Volatile Organic Compound Emissions from Plant Species Used by Caltrans and an Analysis of Their Potential Air Quality Impacts

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Abstract

This document provides information for landscape practitioners regarding biogenic volatile organic compounds (BVOCs) that can be produced by plant species commonly used by Caltrans for erosion control, graffiti control, ornamental planting, functional planting, mitigation planting, and vegetative barriers. BVOCs, such as isoprene and terpenes, can contribute to the secondary formation of ozone (O_3) and fine particulate matter ($PM_{2.5}$) in the atmosphere. Both O_3 and $PM_{2.5}$ are harmful to human health and are regulated by the U.S. Environmental Protection Agency (EPA) through the National Ambient Air Quality Standards (NAAQS), and by the California Air Resources Board (CARB) through the California Ambient Air Quality Standards (CAAQS). Many areas throughout California are designated as nonattainment of O_3 and $PM_{2.5}$ NAAQS and CAAQS. BVOC emissions are naturally occurring and therefore cannot be regulated, but they can have a significant effect on atmospheric chemistry and air quality. The potential for plants to emit BVOCs and impact O_3 and $PM_{2.5}$ air quality can be considered when selecting plants for urban greening efforts and planting in Caltrans' right-of-way.

Data from the scientific literature were analyzed for nearly 260 plant species commonly used or recommended for use by Caltrans. These plant species were selected from the Caltrans Highway Planting Database and Specification Tool (TransPLANT Database) and from contract planting plan sheets of previous projects. For each plant species considered, the potential for BVOC emissions to adversely impact O_3 and/or $PM_{2.5}$ air quality was determined based on the specific BVOCs emitted and the quantity of BVOC emissions produced. Qualitative ratings of low, medium, and high were developed and assigned to each species based on the O_3 formation potential and the $PM_{2.5}$ formation potential of the BVOCs emitted. Because of the complex nature of collecting BVOC

emissions data for plants and the vast number of individual plant species, the data available in the literature cover only a subset of plant subspecies that are used across Caltrans districts. The methods used to analyze the available BVOC emissions data and develop these ratings are provided in Section 3 of this document.

The results of this analysis are presented in Section 5 (Table 4) of this document. Ratings for the O_3 formation potential (OFP) and secondary organic aerosol formation potential (SOAP) are provided for each plant species when there were sufficient data to make an assignment. Many plants share the same ratings for O_3 formation potential and $PM_{2.5}$ formation potential since both terms are proportional to BVOC emission rates. Some genera of plants frequently cited in the scientific literature as high emitters of BVOCs include *Populus* (poplars and cottonwoods), *Salix* (willows), *Platanus* (sycamores), *Eucalyptus* (gums), *Quercus* (oaks), and *Trichostema* (bluecurls), and most species in these genera are rated as “medium” or “high” in their potential to form O_3 and/or $PM_{2.5}$. Notably, plants from the *Pinus* genus (pines) are often cited in scientific literature as being higher emitters of BVOCs, but they are rated as “low” or “medium” in their potential to form O_3 and/or $PM_{2.5}$. This stems from different rating system criteria that are based on different typical scales used to measure O_3 and $PM_{2.5}$ concentrations in ambient air. Such variations can lead to large differences in (1) the range of emission rates for each BVOC and (2) the factors that reflect the potential (or lack of potential) for those BVOCs to form O_3 and $PM_{2.5}$. The literature shows substantial variability of BVOC emission rates across plant species within some genera and across different measurement studies of the same genus and/or species.

Table 4 in this document is provided to assist Caltrans staff with identifying plant species that have the least potential to adversely impact O_3 and/or $PM_{2.5}$ air quality. Additional information that Caltrans staff might otherwise consider for plant selections (e.g., applicable climate zones and planting specifications) are not considered in this table. The BVOC ratings in this table should be considered within the context of project location and the characteristics of the emission sources contributing to the area and its geography and climatology. **Plant selection is the responsibility of the district landscape architects or revegetation specialists**.

1. Introduction

A literature review was conducted of biogenic volatile organic compound (BVOC) emissions from plants commonly used or recommended by Caltrans for erosion control, graffiti control, ornamental planting, functional planting, and mitigation planting to determine the extent to which these plants tend to emit BVOCs and the potential of those compounds to impact air quality. The review was motivated by the recognition that atmospheric BVOCs in urban areas can adversely impact air quality via subsequent chemical and physical processes leading to the secondary formation of ozone (O_3) and secondary organic aerosols (SOAs), which are a key contributor to fine particulate matter ($PM_{2.5}$). Potential emissions of BVOCs can therefore be considered when selecting plants for urban greening efforts and planting in Caltrans' right-of-way.

To better inform the selection of plants for use in Caltrans projects, data from the scientific literature were compiled and analyzed to assign the plants commonly used or recommended for use by Caltrans a rating of low, medium, or high potential to emit BVOCs. Moreover, where the available data were detailed enough, the BVOC emission rates compiled from the literature were also used in combination with BVOC-specific air quality-related factors to estimate ratings of the potential for each plant to form O_3 and SOAs. These three sets of ratings (i.e., of the potential for plants to emit BVOCs, to form O_3, and to form SOAs) are provided in **Table 4** in Section 5. Only plants in the Caltrans TransPLANT Highway Planting Database and Specification Tool[1] (TransPLANT Database) and from contract planting plan sheets of previous projects for which data were available in the literature are included in Table 4. Although these plants may be common and even preferred choices for typical planting selections, some may simultaneously have the potential to adversely impact air quality under certain conditions.

Because of the complex nature of collecting BVOC emissions data for plants and the vast number of individual plant species, the data available in the literature cover a relatively limited number of plants, and many of the hundreds of plant subspecies used across Caltrans districts (especially grasses and forbs[2]) are not represented in Table 4. Despite the limited BVOC emissions data available, Table 4 includes nearly 260 plant species/subspecies and their potential to emit BVOCs and for those to participate in the formation of O_3 and SOAs. In addition to typical plant-selection factors (e.g., climate zone, growth characteristics, or drought tolerance), Caltrans district staff may consider the ratings in Table 4 as qualitative indicators of the potential for a plant to adversely impact air quality, wherein higher BVOC emissions may negatively impact air quality by contributing to the subsequent formation of O_3 and SOAs depending on the specific BVOCs emitted and other factors.

This technical memorandum provides an assessment of available information on biogenic emissions and their potential contributions to air pollution, and it provides a discussion of how BVOCs contribute to secondary formation of O_3 and SOAs. As previously noted, this memo also provides a look-up table of BVOC emissions potential, O_3 formation potential (OFP), and SOA formation potential (SOAP) ratings for nearly 260 plant species/subspecies, as well as other information on plant species to provide context for the individual ratings. Based on this assessment, plant species that would be

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[1] **Caltrans Highway Planting Database and Specification Tool** (https://transplant.dot.ca.gov/TransPlant.php).

[2] Forbs are herbaceous (non-woody) plants with narrow and broad leaves. Forbs are sometimes referred to as herbs.

expected to have the least potential to negatively impact air quality would emit (1) lower levels of BVOC emissions, and (2) BVOCs with lesser potential to form O_3 and SOAs, compared with other plant species.

This memorandum is intended to inform the selection of optimum plant species for erosion control, graffiti control, ornamental planting, functional planting, and mitigation planting while minimizing potential negative air quality impacts. It is provided to assist Caltrans staff with identifying plant species that have the least potential to adversely impact air quality. Additional information that Caltrans staff might otherwise consider for plant selections (e.g., applicable climate zones and planting specifications) are not reproduced in this document. The ratings for BVOC emissions potential, OFP, and SOAP need to be considered within the context of project location and the characteristics of the emission sources contributing to the area and its geography and climatology. **Plant selection is the responsibility of the district landscape architects or revegetation specialists.**

This document is organized as follows:

- **Section 2** provides general background information about the role of plants and their natural emissions of volatile organic compounds (VOCs) in air quality.
- **Section 3** describes the strategy used to perform the literature review, provides an overview of the relevant literature found, and describes the approach used to qualitatively rate the potential of each plant species to impact air quality.
- **Section 4** summarizes the key findings of the literature review and recommendations for further consideration.
- **Section 5** presents a list of plant species adapted to California climate zones based on contract planting plan sheets of previous projects (and, to a lesser extent, the TransPLANT Database), and the qualitative estimates of their potential to emit BVOCs and for those to form O_3 and/or SOAs.

2. Background

This section provides general background information on plants, biogenic emissions, and how biogenic emissions contribute to air pollution.

2.1 The Role of Plants in Ambient Air Quality

Certain plant species provide many benefits. For example, plants can provide shade and other cooling effects and can remove pollutants such as O_3, nitrogen dioxide (NO_2), and particulate matter (PM) from the atmosphere. Several factors affect the rate of removal of those pollutants, including the plant or tree species and its leaf characteristics; the chemical composition of an air parcel and the length of time the air parcel is in contact with a leaf; and the surface area of the leaves of a given plant or tree.[3] Such benefits can help "shield" neighboring communities from roadway air pollution through the use of vegetative barriers along roadways.

2.2 Biogenic Emissions

While plants and trees generally can benefit society and ambient air quality,[4] some species can have negative impacts on air quality. VOCs are reactive chemicals that come from two major sources: (1) anthropogenic VOCs (AVOCs) emitted from human activity, and (2) BVOCs emitted by plants and trees (Gu et al., 2021). BVOC emissions account for approximately 90% of global annual VOC emissions (Guenther et al., 2012; Crippa et al., 2020), although the contribution of AVOCs can be larger in urban environments. In the presence of sunlight, VOCs react with nitrogen oxides (NO_x) in the atmosphere to form ground-level O_3 (**Figure 1**). Combustion sources such as gas and diesel-powered motor vehicles and industrial sources emit NO_x.[5] To a lesser extent, BVOCs can also contribute to production of SOAs and $PM_{2.5}$. O_3 and $PM_{2.5}$ are harmful to human health, especially in urban areas (Ren et al., 2017).

[3] **Trees and Air Quality, California Air Resources Board** (https://ww2.arb.ca.gov/sites/default/files/cap-and-trade/offsets/CARB_2012_trees_and_air_quality.pdf).

[4] **"Ambient Air" Guidance, U.S. Environmental Protection Agency** (https://www.epa.gov/nsr/ambient-air-guidance). Ambient air quality is defined by the U.S. EPA as "*that portion of the atmosphere, external to buildings, to which the general public has access*."

[5] **U.S. Environmental Protection Agency's Report on the Environment** (https://www.epa.gov/report-environment).

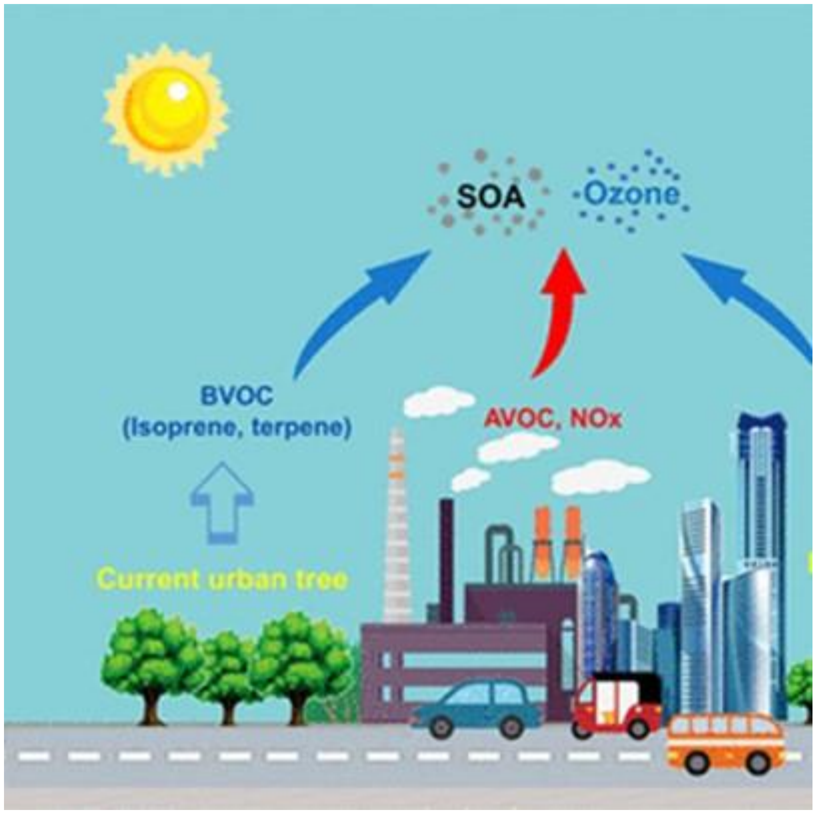

Figure 1. Illustration of VOC emissions and their contribution to secondary ozone and organic aerosol formation. Adapted from Gu et al. (2021).

Biogenic emissions play an important role in regional air quality and global atmospheric chemistry. BVOC emissions are functions of the leaf mass of a plant or tree species, emission factors, temperature, and light conditions.[6] Isoprene (C_5H_8) is the predominant BVOC emitted by plants and trees, and it plays a key role in contributing to the formation of O_3 and also affects the lifetime of other chemical species in the atmosphere (Hu, 2015). Other important BVOCs emitted by plants and trees include monoterpenes ($C_{10}H_{16}$) and sesquiterpenes ($C_{15}H_{24}$) (Owen et al., 2001; Keeling and Bohlmann, 2006). Grass species can emit oxygenated VOCs such as acetaldehyde and acetone, as well as some monoterpenes (Kirstine et al., 1998; Fukui and Doskey, 2000; Laothawornkitkul et al., 2009).

O_3 and $PM_{2.5}$ are criteria pollutants regulated by the U.S. Environmental Protection Agency (EPA) under the National Ambient Air Quality Standards (NAAQS), and by the California Air Resources Board (CARB) under the California Ambient Air Quality Standards. Biogenic emission sources can be widespread and ubiquitous contributors to background air chemistry and formation of O_3 and SOAs (or $PM_{2.5}$). Therefore, it is

[6] **Emission Inventory - Natural Sources, California Air Resources Board** (https://ww2.arb.ca.gov/emission-inventory-natural-sources).

important to account for BVOC emission sources in photochemical grid models used to demonstrate attainment of the NAAQS.[7] BVOC emissions at global and regional scales are accounted for through the use of established models, such as the Biogenic Emission Inventory System and the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2012). However, these models do not provide data on BVOC emission factors at an individual species level; a survey of the scientific literature was therefore necessary to compile such data.

2.3 Environmental Stressors on Plants

Recent studies have shown that plant BVOC emissions are responsive to environmental stress. For example, environmental stressors such as warming, drought, and elevated levels of carbon dioxide (CO_2) and O_3 can inhibit emissions of some BVOCs, and different BVOCs may respond differently to stressors (Feng et al., 2019). Changes to the potential air quality impacts of individual plants in response to stressors will also depend on the OFP and SOAP associated with the BVOCs emitted by healthy plants compared with their stressed counterparts, as well as the atmospheric chemistry regime into which the BVOCs are emitted. Note that although SOA formation increased with an increase in sesquiterpenes in the study of Faiola et al. (2019), sesquiterpenes do not contribute to O_3 formation, as discussed below. Quantification of stress response in order to assign an additional set of ratings that represent potential impacts of specific plant stressors or a combination of stressors was beyond the scope of the literature review and analysis presented here, and additional data would be necessary to supplement the analysis with detailed quantification of stressors on individual plant BVOC emissions.

3. Literature Review and Quantitative Analysis of BVOCs

To assess the potential for plant species commonly used or recommended for use by Caltrans to result in adverse air quality impacts, the literature was reviewed for studies, documents, and databases with relevant BVOC emission rate data. However, emission rates alone do not indicate the potential of the individual or combination of BVOCs emitted by a plant to result in formation of O_3 and/or SOAs. Similar to the approach described by Gu et. al. (2021) in the context of VOC emission inventories developed for Los Angeles County, maximum incremental reactivity (MIR) and SOA yield (Y_{SOA}) factors corresponding to each BVOC and/or class of BVOC were used to calculate the OFP and SOAP of each plant species included in the analysis. As also described by Gu

[7] **Biogenic Emission Sources, U.S. Environmental Protection Agency** (https://www.epa.gov/air-emissions-modeling/biogenic-emission-sources).

et al. (2021), this approach has been well documented and widely used to evaluate the potential contribution of specific BVOCs to the formation of O_3 and SOAs.

For each plant considered in the literature review, its potential to adversely impact air quality was estimated in terms of OFP and SOAP when specific BVOC and/or class of BVOC emission rate data were available. The OFP and SOAP estimates are based on simplifying assumptions about the specific BVOCs emitted by each plant, the magnitude of those emissions, the characteristic reactivity of each BVOC, and the atmospheric conditions into which the BVOCs are emitted. Given those assumptions and the associated uncertainty in quantitative estimates of OFP and SOAP, the analysis focused on developing relative, qualitative ratings for each plant species based on quantitative estimates. This literature review and analysis sought to:

1. Develop a comprehensive list of available BVOC emission rates by plant species used or recommended for use by Caltrans.
2. For each plant species with available BVOC emission rate data of sufficient detail, calculate the OFP and SOAP based on those emission rates and factors representing the reactivity and anticipated air quality impacts of the specific BVOCs.
3. Analyze the BVOC data and calculate OFP and SOAP values to develop ratings of the potential for each plant species to emit BVOCs, to form O_3, and to form SOAs on a relative, qualitative scale (i.e., low, medium, or high potential).
4. Provide an easy-to-reference look-up table of the qualitative ratings developed for each plant species.

Several tools and information sources, including Google and Google Scholar, were used to perform an extensive review of the scientific literature, online databases, and other resources. Combinations of keywords used for the search included, but were not limited to, "*BVOC emissions from plants*"; "*BVOC emissions from specific plant species*"; "*VOCs emitted from trees or shrubs*"; and "*emission rates of isoprene and monoterpenes from plants.*" The relevant references, among more than 50 studies and other data sources that reported BVOC emission rates data, are listed in **Table 1**.

Table 1. Summary of references pertaining to BVOC emissions from plants that were reviewed or considered as part of the literature review.

Table Summary: This table provides a summary of the references that were identified and used to develop the look-up table of BVOC emissions potential shown in Table 4 of this document.

Type of Document	Author	Year	Title	Type of Plant
Journal - Atmospheric Environment	Arey et al.	1995	Hydrocarbon emissions from natural vegetation in California's South Coast Air Basin	Tree and shrub
Journal - Science of the Total Environment	Aydin et al.	2014	Biogenic volatile organic compound (BVOC) emissions from forested areas in Turkey: Determination of specific emission rates for thirty-one tree species	Tree
Journal - Environmental Pollution	Bao et al.	2023	A meta-analysis on plant volatile organic compound emissions of different plant species and responses to environmental stress	Tree
Journal - Atmospheric Environment	Benjamin et al.	1996	Low-emitting urban forests: a taxonomic methodology for assigning isoprene and monoterpene emission rates	Tree and shrub
Journal - Environmental Pollution	Calfapietra et al.	2013	Role of Biogenic Volatile Organic Compounds (BVOC) emitted by urban trees on ozone concentration in cities: A review	Tree
Journal - Journal of Environmental Quality	Dunn-Johnston et al.	2016	Isoprene emission factors for subtropical street trees for regional air quality modeling	Tree
Journal - Atmospheric Environment	Geron et al.	2006	Biogenic volatile organic compound emissions from desert vegetation of the southwestern US	Shrub
Journal - Atmospheric Environment	Guenther et al.	1994	Natural volatile organic compound emission rate estimates for U.S. woodland landscapes	Tree
Journal - Atmospheric Environment	Hewitt and Street	1992	A qualitative assessment of the emission of non-methane hydrocarbon compounds from the biosphere to the atmosphere in the U.K.: present knowledge and uncertainties	Tree and grass
Journal - Atmospheric Environment	Karlik and Winer	2001	Measured isoprene emission rates of plants in California landscapes: comparison to estimates from taxonomic relationships	Tree

Type of Document	Author	Year	Title	Type of Plant
Thesis	Oldham	2002	Estimating biogenic non-methane hydrocarbon emissions for the Wasatch Front through a high-resolution, gridded, biogenic volatile organic compound emissions inventory	Tree and grass
Journal - Atmospheric Environment	Owen et al.	2001	Volatile organic compounds (VOCs) emitted from 40 Mediterranean plant species: VOC speciation and extrapolation to habitat scale	Tree and shrub
Journal - Science of the Total Environment	Wagner and Kuttler	2014	Biogenic and anthropogenic isoprene in the near-surface urban atmosphere — a case study in Essen, Germany	Tree
Journal - Atmospheric Environment	Winer et al.	1992	Emission rates of organics from vegetation in California's Central Valley	Tree and herb
Journal - Journal of Geophysical Research	Varshney and Singh	2003	Isoprene emission from Indian trees	Tree

3.1 BVOC Emissions from Plants Used by Caltrans

Emission rates of BVOCs, including isoprene, monoterpenes, sesquiterpenes, other terpenes, and other VOCs (OVOCs), for plant species in the Caltrans TransPLANT Database and contract planting plan sheets of previous projects were compiled or assigned based on the information from the references listed in Table 1. The BVOC emission rates from the literature studies were typically reported in units of micrograms of BVOC per gram of dry leaf weight per hour ($\mu g\ g^{-1}\ h^{-1}$). In cases where the BVOC emission rate was reported in micrograms of carbon per gram per hour ($\mu g\ C\ g^{-1}\ h^{-1}$), the units were converted to $\mu g\ g^{-1}\ h^{-1}$ by multiplying the emission rate by the ratio of the molecular weight of the respective BVOC to the molecular weight of the number of carbon atoms in that BVOC. In some cases, the BVOC emission rates were reported in moles per square meter per second ($mol\ m^{-2}\ s^{-1}$). Emission rates for these BVOCs could not be converted to $\mu g\ g^{-1}\ h^{-1}$ because the species' foliar (leaf) mass ($g\ m^{-2}$) data were not available. Therefore, the few species with emission rates reported in units of $mol\ m^{-2}\ s^{-1}$ were not included in the data analyses. For plant species with no reported BVOC emission rates, the BVOC emission rates for their respective genus, when available, were assigned to the individual species. Additionally, all species with the same scientific name but different common names[8] were assigned the same reported BVOCs emission rates. Once the emission rates were compiled and converted to common units (i.e., µg g^{-1} h^{-1}), they were used to (1) estimate a corresponding OFP and SOAP for each plant species, and (2) develop the BVOC emissions potential ratings for each plant species.

3.2 Calculation of OFP and SOAP

Similar to the approach used by Gu et al. (2021) in their BVOC emissions inventory for Los Angeles County, OFP and SOAP were calculated on the basis of each plant species i (i.e., OFP_i and $SOAP_i$) using Equations 1 and 2 below:

$$OFP_i = \sum_j (E_{i,j} \times MIR_j) \quad \textbf{Equation 1}$$

$$SOAP_i = \sum_j (E_{i,j} \times Y_{SOA,j}) \quad \textbf{Equation 2}$$

where

$E_{i,j}$ = the emission rate of an individual BVOC or class of BVOC j for plant species i

MIR_j = the maximum incremental reactivity of an individual BVOC or class of BVOC j

$Y_{SOA,j}$ = the SOA yield of an individual BVOC or class of BVOC j

The emission rates in these equations are those described in **Section 3.1** above and have units of µg g^{-1} h^{-1}. The MIR and Y_{SOA} factors for BVOCs in this analysis derived from Gu et al. (2021) are summarized in **Table 2** below.

[8] Different common names for a plant species may be used for various reasons. In some cases, the same plant species may have different common names in different cultures and languages. Different common names may also be used to differentiate between physical characteristics of plant subspecies such as flower color or physical size. For example, see Streich and Todd (2014) or the discussion about nomenclature of scientific plant names from Oregon State University's Department of Horticulture at **Scientific Plant Names (Binomial Nomenclature)** (https://landscapeplants.oregonstate.edu/scientific-plant-names-binomial-nomenclature).

Table 2. Parameters used to estimate plant-specific OFP and SOAP.

Table Summary: MIR and Y_{SOA} for BVOCs (or classes of BVOCs) used to estimate plant-specific OFP and SOAP.

BVOC	MIR (g O_3/g BVOC)	Y_{SOA} (µg SOA m^{-3} / µg BVOC m^{-3})
Isoprene	10.6	0.021
Monoterpenes	4.43	0.156
Sesquiterpenes	0	0.388
Oxygenated monoterpenes (e.g., camphor)	2.13	0.186
Aromatics	4.97	0.021
Others	3.09	0

These data reflect an inverse relationship between MIR and Y_{SOA}. For example, isoprene has a relatively high MIR but a relatively low Y_{SOA} compared with monoterpenes and aromatics. Conversely, sesquiterpenes have zero MIR (i.e., they do not participate in ozone chemistry) but a relatively high Y_{SOA}. This trend is a result of differences in the atmospheric chemical reactivity of different BVOCs and their oxidation products. BVOCs that are oxidized to more volatile reaction products in the atmosphere are more likely to participate in the gas-phase reactions that form O_3. On the other hand, SOAs are formed via gas-to-particle phase processes, including nucleation and condensation of semi-volatile organic compounds and low-volatility organic compounds, and subsequent coagulation. The OFP and SOAP ratings listed in Table 4 are based on the MIR and Y_{SOA} data in Table 2 as well as the speciated BVOC emission rates compiled from the literature. Therefore, the ratings for each plant are based on the specific composition and magnitude of BVOCs emitted by the plant and the corresponding reactivity potentials summarized in Table 2.

3.3 Qualitative Ratings of BVOC Emissions Potential, OFP, and SOAP

The reported emission rates of individual BVOCs and classes of BVOCs were summed to obtain a total BVOC emission rate for each plant species. When more than one study measured emission rates of the same BVOC or class of BVOCs for the same plant, the rates were averaged before summing across all emitted BVOCs for that plant. Each plant was then rated as a low, medium, or high BVOC emitter based on criteria proposed by Karlik and Winer (2001), Dunn-Johnston et al. (2016), and Varshney and Singh (2003):

- Low BVOC emitter (emission rate < 10 µg g^{-1} h^{-1})
- Medium BVOC emitter (10 µg g^{-1} h^{-1} ≤ emission rate < 25 µg g^{-1} h^{-1})
- High BVOC emitter (emission rate ≥ 25 µg g^{-1} h^{-1})

The assigned BVOC emissions potential ratings for relevant plant species are listed in Table 4. However, those ratings only represent the potential for a plant to emit BVOCs and do not take into account the specific chemical species emitted or their potential to form O_3 or SOAs.

For all of the plants listed in Table 4, the calculated values of OFP and SOAP (as described above in **Section 3.2**) were analyzed statistically and organized as low, medium, and high based on thresholds that yielded roughly equal-sized bins of plants while also considering natural breaks in the ranges of values. The variability in the range of calculated OFP and SOAP values is substantial: the range of calculated OFP values spanned nearly a factor of 1000 (from roughly 0.2 to 858 µg O_3 g^{-1} h^{-1}); while the range of calculated SOAP values spanned about a factor of 100 (from 0 to 6.7 µg SOA m^{-3} g^{-1} h^{-1}).

The OFP ratings were assigned as follows:

- Low OFP (formation rate ≤ 16 µg O_3 g^{-1} h^{-1})
- Medium OFP (16 µg O_3 g^{-1} h^{-1} < formation rate ≤ 159 µg O_3 g^{-1} h^{-1})
- High OFP (formation rate > 159 µg O_3 g^{-1} h^{-1})

The SOAP ratings were assigned as follows:

- Low SOAP (formation rate ≤ 0.3 µg SOA m^{-3} g^{-1} h^{-1})
- Medium SOAP (0.3 µg SOA m^{-3} g^{-1} h^{-1} < formation rate ≤ 0.6 µg SOA m^{-3} g^{-1} h^{-1})
- High SOAP (formation rate > 0.6 µg SOA m^{-3} g^{-1} h^{-1})

Many plants share the same ratings for OFP and SOAP, because both parameters are proportional to BVOC emission rates. However, these two quantities are based on different units of measure and differ in magnitude. To illustrate this point, **Table 3** lists the OFP and SOAP values and ratings for a small subset of plant species. Based on the calculated OFP and SOAP values, a low rating was assigned for wildrye and variegated dwarf ivy, a medium rating was assigned for Douglas fir and ponderosa pine, and a high rating was assigned for *Salix*-genus willows and sweet gum. Some plants emit primarily BVOCs that may form O_3 but little or no SOAs. Isoprene is the most reactive BVOC for O_3 formation but has a low reported SOA yield (see Table 2). For example, only isoprene emissions were reported in the literature for California sycamore, and the calculated OFP and SOAP values for this plant correspond to a medium OFP rating and a low SOAP rating. On the other hand, monoterpenes and sesquiterpenes have relatively high reported SOA yields and small OFP, but most plant species that have a high SOAP rating also have a high OFP rating (e.g., sweet gum) because they also emit a significant amount of other BVOC species such as isoprene that contribute to O_3

formation. One species in this report, big sagebrush, has a high SOAP rating and a medium OFP rating. Several species (e.g., lodgepole pine) have a medium SOAP rating and a low OFP rating.

Table 3. OFP and SOAP values and ratings for selected plants.

Table Summary: This table lists the OFP and SOAP values and their ratings for selected plant species described in the text above. See Table 4 for the complete table of OFP and SOAP ratings.

Common Name	OFP ($\mu g\ O_3\ g^{-1}\ h^{-1}$)	OFP Rating	SOAP (μg SOA $m^{-3}\ g^{-1}\ h^{-1}$)	SOAP Rating
Wildrye	0.2	Low	0	Low
Variegated Dwarf Ivy	5.7	Low	0	Low
Douglas Fir	24	Medium	0.4	Medium
Ponderosa Pine	22	Medium	0.5	Medium
Salix-genus Willows	422	High	0.9	High
Sweet Gum	857	High	2.2	High
California Sycamore	116	Medium	0.2	Low
Big Basin Sagebrush	42	Medium	1.3	High
Lodgepole Pine	16	Low	0.5	Medium

4. Summary of Key Findings and Recommendations

A look-up table of BVOC emissions potential, OFP, and SOAP ratings (Table 4) was developed based on the current scientific literature and other data sources. This look-up table may help Caltrans staff make more informed decisions about planting in Caltrans' right-of-way. Selecting plants depends on their intended purpose, of course, and many other factors, such as geographic location, plant growth characteristics, and plant watering and maintenance requirements. Table 4, which reflects the quantitative analysis of literature review findings discussed in this document, focuses on factors related to the potential for individual plants to emit BVOCs and the subsequent potential for those compounds to participate in the formation of O_3 and SOAs. The ratings for each plant in Table 4 have inherent limitations based on assumptions about the underlying study data from the literature (e.g., parameter values used to derive SOA yield factors are intended to reflect conditions in Los Angeles County). Several key features of the data and related limitations of the ratings in Table 4 are summarized below.

Some genera of plants frequently cited in the scientific literature as high emitters of isoprene and/or monoterpenes include *Populus*, *Salix*, *Platanus*, *Eucalyptus*, *Quercus,* and *Trichostema* (e.g., Laothawornkitkul et al., 2009). Notably, plants in the *Pinus* genus are often cited as being higher emitters of monoterpenes, but they are listed as having low BVOC emissions potential in Table 4 based on the data that were compiled and the scheme used here to classify BVOC emitters. This finding is a result of different rating system criteria that are in turn based on different typical scales used for measuring O_3 and SOA (or PM) concentrations in ambient air. Such variations can lead to large differences in (1) the range of emission rates for each BVOC and class of BVOCs (e.g., isoprene and monoterpenes); and (2) the factors that reflect the potential (or lack of potential) for those BVOCs to form O_3 and SOAs. For example, based on the data compiled from the literature, (1) emission rates of isoprene and monoterpenes for studied plants range from below detection limits to about 80 and 40 $\mu g\ g^{-1}\ h^{-1}$, respectively; and (2) the range of values used to estimate potential air quality impacts in terms of OFP is nearly 30 times the range of values used to estimate impacts in terms of SOAP.[9] Additionally, the OFP and SOAP values of a BVOC or class of BVOCs are typically inversely related: BVOCs with a high (low) OFP often have a low (high) SOAP.

The literature reveals substantial variability in BVOC emission rates across plant species within the same genus and between studies of the same genus and/or species. In this analysis, the potential for each plant to emit BVOCs is based on summing the measured emission rates of individual BVOCs reported in the literature for each plant relative to that of all other plants analyzed. When more than one study reported measured rates of BVOC emissions for the same plant, the average of each of those BVOCs was calculated before summing over different BVOCs.[10] However, as indicated above, each BVOC or class of BVOCs has a unique potential for impacting air quality via reactions in the atmosphere that can lead to the formation of O_3 and SOAs. To estimate a plant's potential to impact air quality, the emission rate of each individual BVOC or class of BVOCs was weighted (i.e., multiplied) by the factors that represent the potential to form O_3 (i.e., MIR) and SOA (i.e., Y_{SOA}).

Significant variability between BVOC emission rates and the potential for BVOCs to impact air quality can occur due to many factors. Leaf mass, ambient temperature, and light intensity can affect BVOC emissions from individual plants. Soil conditions and local environmental stressors such as drought can also affect BVOC emissions. Climatology and geography are important factors in terms of the potential air quality impacts of BVOC emissions from plants. Ambient concentrations of O_3, $PM_{2.5}$, NO_x, and

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[9] For example, across all BVOCs in this analysis, the highest MIR value of 10.60 g O_3 per g BVOC is associated with isoprene, and the highest Y_{SOA} value of 0.39 μg SOA m^{-3} per μg BVOC m^{-3} is associated with sesquiterpenes.

[10] Although an average emission rate was calculated in this analysis for a single BVOC or class of BVOCs when more than one value for the same plant was reported, application of only a lower or higher rate might be justified depending on the planting location of interest.

VOCs—and local atmospheric chemistry conditions—can influence the extent to which BVOC emissions may create secondary O_3 or $PM_{2.5}$ (Koplitz et al., 2022). Although many factors can affect real-world BVOC emissions and their subsequent air quality impacts, generally, areas where ambient O_3 and/or $PM_{2.5}$ concentrations exceed state or federal ambient air quality standards are ideal locations to consider the ratings for plant species summarized in Table 4 and the potential air quality impacts associated with the selection of plants for Caltrans projects. Since O_3 and $PM_{2.5}$ can be transported long distances downwind, projects that are near (e.g., within 50-100 miles) areas where ambient O_3 and/or $PM_{2.5}$ concentrations exceed state or federal ambient air quality standards are also good candidates to consider the ratings for plant species summarized in Table 4. Note that the EPA Green Book[11] provides the latest information about areas that do not meet federal air quality standards, while the CARB website provides the latest information regarding state air quality standards.[12] Practioners can also consult with air quality specialists in their Caltrans District office or Caltrans Headquarters to identify applicable air quality designations for project locations.

As discussed in relation to plant responses to environmental stressors (**Section 2.3**) and the reactivity parameters (i.e., MIR and Y_{SOA}) used to calculate OFP and SOAP (Table 2), the response of SOA formation to changes in BVOC emissions is dependent on the chemical reactivity of the specific BVOCs associated with different plants in different regions of the state. Even when these changes occur in an area that is not favorable for O_3 and/or $PM_{2.5}$ formation, such changes can still influence O_3 and/or $PM_{2.5}$ formation downwind. The data in Table 4 are intended to inform the selection of plants by providing the OFP and SOAP ratings for specific plants that may commonly be considered for different ecological and climatalogical conditions across the state. However, these ratings need to be considered within the context of project location and the characteristics of the emission sources contributing to the area and its geography and climatology.

Additional limitations of the analysis presented here result from (1) the sheer number of plant species that are used or recommended for use by Caltrans, and (2) a general lack of available data at the individual plant species level. Therefore, focus remained on the plant species for which there were BVOC data available. In many cases, genus-level data were assigned to plant species for which species-specific data were lacking. For some plants, BVOC emission rates at the genus and species levels were found to differ widely in the literature, and limiting assumptions were used to develop the quantitative-based ratings of BVOC emissions potential, OFP, and SOAP. Furthermore, many of the available studies are narrowly focused on specific plants (especially trees); most of these studies do not include groundcover, grasses, or small shrubs, which are

[11] **Nonattainment Areas for Criteria Pollutants (EPA Green Book)** (https://www.epa.gov/green-book).
[12] **Maps of State Area Designations** (https://ww2.arb.ca.gov/resources/documents/maps-state-and-federal-area-designations).

commonly used for erosion control in the low and mid zones of stormwater drainage features.[13]

Through discussion with Dr. Alex Guenther, an international leader in atmospheric and terrestrial ecosystem research at the University of California, Irvine and developer of the MEGAN model, we learned that many of the emission factors used to model BVOCs are based on decades-old studies of trees. Such studies do not reflect current scientific practices. Therefore, gaps in the existing data for plant-specific BVOC emission rates preclude the estimation of emissions potential ratings and subsequent OFP and SOAP ratings for all plants typically used by Caltrans. A broader update of the available literature and published BVOC emission rate data is necessary to expand the quantitative analysis described in this document and the numbers of different types of plants included in Table 4. Recent work by Gu et al. (2021), on which the methods for estimating OFP and SOAP in Table 4 are based, emphasizes the need for a more thorough evaluation of BVOC emissions from urban plants as well as the potential for plants to remove pollutants such as O_3 and PM from the air via uptake and deposition. The study of Gu et al. (2021), and its BVOC inventory development, also illustrates the high level of complexity associated with estimating natural (and anthropogenic) VOC emissions and their potential air quality impacts in a real-world environment. Additionally, Guenther et al. (2012) had previously documented the need for more studies pertaining to below- and in-canopy processes (e.g., deposition) that may remove BVOCs and their reaction products before they are transported above the canopy. The observations summarized here furthermore suggest that the ratings provided in Table 4, although based on a quantitative analysis of published data, should be considered only on a relative, qualitative basis.

5. Summary of BVOC Emissions, Ozone Formation, and SOA Formation Potential Ratings by Plant Species

This section contains the look-up table of BVOC emissions potential, ozone formation potential (OFP), and secondary organic aerosol formation potential (SOAP) ratings by plant species based on the current literature and other data sources, as described throughout this document (Table 4). The table is organized by plant type (tree, shrub, and other species) and ordered alphabetically by the common name of each plant species within those categories. Note that in some cases there are multiple entries for the same species in the table, due to variations in common names that are used for certain plant species or subspecies across different Caltrans districts.

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[13] See examples of stormwater guidance material and recommended plants for different planting zones at **Landscaping Guidance for Stormwater BMPs** (https://www.waterboards.ca.gov/rwqcb2/water_issues/programs/stormwater/muni/nrdc/appnd_a.pdf) and **Low Impact Development (LID) Planting Zones and Plant List** (https://www.waterboards.ca.gov/rwqcb3/water_issues/programs/stormwater/docs/salinas/appndx_g.pdf).

This table is intended to inform the selection of optimum plant species for erosion control, graffiti control, ornamental planting, functional planting, and mitigation planting while minimizing potential air quality impacts; it is provided to assist Caltrans staff with identifying plant species that have the least potential to adversely impact air quality. Additional information that Caltrans staff might otherwise consider when selecting plants (for example, applicable climate zones and planting specifications) are not considered in this table. The BVOC emissions potential, OFP ratings, and SOAP ratings in this table should be considered within the context of project location and the characteristics of the emission sources contributing to the area and its geography and climatology. **Plant selection is the responsibility of the district landscape architects or revegetation specialists.**

Table 4. Look-up table of estimated BVOC emissions potential, ozone formation potential (OFP), and secondary organic aerosol formation potential (SOAP) ratings by plant species.[1]

Table Summary: This table lists qualitative ratings of the potential of plant species to emit BVOCs, and for those BVOCs to form O_3 and SOAs, as estimated in the analysis described in this document using data reported in the literature. These plant species were selected from the Caltrans Highway Planting Database and Specification Tool (TransPLANT Database) and from Caltrans contract planting plans sheets of previous projects. Only plant species for which all relevant data were found or assigned are included in the table. The table is organized by plant type (tree, shrub, and other species) and ordered alphabetically by the common name of each plant species within those categories. Note that the same common name has been used in Caltrans project planting plans across districts for several subspecies or varieties of some plant species listed in the table. The following ranges of calculated potentials were used to develop the qualitative ratings: Emissions Potential values based on emission rates in units of micrograms of BVOC per gram of dry leaf weight per hour ($\mu g\ g^{-1}\ h^{-1}$) are defined as low (Emissions Potential < 10 $\mu g\ g^{-1}\ h^{-1}$); medium (10 $\mu g\ g^{-1}\ h^{-1}$ ≤ Emissions Potential < 25 $\mu g\ g^{-1}\ h^{-1}$); and high (Emissions Potential ≥ 25 $\mu g\ g^{-1}\ h^{-1}$); OFP values in units of micrograms of O_3 per gram of dry leaf weight per hour ($\mu g\ g^{-1}\ h^{-1}$) are defined as low (OFP ≤ 16 $\mu g\ g^{-1}\ h^{-1}$); medium (16 $\mu g\ g^{-1}\ h^{-1}$ < OFP ≤ 159 $\mu g\ g^{-1}\ h^{-1}$); and high (OFP > 159 $\mu g\ g^{-1}\ h^{-1}$); and SOAP values in (concentration) units of SOAs in air ($\mu g\ m^{-3}$) per gram of dry leaf weight per hour (full units of $\mu g\ m^{-3}\ g^{-1}\ h^{-1}$) are defined as low (SOAP ≤ 0.3 $\mu g\ m^{-3}\ g^{-1}\ h^{-1}$), medium (0.3 $\mu g\ m^{-3}\ g^{-1}\ h^{-1}$ < SOAP ≤ 0.6 $\mu g\ m^{-3}\ g^{-1}\ h^{-1}$), and high (SOAP > 0.6 $\mu g\ m^{-3}\ g^{-1}\ h^{-1}$).

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
Tree Species						
ACACIA 'LOW BOY'	ACACIA LOWBOY	Tree	Low	Assigned	Low	Medium
AFGHAN PINE	PINUS ELDARICA	Tree	Low	Assigned	Low	Medium
ALEPPO PINE	PINUS HALEPENSIS	Tree	Low	Found	Low	Low
AMERICAN SWEET GUM	LIQUIDAMBAR STYRACIFLUA	Tree	High	Assigned	High	High
AMERICAN SWEET GUM	LIQUIDAMBAR STYRACIFLUA 'BURGUNDY'	Tree	High	Assigned	High	High
AMERICAN SWEET GUM	LIQUIDAMBAR STYRACIFLUA 'FESTIVAL'	Tree	High	Assigned	High	High
AMERICAN SWEET GUM	LIQUIDAMBAR STYRACIFLUA 'ROTUNDILOBA'	Tree	High	Assigned	High	High
ARMSTRONG RED MAPLE	ACER RUBRUM 'ARMSTRONG'	Tree	Low	Found	Low	Medium
ASH TREE	FRAXINUS LATIFOLIA	Tree	Low	Assigned	Low	Low
ATLAS CEDAR	CEDRUS ATLANTICA	Tree	Low	Assigned	Low	Low

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
BALSAM POPLAR	POPULUS BALSAMIFERA	Tree	High	Assigned	High	High
BIG LEAF MAPLE	ACER MACROPHYLLUM	Tree	Low	Found	Low	Low
BISHOP PINE	PINUS MURICATA	Tree	Low	Assigned	Low	Medium
BLACK COTTONWOOD	POPULUS BALSAMIFERA SSP. TRICHOCARPA	Tree	High	Assigned	High	High
BLACK OAK	QUERCUS KELLOGGII	Tree	High	Found	High	High
BLACKWOOD ACACIA	ACACIA MELANOXYLON	Tree	Low	Found	Low	Low
BLOODGOOD JAPANESE MAPLE	ACER PALMATUM 'BLOODGOOD'	Tree	Low	Assigned	Medium	Medium
BLUE OAK	QUERCUS DOUGLASII	Tree	Medium	Found	High	Medium
BLUE PALO VERDE	CERCIDIUM FLORIDUM	Tree	Low	Assigned	Low	Low
BOX ELDER	ACER NEGUNDO	Tree	Low	Assigned	Low	Low
CALIFORNIA BLACK OAK	QUERCUS KELLOGGII	Tree	High	Found	High	High
CALIFORNIA BLACK WALNUT	JUGLANS CALIFORNICA	Tree	Low	Assigned	Low	Medium
CALIFORNIA BOX ELDER	ACER NEGUNDO 'CALIFORNICUM'	Tree	Low	Assigned	Low	Low
CALIFORNIA PEPPER	SCHINUS MOLLE	Tree	Low	Assigned	Medium	Medium
CALIFORNIA REDBUD	CERCIS OCCIDENTALIS	Tree	Low	Found	Low	Low
CALIFORNIA SYCAMORE	PLATANUS RACEMOSA	Tree	Medium	Assigned	Medium	Low
CANARY ISLAND PINE	PINUS CANARIENSIS	Tree	Low	Found	Low	Medium
CANYON LIVE OAK	QUERCUS CHRYSOLEPIS	Tree	Medium	Assigned	High	Medium
CAROLINA CHERRY LAUREL	PRUNUS CAROLINIANA	Tree	Low	Assigned	Low	Low
CATALINA CHERRY	PRUNUS ILICIFOLIA	Tree	Low	Assigned	Low	Low
CATALINA CHERRY	PRUNUS ILICIFOLIA 'LYONII'	Tree	Low	Found	Low	Low
CATCLAW	ACACIA GREGGII	Tree	Low	Assigned	Low	Medium

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
CHERRY PLUM	PRUNUS CERASIFERA 'THUNDERCLOUD'	Tree	Low	Assigned	Low	Low
CHERRY PLUM	PRUNUS CERASIFERA	Tree	Low	Assigned	Low	Low
CHINESE ELM	ULMUS PARVIFOLIA	Tree	Low	Found	Low	Low
COAST LIVE OAK	QUERCUS AGRIFOLIA	Tree	High	Found	High	High
COAST REDWOOD	SEQUOIA SEMPERVIRENS	Tree	Low	Found	Low	Low
COAST REDWOOD	SEQUOIA SEMPERVIRENS 'LOS ALTOS'	Tree	Low	Found	Low	Low
COAST REDWOOD VAR. APTOS BLUE	SEQUOIA SEMPERVIRENS 'APTOS BLUE'	Tree	Low	Found	Low	Low
COLUMNAR BLUE ATLAS CEDAR	CEDRUS ATLANTICA 'GLAUCA FASTIGIATA'	Tree	Low	Assigned	Low	Low
CORK OAK	QUERCUS SUBER	Tree	Low	Found	Low	Low
COULTER PINE	PINUS COULTERI	Tree	Low	Assigned	Low	Medium
DEODAR CEDAR	CEDRUS DEODARA	Tree	Low	Found	Low	Low
DOUGLAS-FIR	PSEUDOTSUGA MENZIESII	Tree	Low	Found	Medium	Medium
DOUGLAS-FIR	PSEUDOTSUGA MENZIESII VAR. MENZIESII	Tree	Low	Found	Medium	Medium
EASTERN REDBUD	CERCIS CANADENSIS	Tree	Low	Assigned	Low	Low
EASTERN REDBUD	CERCIS CANADENSIS 'FOREST PANSY'	Tree	Low	Assigned	Low	Low
ELDARICA PINE	PINUS ELDARICA	Tree	Low	Assigned	Low	Medium
FESTIVAL SWEETGUM	LIQUIDAMBAR STYRACIFLUA 'FESTIVAL'	Tree	High	Assigned	High	High
FLOWERING PEACH	PRUNUS PERSICA 'HELEN BORCHERS'	Tree	Low	Found	Medium	Medium
FLOWERING PLUM	PRUNUS BLIREIANA	Tree	Low	Assigned	Low	Low
FREMONT COTTONWOOD	POPULUS FREMONTII	Tree	High	Assigned	High	High
FREMONT POPLAR	POPULUS FREMONTII	Tree	High	Assigned	High	High
FRUITLESS OLIVE	OLEA EUROPAEA 'SWAN HILL'	Tree	Low	Found	Low	Low

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
GARRY OAK	QUERCUS GARRYANA	Tree	High	Found	High	High
GIANT SEQUOIA	SEQUOIADENDRON GIGANTEUM	Tree	Low	Found	Low	Low
GINKGO	GINKGO BILOBA	Tree	Low	Found	Low	Medium
GINKGO 'SARATOGA'	GINKGO BILOBA 'SARATOGA'	Tree	Low	Found	Low	Medium
GINKO/MAIDEN HAIR TREE	GINKGO BILBOA 'AUTUMN GOLD'	Tree	Low	Found	Low	Medium
GOODDING'S BLACK WILLOW	SALIX GOODDINGII	Tree	High	Assigned	High	High
GRAND FIR	ABIES GRANDIS	Tree	Low	Assigned	Low	Medium
GREY PINE	PINUS SABINIANA	Tree	Low	Found	Low	Low
HALKA HONEYLOCUST	GLEDITSIA TRIACANTHOS INERMIS 'HALKA'	Tree	Low	Found	Low	Low
HOLLY OAK	QUERCUS ILEX	Tree	High	Found	High	High
HOLLYLEAF CHERRY	PRUNUS ILICIFOLIA	Tree	Low	Assigned	Low	Low
HOLLYLEAF CHERRY	PRUNUS ILICIFOLIA SSP. ILICIFOLIA	Tree	Low	Assigned	Low	Low
HOLLYWOOD JUNIPER	JUNIPERUS CHINENSIS 'TORULOSA'	Tree	Low	Found	Low	Low
HYBRID FAN PALM	WASHINGTONIA FILIBUSTA	Tree	Medium	Assigned	High	Medium
HYBRID REDBUD	CERCIS CANADENSIS 'FOREST PANSY'	Tree	Low	Assigned	Low	Low
IDAHO LOCUST	ROBINIA AMBIGUA 'IDAHOENSIS'	Tree	Medium	Assigned	High	Medium
INTERIOR LIVE OAK	QUERCUS WISLIZENII	Tree	Medium	Found	Medium	Low
ITALIAN CYPRESS	CUPRESSUS SEMPERVIRENS	Tree	Low	Found	Low	Low
JEFFREY PINE	PINUS JEFFREYI	Tree	Low	Assigned	Low	Medium
JELECOTE PINE	PINUS PATULA	Tree	Low	Assigned	Low	Medium
KANZAN JAPANESE FLOWERING CHERRY	PRUNUS SERRULATA 'KANZAN'	Tree	Low	Assigned	Low	Low
KRAUTER VESUVIUS PLUM	PRUNUS CERASIFERA 'KRAUTER VESUVIUS'	Tree	Low	Assigned	Low	Low

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
LEMON SCENTED GUM	EUCALYPTUS CITRIODORA	Tree	High	Found	High	High
LIQUID AMBER	LIQUIDAMBAR STYRACIFLUA	Tree	High	Assigned	High	High
LODGEPOLE PINE	PINUS MURRYANA	Tree	Low	Assigned	Low	Medium
LOMBARDY POPLAR	POPULUS NIGRA 'ITALICA'	Tree	High	Assigned	High	High
LONDON PLANE	PLATANUS ACERIFOLIA	Tree	Medium	Found	High	Medium
LONDON PLANE	PLATANUS ACERIFOLIA 'COLUMBIA'	Tree	Medium	Found	High	Medium
MAGNOLIA 'RUSSET'	MAGNOLIA GRANDIFLORA 'RUSSET'	Tree	Low	Assigned	Low	Medium
MAIDENHAIR TREE	GINKGO BILOBA	Tree	Low	Found	Low	Medium
MAIDENHAIR TREE	GINKGO BILOBA 'FAIRMOUNT'	Tree	Low	Found	Low	Medium
MANNA GUM	EUCALYPTUS VIMINALIS	Tree	Low	Found	Medium	Low
MESA OAK	QUERCUS ENGELMANNII	Tree	High	Assigned	High	High
MEXICAN FAN PALM	WASHINGTONIA ROBUSTA	Tree	Medium	Found	Medium	Low
MODESTO ASH	FRAXINUS VELUTINA MODESTO	Tree	Low	Found	Low	Low
MONROE VINE MAPLE	ACER CIRCINATUM 'MONROE'	Tree	Low	Assigned	Low	Low
MONTEREY PINE	PINUS RADIATA	Tree	Low	Found	Low	Low
MOUNTAIN DOGWOOD	CORNUS NUTTALLII	Tree	Low	Assigned	Low	Low
MT. FUJI FLOWERING CHERRY	PRUNUS SERRULATA 'SHIROTAE'	Tree	Low	Assigned	Low	Low
NORTHERN RED OAK	QUERCUS RUBRA	Tree	High	Found	High	High
OREGON ASH	FRAXINUS LATIFOLIA	Tree	Low	Assigned	Low	Low
OREGON OAK	QUERCUS GARRYANA	Tree	High	Found	High	High
PACIFIC DOGWOOD	CORNUS NUTTALLII	Tree	Low	Assigned	Low	Low
PACIFIC WILLOW	SALIX LUCIDA LASIANDRA	Tree	High	Assigned	High	High

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
PALO ALTO SWEET GUM	LIQUIDAMBAR STYRACIFLUA 'PALO ALTO'	Tree	High	Assigned	High	High
PALO VERDE	CERCIDIUM FLORIDUM	Tree	Low	Found	Low	Low
PERUVIAN PEPPER	SCHINUS MOLLE	Tree	Low	Found	Medium	Medium
PIN OAK	QUERCUS PALUSTRIS	Tree	High	Found	High	Medium
PONDEROSA PINE	PINUS PONDEROSA	Tree	Low	Assigned	Medium	Medium
PRINCETON SENTRY MAIDENHAIR TREE	GINKGO BILOBA 'PRINCETON SENTRY'	Tree	Low	Found	Low	Medium
PURPLE EASTERN REDBUD	CERCIS CANADENSIS 'FOREST PANSY'	Tree	Low	Assigned	Low	Low
PURPLE LEAF PLUM	PRUNUS CERASIFERA	Tree	Low	Assigned	Low	Low
PURPLE LEAF PLUM (FRUITLESS)	PRUNUS VESUVIUS	Tree	Low	Assigned	Low	Low
PURPLE PONY PLUM	PRUNUS CERSIFERA 'PURPLE PONY'	Tree	Low	Assigned	Low	Low
PURPLE ROBE LOCUS	ROBINIA X AMBIGUA 'PURPLE ROBE'	Tree	Medium	Assigned	High	Medium
RAYWOOD ASH	FRAXINUS ANGUSTIFOLIA	Tree	Low	Assigned	Low	Low
RAYWOOD ASH	FRAXINUS OXYCARPA 'RAYWOOD'	Tree	Low	Assigned	Low	Low
RED FIR	ABIES MAGNIFICA	Tree	Low	Assigned	Low	Medium
RED GUM	EUCALYPTUS CAMALDULENSIS	Tree	Medium	Found	Medium	Medium
RED OAK	QUERCUS RUBRA	Tree	High	Found	High	High
RED WILLOW	SALIX LAEVIGATA	Tree	High	Assigned	High	High
REDBUD	CERCIS CANADENSIS 'FOREST PANSY'	Tree	Low	Assigned	Low	Low
REDBUD	CERCIS OCCIDENTALIS	Tree	Low	Assigned	Low	Low
ROUND-LOBED SWEETGUM	LIQUIDAMBAR STYRACIFLUA 'ROTUNDILOBA'	Tree	High	Assigned	High	High
SARGENT CHERRY	PRUNUS SARGENTII	Tree	Low	Assigned	Low	Low
SCARLET OAK	QUERCUS COCCINEA	Tree	Medium	Found	High	High

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
SEIRYU JAPANESE MAPLE	ACER PALMATUM 'SEIRYU'	Tree	Low	Assigned	Medium	Medium
SHORE PINE	PINUS CONTORTA	Tree	Low	Assigned	Medium	Medium
SHUMARD RED OAK	QUERCUS SHUMARDII	Tree	High	Assigned	High	High
SIERRA REDWOOD	SEQUOIADENDRON GIGANTEUM	Tree	Low	Found	Low	Low
SILVER DOLLAR GUM	EUCALYPTUS POLYANTHEMOS	Tree	Medium	Found	Medium	Low
SITKA SPRUCE	PICEA SITCHENSIS	Tree	Low	Found	Medium	Low
SKYMASTER OAK	QUERCUS ROBUR 'PYRAMICH'	Tree	High	Assigned	High	High
SOQUEL COAST REDWOOD	SEQUOIA SEMPERVIRENS 'SOQUEL'	Tree	Low	Found	Low	Low
SOUTHERN CALIFORNIA BLACK WALNUT	JUGLANS CALIFORNICA	Tree	Low	Assigned	Low	Medium
SOUTHERN LIVE OAK	QUERCUS VIRGINIANA	Tree	High	Assigned	High	High
STAR MAGNOLIA	MAGNOLIA STELLATA 'ROYAL STAR'	Tree	Low	Assigned	Low	Medium
SUGAR GUM	EUCALYPTUS CLADOCALYX	Tree	Low	Found	Medium	Low
SUGAR PINE	PINUS LAMBERTIANA	Tree	Low	Assigned	Low	Medium
SUNBURST LOCUST	GLEDITSIA TRIACANTHOS 'SUNBURST'	Tree	Low	Found	Low	Low
SWEET GUM	LIQUIDAMBAR STYRACIFLUA	Tree	High	Assigned	High	High
SYCAMORE MAPLE	ACER PSEUDOPLATANUS	Tree	Low	Assigned	Medium	Medium
TECATE CYPRESS	CUPRESSUS FORBESII	Tree	Low	Found	Low	Low
TORREY PINE	PINUS TORREYANA	Tree	Low	Assigned	Low	Medium
TRIDENT MAPLE	ACER BUERGERIANUM	Tree	Low	Assigned	Low	Low
TULIP TREE	LIRIODENDRON TULIPIFERA	Tree	Low	Assigned	Low	Low
VALLEY OAK	QUERCUS LOBATA	Tree	Medium	Found	Medium	Medium
VINE MAPLE	ACER CIRCINATUM	Tree	Low	Assigned	Low	Low

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
VIRGINIA OAK	QUERCUS VIRGINIANA	Tree	High	Assigned	High	High
WESTERN HEMLOCK	TSUGA HETEROPHYLLA	Tree	Low	Assigned	Low	Low
WESTERN REDBUD	CERCIS OCCIDENTALIS	Tree	Low	Assigned	Low	Low
WHITE FIR	ABIES CONCOLOR	Tree	Low	Found	Medium	Medium
Shrub Species						
ACACIA	ACACIA REDOLENS	Shrub	Low	Assigned	Low	Medium
AMERICAN DOGWOOD	CORNUS SERICEA	Shrub	Low	Assigned	Low	Low
AUSTRIAN BRIAR	ROSA FOESTIDA 'PERSIANA'	Shrub	Low	Assigned	Low	Low
BANKS' YELLOW ROSE	ROSA BANKSIAE 'LUTEA'	Shrub	Low	Assigned	Low	Low
BAR HARBOR JUNIPER	JUNIPERUS HORIZONTALIS 'BAR HARBOR'	Shrub	Low	Found	Low	Low
BIG BASIN SAGEBRUSH	ARTEMISIA TRIDENTATA TRIDENTATA	Shrub	Medium	Found	Medium	High
BIG BERRY MANZANITA	ARCTOSTAPHYLOS GLAUCA	Shrub	Low	Assigned	Low	Low
BIG SAGEBRUSH	ARTEMISIA TRIDENTATA TRIDENTATA	Shrub	Medium	Assigned	Medium	High
BLACK SAGE	SAVIA MELLIFERA	Shrub	Low	Found	Medium	High
BLUE CHIP JUNIPER	JUNIPERUS HORIZONTALIS 'BLUE CHIP'	Shrub	Low	Assigned	Low	Low
BROWN DOGWOOD	CORNUS GLABRATA	Shrub	Low	Assigned	Low	Low
BUFFALO JUNIPER	JUNIPERUS SABINA 'BUFFALO'	Shrub	Low	Assigned	Low	Low
CALIFORNIA HUCKLEBERRY	VACCINIUM OVATUM	Shrub	Low	Found	Low	Low
CALIFORNIA SAGEBRUSH	ARTEMISIA CALIFORNICA	Shrub	High	Found	Medium	Low
CALIFORNIA SAGEBRUSH 'MONTARA'	ARTEMISIA CALIFORNICA X MONTARA	Shrub	High	Assigned	Medium	Low
CALIFORNIA SCRUB OAK	QUERCUS BERBERIDIFOLIA	Shrub	High	Found	High	High

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
CALIFORNIA WILD ROSE	ROSA CALIFORNICA	Shrub	Low	Found	Low	Low
CARPET JUNIPER	JUNIPERUS HORIZONTALIS 'WIL TONII'	Shrub	Low	Assigned	Low	Low
CARPET ROSE	ROSA 'FLOWER CARPET RED'	Shrub	Low	Assigned	Low	Low
CHAPARRAL WHITETHORN	CEANOTHUS LEUCODERMIS	Shrub	Medium	Found	Medium	High
COAST WILLOW	SALIX HOOKERIANA	Shrub	High	Assigned	High	High
COMPACT SHINY XYLOSMA	XYLOSMA CONGESTUM 'COMPACTUM'	Shrub	Low	Found	Medium	Low
COMPACT STRAWBERRY TREE	ARBUTUS UNEDO 'COMPACTA'	Shrub	Low	Assigned	Low	Low
COTONEASTER	ACACIA REDOLENS	Shrub	Low	Assigned	Low	Medium
COYOTE BRUSH	BACCHARIS PILULARIS 'PIGEON POINT'	Shrub	Low	Found	Low	Low
COYOTE BRUSH	BACCHARIS PILULARIS 'PROSTRATA'	Shrub	Low	Found	Low	Low
COYOTE BRUSH	BACCHARIS PILULARIS v. CONSANGUINEA	Shrub	Low	Found	Low	Low
COYOTE BUSH	BACCHARIS PILULARIS PILULARIS	Shrub	Low	Found	Low	Low
COYOTE BUSH	BACCHARIS PILULARIS 'TWIN PEAKS'	Shrub	Low	Found	Low	Low
DESERT CARPET	ACACIA REDOLENS 'PROSTRATA'	Shrub	Low	Assigned	Low	Medium
DESERT CARPET ACACIA	ACACIA REDOLENS 'DESERT CARPET'	Shrub	Low	Assigned	Low	Medium
DESERT PEACH	PRUNUS ANDERSONII	Shrub	Low	Assigned	Low	Low
DWARF BOTTLEBRUSH	CALLISTEMON CITRINUS 'LITTLE JOHN'	Shrub	Medium	Found	High	Medium
DWARF COYOTE BRUSH	BACCHARIS PILULARIS CONSANGUINEA	Shrub	Low	Found	Low	Low
DWARF COYOTE BRUSH	BACCHARIS PILULARIS 'PIGEON POINT'	Shrub	Low	Found	Low	Low
DWARF COYOTE BRUSH	BACCHARIS PILULARIS 'PIGEON POINT'	Shrub	Low	Found	Low	Low
DWARF COYOTE BRUSH	BACCHARIS PILULARIS 'TWIN PEAKS'	Shrub	Low	Found	Low	Low
DWARF HEAVENLY BAMBOO	NANDINA DOMESTICA 'NANA PURPUREA'	Shrub	High	Assigned	High	Medium

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
DWARF MYRTLE	MYRTUS COMMUNIS 'COMPACTA'	Shrub	High	Assigned	High	High
DWARF XYLOSMA	XYLOSMA CONGESTUM 'COMPACTA'	Shrub	Low	Found	Medium	Low
FIRE MEIDILAND ROSE	ROSA MEIDILAND 'FIRE MEIDILAND'	Shrub	Low	Assigned	Low	Low
FIRE MEIDILAND ROSE	ROSA MEIDILAND 'MEIPSIDUE'	Shrub	Low	Assigned	Low	Low
FIREPOWER HEAVENLY BAMBOO	NANDINA DOMESTICA 'FIREPOWER'	Shrub	High	Assigned	High	Medium
GLOSSY XYLOSMA	XYLOSMA CONGESTUM	Shrub	Low	Found	Medium	Low
GOLD COAST JUNIPER	JUNIPERUS CHINENSIS 'GOLD COAST'	Shrub	Low	Found	Low	Low
GULF STREAM HEAVENLY BAMBOO	NANDINA DOMESTICA 'GULF STREAM'	Shrub	High	Assigned	High	Medium
HOOKER'S WILLOW	SALIX HOOKERIANA	Shrub	High	Assigned	High	High
HUCKLEBERRY	VACCINIUM OVATUM	Shrub	Low	Assigned	Low	Low
ICE BLUE JUNIPER	JUNIPERUS HORIZONTALIS 'MONBER'	Shrub	Low	Assigned	Low	Low
ICE MEIDILAND ROSE	ROSA MEIDILAND 'ICE MEIDILAND'	Shrub	Low	Assigned	Low	Low
JAPANESE GARDEN JUNIPER	JUNIPERUS PROCUMBENS 'NANA'	Shrub	Low	Assigned	Low	Low
KLEINA	XYLOSMA CONGESTUM	Shrub	Low	Found	Medium	Low
LADY BANKS ROSE	ROSA BANKSIAE	Shrub	Low	Assigned	Low	Low
LADY BANKS' YELLOW ROSE	ROSA BANKSIAE 'LUTEA'	Shrub	Low	Assigned	Low	Low
LEATHER OAK	QUERCUS DURATA	Shrub	High	Assigned	High	High
LEMON BOTTLEBRUSH	CALLISTEMON CITRINUS	Shrub	Medium	Found	High	Medium
LOW GROWING ACACIA	ACACIA REDOLENS 'LOW BOY'	Shrub	Low	Assigned	Low	Medium
LOWBOY PROSTRATE ACACIA	ACACIA REDOLENS 'LOW BOY'	Shrub	Low	Assigned	Low	Medium
MAGIC MEIDILAND ROSE	ROSA MEIDILAND 'MEIBONRIB'	Shrub	Low	Assigned	Low	Low
MAGIC MEIDILAND ROSE	ROSA MEIDILAND 'MEIPADAN'	Shrub	Low	Assigned	Low	Low

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
MEIDILAND ROSE PINK FLOWERS	ROSA MEIDILAND 'PINK'	Shrub	Low	Assigned	Low	Low
MYRTLE	MYRTUS COMMUNIS	Shrub	High	Found	High	High
NARROWLEAF WILLOW	SALIX EXIGUA	Shrub	High	Assigned	High	High
NEVADA EPHEDRA	EPHEDRA NEVADENSIS	Shrub	Medium	Assigned	Medium	Low
NUTT WILLOW	SALIX EXIGUA	Shrub	High	Assigned	High	High
PIDGEON POINT COYOTE BRUSH	BACCHARIS PILULARIS 'PIGEON POINT'	Shrub	Low	Found	Low	Low
PLUM PASSION HEAVENLY BAMBOO	NANDINA DOMESTICA 'PLUM PASSION'	Shrub	High	Assigned	High	Medium
POPCORN DRIFT ROSE	ROSA MEIDILAND 'POPCORN DRIFT'	Shrub	Low	Assigned	Low	Low
PROSTRATE ACACIA	ACACIA REDOLENS	Shrub	Low	Assigned	Low	Medium
PROSTRATE COYOTE BRUSH	BACCHARIS PILULARIS 'TWIN PEAKS'	Shrub	Low	Found	Low	Low
RABBIT BRUSH	CHRYSOTHAMNUS NAUSEOSUS	Shrub	Low	Assigned	Low	Low
RAMANAS ROSE	ROSA RUGOSA	Shrub	Low	Assigned	Low	Low
RED FIRE MEIDILAND ROSE	ROSA MEIDILAND 'MEIPSIDUE'	Shrub	Low	Assigned	Low	Low
RED MEIDILAND ROSE	ROSA MEIDILAND 'MEINEBLE'	Shrub	Low	Assigned	Low	Low
RED MEIDILAND ROSE	ROSA MEIDILAND 'SEVILLANA'	Shrub	Low	Assigned	Low	Low
RED MEIDLAND	ROSA 'MEIDLAND'	Shrub	Low	Assigned	Low	Low
REDOSIER DOGWOOD	CORNUS SERICEA	Shrub	Low	Assigned	Low	Low
ROSE	ROSA 'MEIDILAND'	Shrub	Low	Assigned	Low	Low
RUBBER RABBITBRUSH	CHRYSOTHAMNUS NAUSEOSUS	Shrub	Low	Assigned	Low	Low
SANDBAR WILLOW	SALIX EXIGUA	Shrub	High	Assigned	High	High
SANDBAR WILLOW	SALIX INTERIOR	Shrub	High	Assigned	High	High
SHADSCALE	ATRIPLEX CONFERTIFOLIA	Shrub	Low	Found	Medium	Medium

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
SHINY LEAF XYLOSMA	XYLOSMA CONGESTUM	Shrub	Low	Found	Medium	Low
SHINY XYLOSMA	XYLOSMA CONGESTUM	Shrub	Low	Found	Medium	Low
SHORE JUNIPER	JUNIPERUS CONFERTA	Shrub	Low	Assigned	Low	Low
SILVERY PROSTRATE JUNIPER	JUNIPERUS HORIZONTALIS	Shrub	Low	Assigned	Low	Low
SILVERY PROSTRATE JUNIPER	JUNIPERUS HORIZONTALIS 'HUGHES'	Shrub	Low	Assigned	Low	Low
SITKA WILLOW	SALIX SITCHENSIS	Shrub	High	Assigned	High	High
STRAWBERRY TREE	ARBUTUS UNEDO	Shrub	Low	Found	Low	Low
TRUE MYRTLE	MYRTUS COMMUNIS	Shrub	High	Found	High	High
TWIN PEAKS COYOTE BUSH	BACCHARIS PILULARIS 'TWIN PEAKS'	Shrub	Low	Found	Low	Low
TWIN PEAKS NO. 2 DWARF COYOTE BUSH	BACCHARIS PILULARIS 'TWIN PEAKS NO. 2'	Shrub	Low	Found	Low	Low
VARIEGATED COMMON MYRTLE	MYRTUS COMMUNIS 'VARIEGATA'	Shrub	High	Assigned	High	High
VARIEGATED MYRTLE	MYRTUS COMMUNIS 'VARIEGATA'	Shrub	High	Assigned	High	High
WESTERN DOGWOOD	CORNUS STOLONIFERA	Shrub	Low	Assigned	Low	Low
WHITE ICE MEIDILAND ROSE	ROSA MEIDILAND 'MEIVAHYN'	Shrub	Low	Assigned	Low	Low
WHITE LADY BANKS ROSE	ROSA BANKSIAE 'ALBAPLENA'	Shrub	Low	Assigned	Low	Low
WHITE MEIDILAND ROSE	ROSA MEIDILAND 'MEICOUBLAN'	Shrub	Low	Assigned	Low	Low
WHITE MEIDILAND ROSE	ROSA MEIDILAND 'PEARL MEIDILAND'	Shrub	Low	Assigned	Low	Low
WILTON CARPET JUNIPER	JUNIPERUS HORIZONTALIS 'WILTONII'	Shrub	Low	Assigned	Low	Low
WILTONS JUNIPER	JUNIPERUS HORIZONTALIS "WILTONII"	Shrub	Low	Assigned	Low	Low
WOOD ROSE	ROSA GYMNOCARPA	Shrub	Low	Assigned	Low	Low
WOODS' ROSE	ROSA WOODSII	Shrub	Low	Found	Low	Low
WOOLLY BLUECURLS	TRICHOSTEMA LANATUM	Shrub	Medium	Found	Medium	High

Common Name	Scientific Name	Plant Type	Emissions Potential[1]	Data Type[2]	Ozone Formation Potential (OFP) Rating[3]	Secondary Organic Aerosol Formation Potential (SOAP) Rating[4]
XYLOSMA	XYLOSMA CONGESTUM	Shrub	Low	Found	Medium	Low
YELLOW WILLOW	SALIX LUTEA	Shrub	High	Assigned	High	High
Ivy, Grass, and Forb Species						
VARIEGATED DWARF IVY	HEDERA HELIX 'VARIEGATA'	Liana	Low	Found	Low	Low
WILDRYE	ELYMUS CINEREUS	Grass	Low	Found	Low	Low
COMMON SUNFLOWER	HELIANTHUS ANNUUS	Forb	Low	Found	Low	Low

[1] The rating for Emissions Potential is an estimate of the potential for each plant species to emit BVOCs and is based on a sum of emission rates for individual BVOCs (e.g., isoprene and monoterpenes) reported in the literature. These ratings are independent of the potential for an individual BVOC or combination of BVOCs emitted by a given plant species to impact air quality via the formation of O_3 or SOAs.
[2] The Data Type indicates whether the Emissions Potential rating is based on data found in the literature for the individual plant species (or subspecies) listed (i.e., "Found") or the genus (or species) listed (i.e., "Assigned").
[3] Each rating for OFP is an estimate of the potential for each plant species to form O_3 based on analyzed emission rates reported in the literature.
[4] Each rating for SOAP is an estimate of the potential for each plant species to form SOAs based on analyzed emission rates reported in the literature. These ratings were developed using experimental conditions for SOA yields specified by Gu et al. (2021); this study focused on Los Angeles County. Different SOA yields and SOAP ratings might be measured and estimated in areas (urban and rural) where the composition of atmospheric pollutants differs from those in Los Angeles County.

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Caltrans Technical Report Documentation Page

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18. Abstract:

This document provides information for landscape practitioners regarding biogenic volatile organic compounds (BVOCs) that can be produced by plant species commonly used by Caltrans for erosion control, graffiti control, ornamental planting, functional planting, mitigation planting, and vegetative barriers. BVOCs, such as isoprene and terpenes, can contribute to the secondary formation of ozone (O_3) and fine particulate matter ($PM_{2.5}$) in the atmosphere. Both O_3 and $PM_{2.5}$ are harmful to human health and are regulated by the U.S. Environmental Protection Agency (EPA) through the National Ambient Air Quality Standards (NAAQS), and by the California Air Resources Board (CARB) through the California Ambient Air Quality Standards (CAAQS). Many areas throughout California are designated as nonattainment of O_3 and $PM_{2.5}$ NAAQS and CAAQS. BVOC emissions are naturally occurring and therefore cannot be regulated, but they can have a significant effect on atmospheric chemistry and air quality. The potential for plants to emit BVOCs and impact O_3 and $PM_{2.5}$ air quality can be considered when selecting plants for urban greening efforts and planting in Caltrans' right-of-way.

Data from the scientific literature were analyzed for nearly 260 plant species commonly used or recommended for use by Caltrans. These plant species were selected from the Caltrans Highway Planting Database and Specification Tool (TransPLANT Database) and from contract planting plan sheets of previous projects. For each plant species considered, the potential for BVOC emissions to adversely impact O_3 and/or $PM_{2.5}$ air quality was determined based on the specific BVOCs emitted and the quantity of BVOC emissions produced. Qualitative ratings of low, medium, and high were developed and assigned to each species based on the O_3 formation potential and the $PM_{2.5}$ formation potential of the BVOCs emitted. Because of the complex nature of collecting BVOC emissions data for plants and the vast number of individual plant species, the data available in the literature cover only a subset of plant subspecies that are used across Caltrans districts. The methods used to analyze the available BVOC emissions data and develop these ratings are provided in Section 3 of this document.

The results of this analysis are presented in Section 5 (Table 4) of this document. Ratings for the O_3 formation potential (OFP) and secondary organic aerosol formation potential (SOAP) are provided for each plant species when there were sufficient data to

make an assignment. Many plants share the same ratings for O_3 formation potential and $PM_{2.5}$ formation potential since both terms are proportional to BVOC emission rates. Some genera of plants frequently cited in the scientific literature as high emitters of BVOCs include *Populus* (poplars and cottonwoods), *Salix* (willows), *Platanus* (sycamores), *Eucalyptus* (gums), *Quercus* (oaks), and *Trichostema* (bluecurls), and most species in these genera are rated as “medium” or “high” in their potential to form O_3 and/or $PM_{2.5}$. Notably, plants from the *Pinus* genus (pines) are often cited in scientific literature as being higher emitters of BVOCs, but they are rated as “low” or “medium” in their potential to form O_3 and/or $PM_{2.5}$. This stems from different rating system criteria that are based on different typical scales used to measure O_3 and $PM_{2.5}$ concentrations in ambient air. Such variations can lead to large differences in (1) the range of emission rates for each BVOC and (2) the factors that reflect the potential (or lack of potential) for those BVOCs to form O_3 and $PM_{2.5}$. The literature shows substantial variability of BVOC emission rates across plant species within some genera and across different measurement studies of the same genus and/or species.

Table 4 in this document is provided to assist Caltrans staff with identifying plant species that have the least potential to adversely impact O_3 and/or $PM_{2.5}$ air quality. Additional information that Caltrans staff might otherwise consider for plant selections (e.g., applicable climate zones and planting specifications) are not considered in this table. The BVOC ratings in this table should be considered within the context of project location and the characteristics of the emission sources contributing to the area and its geography and climatology. **Plant selection is the responsibility of the district landscape architects or revegetation specialists**.