.75	4	237
Sorbus aria	172	0.12	0[c]; 0.5[f]	0[c]; 1.5[f]	0.25	0.75	43	0
Sorbus aucuparia	49	0.03	0[c]; 0.5[f]	0[c]; 1.5[f]	0.25	0.75	12	11
Sorbus decora	235	0.16	0[c]; 0.5[f]	0[c]; 1.5[f]	0.25	0.75	59	129
Sorbus intermedia	1,060	0.71	0[c]; 0.5[f]	0[c]; 1.5[f]	0.25	0.75	265	37
'Sorbus x thuringiaca	26	0.02	0[c]; 0.5[f]	0[c]; 1.5[f]	0.25	0.75	6	177
Styphnolobium japonicum	891	0.60	N/A	N/A				795
Taxus baccata	813	0.54	N/A[h]	1.1[h]	N/A	1.1	0	19
Tilia sp.	8,915	5.96	0[c]; 5.5[f]	0[c, f]	2.75	0	24,518	0
Tilia cordata	4,930	3.30	0[b, c]	0.7[b]; 0[c]	0	0	0	894
Tilia platyphyllos	554	0.37	0[c]	0[c]	0	0	0	3,501
Tilia x europaea	51,999	34.76	0[c]	0[c]	0	0	0	0
Unknown trees	122,866							
Gone trees	436							
Sum known trees	**149,583**	**100**					**869,768**	**323,717**

References: a: Kesselmeier and Staudt 1999. a[*]: the value of Salix babylonica was taken, since Salix x pendulina is a hybrid of Salix babylonica and either S. fragilis or S. euxina. For the latter species, no literature values were found. b: Curtis et al. 2014. c: Karl et al. 2009. d: Baghi et al. 2012. e: Benjamin and Winer 1997. f: Owen et al. 2003. g: Nowak et al. 2002. This source provides isoprene and monoterpene emission rates on a genus level. h: Noe et al. 2008. i: Isebrands et al. 1999. j: Li et al. 2017. k: König et al. 1995.

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