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The tree BVOC index

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ABSTRACT

Urban trees can produce a number of benefits, among them improved air quality. Biogenic volatile organic compounds (BVOCs) emitted by some species are ozone precursors. Modifying future tree planting to favor lower-emitting species can reduce these emissions and aid air management districts in meeting federally mandated emissions reductions for these compounds. Changes in BVOC emissions are calculated as the result of transitioning to a lower-emitting species mix in future planting. A simplified method for calculating the emissions reduction and a Tree BVOC index based on the calculated reduction is described. An example illustrates the use of the index as a tool for implementation and monitoring of a tree program designed to reduce BVOC emissions as a control measure being developed as part of the State Implementation Plan (SIP) for the Sacramento Federal Nonattainment Area.

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1. Introduction

Trees can affect air quality in several ways: pollutant deposition, temperature reduction, carbon sequestration, and emission of biogenic volatile organic compounds (BVOCs). They can also influence processes not directly related to air quality, such as building energy use, runoff reduction, infrastructure repair, property values, etc. (McPherson et al., 2005).

A number of methods have been developed to quantify BVOC emissions. Models are becoming increasingly more sophisticated, with current research weighted toward the development of process-based emission models and away from empirically-based approaches. Multiple canopy layers have been used to account for effects of solar radiation extinction (Guenther et al., 1995), leaf energy balance models added to better account for temperature effects (Pressley et al., 2006), and process-based strategies introduced to improve model performance (Arneth et al., 2008; Grote, 2007; Keenan et al., 2009; Niinemets et al., 2010). The more empirical approaches are still in use (Millstein and Harley, 2009; Steiner et al., 2008, 2006) and are relatively easy to use for practical applications. The more empirical models may perform as well more complex process-based approaches (Guenther et al., 2006).

Many of these are regional to global scale models that have been developed primarily to provide biogenic emission inventories for use in photochemical modeling (Guenther et al., 2006; Gulden and Yang, 2006; Scott and Benjamin, 2003). Emission factors are assigned per unit land area based on grouping species into plant functional types by land use. One interesting variation on this theme was the development of an urban tree air quality score (UTAQS) for the Birmingham area of the United Kingdom (Donovan et al., 2005). A score is assigned based on relative change in ozone, NO_2 and particulate matter due to effects of various perturbations on BVOC emission rates and deposition; trees are ranked in order of their potential to improve air quality (high, medium or low).

In 2006, the Sacramento Tree Foundation, the Sacramento Metropolitan Air Quality Management District (SMAQMD), the USDA Forest Service the University of California Davis, and Alto-stratus, Inc., an atmospheric research and modeling firm entered into a partnership to evaluate the effects of the urban forest on regional air quality. The goal was to include a voluntary control measure in the Sacramento Regional 8-Hour Ozone Attainment and Reasonable Further Progress Plan based on trees. Once approved, the measure would become an update to the California State Implementation Plan (SIP) for Air Quality. Tree planting is specifically included as an option under guidance issued by the Environmental Protection Agency (U.S. Environmental Protection Agency, 2004) allowing states to include projects that do not have the same high level of certainty as traditional air quality control measures.

Ideally, all tree effects on air quality would be included in tree selection to maximize net benefits. This control measure claims reductions for BVOC emissions only. BVOCs were included as an

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Table 1
Shift in emitter class distribution 2010–2018.

	Emitter class with respect to all trees			
	L	M	H	Total
Baseline (existing trees)	36.3%	28.6%	35.1%	100.0%
Project (trees planted)	36.8%	29.3%	33.9%	100.0%
Change	−0.5%	−0.7%	1.2%	0.0%

initial step in air quality planning because they were most readily quantified. Reductions were achieved by planting lower-emitting species than would be the case in the absence of the control measure. Projected change in regional tree population to a lower-emitter species mix from tree planting was used to estimate future reduced emissions of BVOCs, precursors to ozone formation, and incorporated into a voluntary control measure (SMAQMD, 2008) and included in the Plan approved by five local air quality management districts in the first quarter of 2009[1]. The control measure is in the final revision process in preparation for submittal to the U.S. Environmental Protection Agency.

The approach here to achieving SIP compliance is to reduce BVOC emissions by changing the percentages of high, medium, and low emitting species planted as replacements (lower-emitter mix) compared to the numbers of each species that would be planted in the absence of a SIP program (baseline species mix) (Table 1). The same numbers of trees are planted in both cases. Emitter classes were defined as Low (1 or less), Medium (1–10), and High (greater than 10 μg C g^{-1} dry leaf hr^{-1}) (Benjamin et al., 1996) based on combined emissions of isoprene, monoterpenes, methylbutenol (MBO) and other VOCs (OVOCs). A project is defined here as a tree planting program designed to implement such a species change, and will include agency, non-profit and public participation to meet program goals through tree planting, tracking and verification.

Approximately 6.9 million existing trees were found as part of the Sacramento project. Low-emitters comprised 36.3%, medium-emitters 28.6%, and high-emitters 35.2% of the tree population (Table 1). The project is to be implemented by shifting a minimum of 1.2% (86,000) of these trees to lower-emitting species from 2010–2018 through a combination of community education and planting projects (Table 1). In practice this will be accomplished by shifting the species mix of 650,000 of the approximately 3 million replacement trees planted during the program (2010–2018) to one that contains a higher percentage of lower-emitting species.

This approach has potential drawbacks: 1) since a nearly infinite number of species mixes are possible, it's impossible to know a priori what the actual mix will be, so adopting one scenario as "real" is arbitrary, 2) calculating emission reduction is imprecise because the range of possible values within an emitter class can be 10-fold (e.g., species at the low and high ends of an emitter class), 3) compliance may not result from the adopted shift in the species mix for the same reason as cited above. One can shift the replacement tree species from high to medium emitter class, but the resulting emission reduction can vary widely depending on whether the species chosen is at the low or high end of the medium emitter class. Hence, users may be in compliance with project guidance, but the project may still not reach the targeted reduction, 4) outreach to users that labels tree species as high, medium, and low emitting can be misconstrued and create resistance to participation, 5) emitter class as commonly defined does not account for the effects of tree size on emissions. For example, small, low emitting trees that replace large, high emitting trees could produce greater reductions than anticipated using midpoint values.

[1] Numbers used here reflect modifications not yet (12 February 2011) incorporated into the referenced control measure.

The Tree BVOC Index (TBI) is an alternative method introduced here. It is a prescriptive approach that provides an estimate of projected and actual emission reductions, gives users a clearly defined target to reach and a method to continuously monitor progress, is completely transparent to users and regulators, and eliminates labeling of tree species, thereby facilitating verification and enforcement in a regulatory environment.

The TBI is the dimensionless ratio of emissions from a proposed planting to that of target (reduced) emissions necessary for project compliance. Calculations are readily implemented in a spreadsheet application using numbers of each species planted over the life of the project, the number of years in the project, and tabulated daily emissions values, which account for differences due to species, size, and local climate. A TBI less than or equal to 1.0 informs the user that their tree planting program is on track to meet its goal.

The TBI can be used for pre-project planning and for project management and compliance once a project is initiated. The former determines if a proposed planting schedule and species mix will achieve compliance with a TBI of one or less. The latter can facilitate mid-course corrections in which future species selection is adjusted based on records of surviving trees to date. Analyses can be done for projects implemented by cities, or at the regional level by aggregating projects.

2. Materials and methods

Project inputs include total number of trees planted annually, species fraction (ratio of tree numbers of a single species and age to total tree numbers) foliar biomass by species and year, annual survival rate (here assumed constant across species), and emission factor by species.

2.1. The TBI

The TBI is the ratio of future emissions from a proposed or current planting project with target emissions for project compliance:

$$\mathrm{TBI} = E_{\mathrm{proposed}}/E_{\mathrm{target}} \tag{1}$$

where E_{proposed} is emissions from a proposed planting and E_{target} is maximum emissions allowed (g-C/tree/day) while still maintaining compliance. Emissions can be evaluated for any project year.

The goal of every project participant is to achieve compliance, indicated by a TBI $\leq$ 1.0 (dimensionless). Reaching this target means that the reduction in BVOC emissions of trees planted is sufficient to achieve the total reductions set for the final year of the project. There is equity for all partner communities since any combination of tree numbers and species mix is allowed as long as the resulting TBI $\leq$ 1.0.

Derivation of the TBI is described subsequently, and in what follows data from the Sacramento regional control measure described earlier are used to illustrate the methods.

2.2. Project emissions reduction

The attainment shortfall for the Sacramento Federal Ozone Nonattainment Area (SFNA) is 4 tons/day (tpd) for VOC and 13 tpd for NO_x (SMAQMD, 2008). The EPA has set a limitation of 6% of the shortfall for emission reduction claims from voluntary measures, or 0.24 tpd VOC for the SFNA. Another program will claim 0.06 tpd of the VOC emission reduction credit, reducing the tree planting target to 0.18 tpd. A project emissions reductions goal of 0.28 tpd was selected to provide a margin of error.

2.3. Baseline emissions

Daily BVOC emissions were found as the product of daily emission factor (accounts for differences in emissions related to species, tree size and climate), foliar biomass, species fraction and survival:

$$E = \sum_{i}^{n_i}\left[\mathrm{ec}_i \times \sum_{j}^{n_i}\left(m_{i,j} \times \mathrm{np}_{i,j} \times \mathrm{surv}_j\right)\right] \quad (\mathrm{g-C/tree/day}) \tag{2}$$

where ec_i is the environmentally corrected emission factor (g C kg^{-1} dry leaf day^{-1}) for isoprene, monoterpenes, MBO, and other VOCs combined, $m_{i,j}$ is foliar biomass and $np_{i,j}$ is number of trees planted of species i in the jth year after planting, and $surv_j$ is the fraction of trees surviving in the jth year after planting. Baseline emissions result when the baseline species mix is used in equation (2).

Daily BVOC emissions were also estimated using a simplified form of equation (2):

$$E = \sum_{i}^{n_i} [ec_i \times m_i \times np_i \times \overline{surv}] \quad (g - C/tree/day) \tag{3}$$

where m_i is foliar biomass of species i for average years after planting, np_i is total number of species i planted during the project and $\overline{surv}$ is the average number of trees surviving for all years being analyzed. In essence, average years after planting is used to determine a single value for tree mass, and average survival rate to determine tree numbers, greatly simplifying the calculation. Average years after planting were calculated as:

$$\text{Average years after planting} = (\text{program start year} - \text{program ending year})/2. \tag{4}$$

2.4. Target emissions

Target emissions result when a lower-emitter species mix is selected that satisfies the condition $(E_{baseline} - E_{target})$ = project emissions reduction. A trial-and-error process of adjusting the species mix and/or tree numbers is used to adjust target emissions until the desired project emissions reduction is found. This is the maximum emissions allowable from project trees to achieve the desired project emissions reduction. Any amount less than this leads to overall reductions greater than the project goal.

2.5. Tree numbers and survival

Survival was based on annual mortality of 4% (Lindleaf, 2007; Nowak et al., 2004; Watt et al., 2009). Each year of the project, trees are removed based on annual mortality and new trees are planted so as to keep the total number of trees constant.

Number of replacement trees was estimated from number of existing trees of each species and annual mortality. Each tree removed from the existing population was replaced with a new tree of the same species. New tree planting associated with projected future development, or efforts to increase existing tree canopy cover by adding new trees, was not considered. Division by the number of surviving project trees gives emissions per tree.

2.6. Emission factors

Daily emission factors for each species were calculated from mass-based emission factors (μg C g^{-1} dry leaf hr^{-1}) under standard conditions (30 °C and 1000 μmol m^{-2} s^{-1} photosynthetically active radiation or PAR), environmentally adjusted for hourly changes in air temperature and solar radiation using emission algorithms from (Guenther et al., 1993) and (Harley et al., 1998). Data for the example are from a single monitoring location for the 3-day episode from 31 July to 2 August 2000, a high ozone period captured during the Central California Ozone Study (CCOS) (Fujita et al., 2001). Within-canopy vertical variation in leaf mass, temperature and solar radiation were not explicitly accounted for (Scott and Benjamin, 2003). Detailed canopy modeling has not been found to substantially improve model performance (Guenther et al., 2006). In addition, the assumption of horizontal homogeneity most canopy models are based on may not apply in the spatially heterogeneous urban environment. Resulting hourly adjustments for isoprene, monoterpenes, MBO and OVOCs were summed to produce daily values, and the average of the three daily values was used.

Emission factors in the example were assigned to each tree species and corrected for environmental conditions following the method of (Scott and Benjamin, 2003). A phylogenetic procedure (Benjamin et al., 1996) was used to assign values by genus (31%), family (10%) and order (3%) for trees not identified at the species level (56%). Branch-level isoprene measurements were within ±50% of phylogenetically assigned emission factors for 13 of 19 species reported (Karlik and Winer, 2001). The primary source of isoprene and monoterpene emission factors for the example was branch-level data (Benjamin et al., 1996; Scott and Benjamin, 2003). Species that could not be determined from this source (~15%) were assigned values from Nowak et al. (2002) or Wiedinmyer (2001). Branch-level data from Benjamin et al. (1996) were utilized where possible to be consistent with the environmental correction algorithms used and to minimize intraspecific variation in emission factors (Geron et al., 2001; Kesselmeier et al., 1998).

Methylbutenol (MBO) emissions occur only from certain pine species; as branch enclosure data were unavailable, leaf cuvette-based emission factors were used for MBO emitting conifer species (Harley et al., 1998; Scott and Benjamin, 2003). OVOC emissions were calculated as 30% of total isoprene, monoterpene and MBO emissions for the host of other carbon compounds emitted from vegetation in addition to isoprene, monoterpenes and MBO (Scott and Benjamin, 2003). While more recent work has begun to identify several type of OVOCs (Chang et al., 2009; Guenther et al., 2006) as a practical matter the formulation used here continues to be applied in California (Millstein and Harley, 2009; Steiner et al., 2008, 2006).

In theory, any method could be used to determine the BVOC emissions in the TBI; hourly environmental corrections are accomplished external to the TBI itself. If the method in the current example is used, preference should be given to branch enclosure-based emission factors to maintain compatibility with the environmental correction algorithm used here (Guenther et al., 1994; Ortega and Helmig, 2008). Determination of emission factors for a particular geographical region will differ due to the distributed nature of the data currently available. In some cases, species specific lists of emission factors may exist, as in Las Vegas, Nevada (Papiez et al., 2009) or the desert southwest region (Geron et al., 2006). This is unlikely to be the case in general. A comprehensive review of literature containing emission factor data for the period 1979–2007 summarizes 46 possible data sources (Ortega and Helmig, 2008); a companion paper details measurement techniques for emission factor determination (Ortega et al., 2008). In some sources only a single species may be considered (Funk et al., 2005; Singsaas et al., 1999). The most comprehensive online data are at Wiedinmyer (2001). A recent review from the European perspective is given by Keenan et al. (2009).

2.7. Foliar biomass

Foliar biomass for each species and year after planting was calculated from tree growth curves developed from measurements in four California cities: Modesto (McPherson et al., 1999, 2001), Claremont (McPherson et al., 2001), Berkeley (Maco et al., 2005) and Santa Monica (McPherson and Simpson, 2002; McPherson et al., 2000). In these studies, 20–25 of the most common street tree species were intensively measured to develop growth equations. These data are being developed for 16 cities across the United States (Peper et al., 2001a,b).

Protocols were developed to assign growth equations to species for which no data were available, or for which multiple data sets contained the same species. For species present in more than one data set, preferred city order for selecting growth equations was Modesto, followed by Claremont, Berkeley and Santa Monica in order. Modesto was first choice, being most similar in climate and geography to Sacramento. Claremont was second in priority because of similar growth patterns to those in Modesto (McPherson et al., 1999, 2001). Trees in the latter two cities tended to be more heavily pruned in relation to Sacramento (McPherson and Simpson, 2002; McPherson et al., 2000; Maco et al., 2005). An exception occurred for the pioneering Modesto study where foliar biomass was not measured. In this case growth equations for foliar biomass were derived from foliar biomass to leaf area ratios from Claremont and Berkeley for 85% and 15% of species, respectively, and leaf area growth curves from Modesto measurements.

When data for the subject species were absent, a species was assigned using a process similar to that used in McPherson et al. (1999) to match crown size and density, primary determinants of foliar biomass, as closely as possible between subject and assigned species. This was done by first taking a phylogenetic approach like that used to assign BVOC emission factors for a species not in the database as described in the preceding section. Selection was based on matching by genus and then by family to the measured data using the preferred city order. If the resulting assignment was different in terms of mature size, life form, or growth rate from the subject species, a better match was sought among the measured data.

3. Results

3.1. Project emissions reduction

Project emissions reduction (0.28 tpd) resulting from the two methods (equations (2) and (3)) were identical to two decimal places (Table 2). Conversion to emissions per tree by dividing total emissions by surviving project trees (539,258 trees, equation (2)) or average number of project trees surviving during the period 2010–2018 (594,629 trees, equation (3)) resulted in project emissions reduction of 0.48 and 0.42 g-C/tree/day for equations (2) and

Table 2
Project emission reductions, baseline and target emissions.

Step	Emissions	Total emissions tpd		Emissions per tree g-C/tree/day	
		Equation (2)	Equation (3)	Equation (2)	Equation (3)
1	Baseline	0.72	0.69	1.21	1.05
2	Target	0.44	0.42	0.73	0.63
3	Project reduction	0.28	0.28	0.48	0.42

(3), respectively. Average project tree number was the average of the total number of trees planted (650,000) and the number surviving in 2018 after accounting for 4% annual mortality (539,258).

3.2. Baseline and target emissions

Baseline emissions after 11 years (in 2018) were 0.72 tpd (equation (2)) and 0.69 tpd (equation (3)) (Table 2); species mix and tree numbers were manipulated so that target emissions were 0.44 tpd, such that $E_{\text{baseline}} - E_{\text{target}} = 0.28$ tpd, the desired project emissions reduction. Target emissions were 0.42 tpd based on equation (3). Planting of lower-emitting species commenced in 2010, so that average years after planting was 4 ((2018 − 2010)/2).

3.3. Tree numbers and mortality

Approximately 275,000 trees (4% of 6.9 million) were replaced annually from 2008 through the 2018 target date for a total of approximately 3 million trees.

3.4. TBI example

The TBI is calculated for the Sacramento project using a hypothetical planting of 100 trees of six species planted over a 9 year period (2010–2018) (Table 3). Equation (3) is used to illustrate the potential utility of this approach (equation (2) yields similar results). Average emissions for the 100 trees weighted by species abundance are 0.32 g-C/tree/day (Table 3), calculated here using equation (3). The example planting is in compliance because the TBI is less than 1.0 (0.32/0.61 = 0.52).

4. Discussion

4.1. Application

This approach provides maximum flexibility to users. They are free to select the right species to best match local site conditions, as long as they achieve a TBI of one or less at year-end. Moreover, labeling of species by emitter classes is unnecessary. Should a city fail to achieve a TBI of 1 or less, their TBI could be reduced accordingly the following year. A TBI greater than one will force the city to reduce BVOCs from the population planted in following year(s) by adjusting the numbers planted of each species in the way that best suits their circumstances. Alternatively, a TBI less than one affords more flexibility in species selection the following year. At the project-scale, TBIs registered by other cities may be below the target in amounts sufficient to offset excess emissions from the noncompliant city. All data from all participating cities can be combined to calculate the TBI for the region as a whole.

Table 3
Example calculation of TBI and BVOC emissions from a proposed planting.

Tree species	BVOC emissions ($ec_i \times np_i$; g-C/tree/day)	No. Planted (n_i)	BVOCs × number (g-C/sp/day)
Lagerstroemia indica	0.00	9	0.00
Zelkova serrata	0.00	24	0.00
Acer macrophyllum	0.20	3	0.59
Quercus rubra	1.01	18	18.26
Acer buergerianum	0.02	28	0.57
Pistacia chinensis	0.54	18	9.65
Average number of surviving trees		91.5	29.07
Emissions from proposed planting (E; g-C/tree/day)			0.32
Target emissions for project compliance (g-C/tree/day)			0.61
TBI for planting = 0.32/0.61 (TBI ≤ 1.0 indicates compliance)			0.52

Reporting and regulatory entities can collect information on numbers of each species planted by partner communities and calculate respective TBIs to verify the reported data. Spot checks can verify whether the species reported were planted. These data can be compiled and project-wide results reported in terms of the overall TBI, or as reductions (tons per day) from the baseline.

As a project matures, random spot checks and satellite monitoring could be used to identify dead or unhealthy project trees, and target TBIs could be adjusted accordingly. For example, community A and B each lose 10 2-year old trees, but TBI's are 1.1 and 0.7 for A and B, respectively. The following year Community A's TBI could be adjusted downwards within reasonable limits, or community B's upward, allowing wider latitude in selecting species to replace higher-emitting species.

It is important in terms of project implementation to determine if a species mix can be developed that achieves project emissions reduction necessary for compliance, while at the same time satisfying other important requirements for trees that may exist in a particular jurisdiction. These could include considerations such as water use requirements, possible infrastructure conflicts, energy use reduction on nearby buildings, etc.

4.2. Limitations and opportunities

Given the many uncertainties in model parameterization and data acquisition (Arneth et al., 2008; Guenther et al., 2006; Ortega and Helmig, 2008), model accuracy is difficult to determine. Flux measurements using meteorological techniques (Ortega and Helmig, 2008), stochastic methods (Hanna et al., 2005) and standard error analysis techniques (Stewart et al., 2003) have all been used to determine uncertainty of modeled emissions. Of these, independent flux measurements of isoprene using micrometeorological techniques probably represent the best estimate of uncertainty currently available for modeled fluxes (Guenther et al., 2006; Ortega et al., 2008). Direct comparisons are difficult to make given that measurement methods, model algorithms and averaging period vary, but uncertainty in the 50–100% appears to be obtainable (Guenther et al., 1999, 2000, 1996; Ortega et al., 2008; Pressley et al., 2006). More empirical models seem to perform as well more complex process-based approaches (Guenther et al., 2006), although this is an active area of research and many questions remain (Arneth et al., 2008; Grote, 2007; Grote and Niinemets, 2008; Niinemets et al., 2010). The concept of canopy response functions (Niinemets et al., 2010) appear to hold promise for better accounting of within-canopy gradients in emission potential in a simple model framework.

Daily emissions for each species calculated with the simplified method (equation (2)) yielded results within 5% of the more rigorous method (equation (3)) for both baseline and target emissions, and project emissions reduction. This would further simplify the calculation of TBI; additional testing should be done to determine if this level of agreement could be expected in all cases.

The method introduced here is limited by its reliance on point measurements of environmental conditions. However, the current model provides a framework through which other effects could be added such as pollutant deposition. The way tree growth and species are incorporated could be extended to emission inventories that use gridded air temperature and solar radiation to adjust emission factors (Scott and Benjamin, 2003), and where leaf mass is determined from spatially explicit tree cover. Emissions and TBI could be determined at the nodes of the grid and grouped by land use. The potential utility of the method suggests that it be calibrated with a more rigorous, gridded emissions calculation.

While the TBI was specifically developed for use in a BVOC tracking program, its scope could be broadened by inclusion of other effects such as BVOC and NO_x deposition. It could be readily extended to ozone, initially by introducing reactivities. Doing the calculations to include ozone formation and deposition would include effects such as air temperature changes due to trees. However, there is uncertainty in ozone reactivity estimates, especially for MBO and OVOC.

Development of more sophisticated modeling techniques, more spatially explicit data, and incorporation of all air quality effects from trees is necessary to quantify the net effect of trees on air quality. This goal is driving ongoing research. More detailed modeling of land cover, land use, meteorology and photochemistry is currently underway in the Sacramento region to better determine the impacts of changing the urban forest canopy and species composition on the range of air quality impacts. Results will include pollutant deposition and air temperature changes resulting from tree cover increases. Findings from this research could be the basis for control measure revisions that better quantify the range of effects of different urban forest structure on air quality.

5. Summary and conclusions

A technique is presented that allows straightforward calculation of BVOC emissions of urban trees based on detailed planting, species, and survival projections. The TBI is well-suited for use in a tree program designed to limit BVOC emissions by judicious selection and subsequent monitoring of trees being planted. It avoids undesirable tree labeling by emitter class, and facilitates compliance by both participating partners and the overall entity responsible for such a program. The overall framework could be extended to include the net effects of trees on air quality.

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