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# Controlling Biogenic Volatile Organic Compounds for Air Quality

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# Controlling Biogenic Volatile Organic Compounds for Air Quality

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This Article tells a story that is true but seems completely wrong: Trees can make air pollution worse. Smog and ground-level ozone require two chemical ingredients to form: nitrous oxides ($NO_x$) and volatile organic compounds (VOCs). On a warm, sunny day, these two precursors combine to form smog and ground-level ozone, a pollutant. While $NO_x$ are pollutants that are largely human-created, VOCs can originate with plants. In fact, emissions of just one type of VOC from trees exceed all human-caused emissions.[1]

This Article presents new research on the impact of plants, especially trees, on air quality. The science is complicated and evolving, but some conclusions are possible. Different species emit greater or lesser amounts of VOCs, and emissions vary through the year. Some plant species also consume atmospheric VOCs, enough to outweigh their own emissions and thus remove VOCs from the air on net. Trees generally have an outsize impact as compared with other plants because trees are large plants and therefore large emitters.[2] Thus, the mix of species in a given area has an impact on air quality. Building on new science, this Article argues that choosing the right trees can improve air quality. Governments should encourage the planting of trees that clean the air, while discouraging or restricting the planting of trees that contribute to air pollution. Many cities are already encouraging tree planting for a variety of environmental and other benefits, but planting the wrong trees will worsen air quality.

## I. VOLATILE ORGANIC COMPOUNDS

Chemical compounds are classified as organic if the compound contains carbon. For historical reasons, carbides, carbonates, cyanides, and simple oxides are considered inorganic even though those molecules do contain carbon. Thus, carbon monoxide and carbon dioxide are not considered organic, despite containing carbon.[3]

VOCs are organic compounds with a high vapor pressure at room temperature. Put another way, these compounds have very low boiling points, and they pass into the surrounding air when their boiling points are reached. For example, formaldehyde boils at negative six degrees Fahrenheit.[4] To remain a liquid at room temperature and atmospheric pressure, formaldehyde must be combined with other chemicals.[5] Many household products—including paint, carpets, and plywood—

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1. *See* Thomas D. Sharkey, *Is it Useful To Ask Why Plants Emit Isoprene?*,36 PLANT, CELL & ENV'T. 517, 517 (2013).
2. *See infra* Section I.
3. *See* 40 C.F.R. § 51.100(s) (2018).
4. Tunga Salthammer, Sibel Mentese & Rainer Marutzky, *Formaldehyde in the Indoor Environment*, 110 CHEM. REV. 2536, 2538 (2010).
5. *Id.*

incorporate formaldehyde.[6] Over time, formaldehyde separates from the binding agents. Once the formaldehyde is unbound, it becomes a gas whenever the ambient temperature is more than negative six degrees Fahrenheit. As a result, many household products "off-gas," releasing formaldehyde over time, which has both short-term and long-term health impacts. Among indoor air pollutants, formaldehyde is the best known, but other VOCs have health impacts as well. Formaldehyde and VOCs have received more attention as indoor air pollutants because indoor air concentrations can be many times higher than outdoor.[7] Outdoor air concentrations of VOCs are lower, but urban air does contain significant concentrations of formaldehyde, exacerbating the health burden caused by indoor air pollution.[8]

Historically, the largest sources of VOCs in cities have been industry and transportation. Many industries emit VOCs, either as a byproduct of the production process or when using the final product.[9] Regulation of industry and transportation has limited VOC emissions from factories and vehicles. Transportation releases VOCs largely from unburnt fuel, either from refueling or from two-stroke engines and engines without catalytic converters.[10] Regulation of transportation, in particular, has reduced VOC emissions by requiring exhaust treatment and reducing losses during refueling and from fuel tanks.[11] In the urban United States, two-stroke engines without catalytic converters are used almost entirely for yardwork: mowers, leaf blowers, and chain saws. As transportation has generated less VOCs, other sources, in particular lawncare equipment, have increased in relative importance. Building exteriors also emit VOCs as the paints and finishes first dry and then later deteriorate. In many cities, these non-transportation sources of VOC emissions are now the dominant source of VOCs and thus the most significant source of pollution.[12]

Certain VOCs form ground-level ozone by reacting with nitrous oxides ($NO_x$) and carbon monoxide. Although both $NO_x$ and carbon monoxide occur naturally, neither occur in sufficiently high concentrations to cause smog.[13] Human activity, including industry and transport, can produce high levels of both $NO_x$ and carbon monoxide. Additionally, certain fertilizers release $NO_x$, a problem made worse because many farms and homeowners with lawns apply too much fertilizer, leading to $NO_x$

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6. *Id.* at 2539.
7. *See id.* at 2537–38.
8. J. Kesselmeier & M. Staudt, *Biogenic Volatile Organic Compounds (VOC): An Overview on Emission, Physiology and Ecology*, 33 J. ATMOSPHERIC CHEM. 23, 48 & Tbl. VI (1999).
9. Brian C. McDonald, Allan H. Goldstein & Robert A. Harley, *Long-Term Trends in California Mobile Source Emissions and Ambient Concentrations of Black Carbon and Organic Aerosol*, 49 ENVTL. SCI. TECH. 5178, 5179 (2015).
10. *Id.*
11. Brian C. McDonald et al., *Volatile Chemical Products Emerging as Largest Petrochemical Source of Urban Organic Emissions*, 359 SCI. 760, 760 (2018).
12. *Id.* at 764–65.
13. *Id.* at 2541. There are a few places where a light blue haze will form naturally. In the Blue Mountains near Sydney and the Great Smokies of North Carolina, trees emit enough VOC to create a light blue haze without any human pollution. Smog, however, is brown or gray, not blue. F.W. Went, *Blue Hazes in the Atmosphere*, 187 NATURE 641, 642–43 (1960).

pollution and ultimately smog.[14] Thus, VOCs are a precursor for the development of smog, if both $NO_x$ and carbon monoxide are present.[15]

Both sunlight and high temperatures accelerate the process of smog formation.[16] For that reason, cities see more smog and ground-level ozone in summer. A warm city at low latitude like Los Angeles is particularly well-situated to produce smog. Because sunlight and temperature cannot be controlled, the only way to reduce smog and ground-level ozone in a city like Los Angeles is to reduce the emission of the primary pollutants (VOCs, $NO_x$, and carbon monoxide) that combine to form the secondary pollutants: smog and ground-level ozone.[17]

The amount of ground-level ozone depends on the ratio of VOCs to $NO_x$ and the composition of VOCs in the atmosphere.[18] Different compounds contribute more or less to the formation of ground-level ozone. In urban areas, industry and transportation produce significant amounts of $NO_x$, and thus the atmospheric reactions that produce ground-level ozone are often constrained by excess $NO_x$. In rural areas, there is often too little $NO_x$ to produce ozone. Suburban areas have more $NO_x$ than rural areas, both because of their proximity to cities, but also their transportation emissions. The result is that ground-level ozone is often worse in suburban and peri-urban areas than downtown.[19] A similar effect occurs within the city, since more $NO_x$ is released during the week from transportation and industry. When $NO_x$ levels fall over the weekend, more ground-level ozone forms.[20]

## II. TREES AND VOLATILE ORGANIC COMPOUNDS

VOCs originating from plants are called biogenic, that is biological in origin. Plants both emit and capture VOCs.[21] As early as 1960, F.W. Went proposed that emissions from trees and other plants could significantly affect the chemistry of Earth's atmosphere.[22] As will be discussed, more recent studies have shown that VOC emissions from plants are ubiquitous. Studies have measured emissions from forests and farmland, looking for the aggregate impact of different plant

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14. Maya Almaraz, Edith Bai, Chao Wang, Justin Trousdell, Stephen Conley, Ian Faloona & Benjamin Z. Houltin, *Agriculture Is a Major Source of NOx Pollution in California*, 4 SCI. ADVANCES 1, 1–2 (2018); Sunyoung Park et al., *Trends and Seasonal Cycles in the Isotopic Composition of Nitrous Oxide Since 1940*, 5 NATURE GEOSCIENCE 261, 261, 264 (2012).

15. Kesselmeier & Staudt, *supra* note 8, at 25. Certain VOCs do not react and thus are not regulated as pollutants. *See* Clear Air Amendments Acts of 1990, Pub. L. No. 101-549, 104 Stat. 2468 (codified as amended in scattered sections of 42 U.S.C. §7401).

16. William P.L. Carter, Arthur M. Winer, Karen R. Darnell & James N. Pitts Jr., *Smog Chamber Studies of Temperature Effects in Photochemical Smog*, 13 ENVTL. SCI. & TECH. 1094, 1094 (1979).

17. *Id.*

18. Carlo Calfapietra, Silvano Fares, Fausto Manes, Arianna Morani, Gregorio Sgrigna & Francesco R. Loreta, *Role of Biogenic Volatile Organic Compounds (BVOC) Emitted by Urban Trees on Ozone Concentration in Cities: A Review*, 183 ENVTL. POLLUTION 71, 73 (2013).

19. *Id.*

20. Rodrigo J. Seguel, Raúl G.E. Morales S. & Manuel A. Leiva G., *Ozone Weekend Effect in Santiago, Chile, 162 Envtl. Pollution* 72, 74 (2012).

21. Calfapietra et al., *supra* note 18, at 73.

22. Went, *supra* note 13, at 642–43 (1960).

communities. Other studies have measured emissions from particular plants grown under controlled conditions. In these studies, a particular plant or even a single branch is enclosed in a plastic bag to measure all the gas being consumed and emitted.[23]

Isoprene is the most common biogenic VOC. Every year, plants release 600 million tons of isoprene.[24] Isoprene emissions are roughly comparable in magnitude to methane emissions and comprise approximately one-third of all hydrocarbon emissions. In fact, isoprene emissions are greater than all human-caused hydrocarbon emissions combined.[25] Trees and bushes emit more isoprene than herbs or crop plants.[26] In part, emissions are a function of plant size and therefore trees will always emit more than smaller plants. Also, the biochemistry of crop plants is different, and crops emit much less isoprene than most tree species.[27] Thus, the reforestation of any land formerly devoted to agriculture can increase VOC emissions and potentially worsen air quality.

Most deciduous trees release isoprene, although the amount varies through the growing season.[28] Trees respond to heat and light by releasing more isoprene.[29] As a result, biogenic VOCs are at their highest levels at the same time that human-caused emissions of other primary pollutants are often at their highest. For example, an increase from 77° to 95° Fahrenheit quadruples isoprene emissions.[30]

But, isoprene emissions are not only a function of daylight and temperature; different species produce very different amounts of isoprene. Some trees emit fifty times more isoprene than others.[31] The differences in emissions reflect differences in the chemistry within different trees, not variations in daylight, temperature, or tree size. The biochemical and biophysical processes within plants appear to vary between species, which explains the differences in emissions.[32] The result is large variation in emissions, both seasonally and locally, because the mix of plants varies from place to place.

Worldwide, the largest emissions of isoprene are found in the tropics, where abundant sunlight and high temperatures result in higher emissions.[33] But, the tropics are not the only place where sunny and hot days produce large isoprene emissions.

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23. *See e.g.,* Ruud J.B. Peters, A.D.V. Johannes, Renesse V. Duivenbode, Jan H. Duyzer & Henk L.M. Verhagen, *The Determinations of Terpenes in Forest Air*, 28 ATMOSPHERIC ENV'T. 2413, 2413 (1994); V.A. Isidorov, I.G. Zenkevich & B.V. Ioffe, *Volatile Organic Compounds in the Atmosphere of Forests*, 19 ATMOSPHERIC ENV'T. 1 (1985).

24. A. Guenther, T. Karl, P. Harley, C. Wiedinmyer, P.I. Palmer & C. Geron,, *Estimates of Global Terrestrial Isoprene Emissions Using MEGAN (Model of Emissions of Gases and Aerosols from Nature)*, 6 ATMOSPHERIC CHEM. & PHYSICS 3181, 3182, 3198 (2006).

25. Sharkey, *supra* note 1, at 517.

26. Kesselmeier & Staudt, *supra* note 12, at 39–40.

27. *Id.*

28. Russell K. Monson, Manual T. Lerdau, Thomas D. Sharkey, David S. Schimel & Ray Fall, *Biological Aspects of Constructing Volatile Organic Compound Emission Inventories*, 29 ATMOSPHERIC ENV'T. 2989, 2995 (1995).

29. Kesselmeier & Staudt, *supra* note 8, at 56

30. Brian Lamb, Alex Guenther, David Gay & Hal Westberg, *A National Inventory of Biogenic Hydrocarbon Emissions*, 21 ATMOSPHERIC ENV'T. 1695, 1697 (1987).

31. Kesselmeier & Staudt, *supra* note 8, at 38.

32. Calfapietra et al., *supra* note 18, at 72.

33. Guenther et al., *supra* note 21, at 3183.

In the southeast United States, isoprene emissions in the summer may rival those in the tropics. The dog days of August in Georgia not only feel like the Amazon, but the atmospheric chemistry resembles a tropical rainforest.[34]

Changes in the landscape have a very large impact on isoprene emissions. Deforestation reduces isoprene emissions, particularly when the forests are replaced with row crops. Crops themselves do not appear to emit isoprene, although some agricultural practices appear to generate VOC emissions.[35] Commercial forestry increases isoprene emissions because several of the most commonly planted species—including poplar, eucalyptus, and oil palm—are major sources of isoprene.[36] Thus, replacing row crops with rows of trees may worsen air quality, although that may depend on the relative contributions of $NO_x$ from excess fertilizer application on crops and increased isoprene emissions from reforestation. That said, excess fertilizer application should not be accepted as an inescapable part of agriculture; excess application can be curbed, which would improve air quality.

The biochemistry of plant VOC emissions is somewhat mysterious. Isoprene emissions tend to peak around 105° Fahrenheit, suggesting that isoprene plays a role in protecting plants from moderate heat stress.[37] But, some trees emit significant biogenic VOCs when the temperature is much lower. For example, certain flowering trees emit biogenic VOCs during the spring flowering season, when the air is not very warm. Although most gas exchange happens through stomata in leaves, these flowering trees are emitting significant biogenic VOCs before there are leaves on the branch.[38] One study found that biogenic VOC emissions during the spring flowering season comprise eleven percent of the total annual emission, even though the trees lack leaves, temperatures are lower, and the days are shorter.[39]

Separate from the role of VOCs in plant respiration and growth, VOCs play an interesting role as a signal both between plants and with animals. Several different species of plants rely on VOC emissions to attract beneficial insects when preyed upon by harmful insects. When attacked by a particular caterpillar, corn seedlings emit monoterpenes. These monoterpenes attract a particular wasp, which preys upon the caterpillar.[40] Similarly, both lima bean plants and apple trees emit specific VOCs to attract predatory mites when the plants are damaged by spider mites.[41] Although interesting scientifically, the role of VOCs in signaling plays a small role in air quality because the quantities involved are small.

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34. Thomas D. Sharkey & Manuel T. Lerdau, *Atmospheric Chemistry and Hydrocarbon Emissions from Plants*, 9 ATMOSPHERIC ENV'T. 1107, 1107 (1999).

35. Guenther et al., *supra* note 21, at 3189.

36. *Id.*

37. Thomas D. Sharkey, Amy E. Wiberly & Autumn R. Donohue, *Isoprene Emissions from Plants: Why and How*, 101 ANNALS OF BOTANY 5, 8 (2008).

38. R. Baghi, D. Helmig, A. Guenther, T.Duhl & R. Daly, *Contribution of Flowering Trees to Urban Atmospheric Biogenic Volatile Organic Compound Emissions*, 9 BIOGEOSCIENCES 3777, 3783–84. (2012).

39. *Id.*

40. Paul W. Pare & James H. Tumlinson, *Plant Volatiles as a Defense Against Insect Herbivores*, 121 PLANT PHYSIOLOGY 325, 325, 328 (1999).

41. *Id.* at 328–29.

There are stress responses that do contribute to poor air quality. Plants respond to stress by changing both the amount and the type of VOC emissions.[42] For example, stressed trees emit more acetaldehyde.[43] Once in the atmosphere, acetaldehyde produces both free radicals, which are harmless, and ground-level ozone.[44] Unfortunately for us, urban trees are often stressed. Cities are hard places for trees because of air pollution (including other VOCs, $NO_x$, and ground-level ozone), compacted soils, polluted stormwater, and excess salt.[45]

Temperature, daylight, and stress are not the only determinants of VOC emissions. Because different species of trees emit different amounts of VOCs, the local mix of trees has a very significant impact on local air quality. Some regions have dominant trees that emit large amounts of VOCs. For example, the loblolly pine is the dominant tree species in the southeast United States today. Loblolly pines, like other pines, do not emit much isoprene but do emit sesquiterpene and monoterpene. Loblolly pines emit enough of these other VOCs to contribute to poor air quality across the region.[46] The dominance of pines across the southeastern United States is partly natural but partly the result of commercial forestry. A forest without human husbandry would have fewer loblolly pines and more mixed hardwoods, producing fewer VOCs.[47]

Similarly, California has a biome that contributes to poor air quality. From the San Francisco Bay to Santa Barbara, the coastal biome is dominated by oaks, including several species of live oak.[48] (Live oaks do not lose their leaves, meaning those trees can emit VOCs the entire year.) From there to the Mexican border, the biome transitions to chaparral, a scrubby plant community. Within chaparral, oaks are dominant, although scrub oak becomes more common at the expense of canyon live oak and coast live oak. In fact, the name chaparral comes from the Spanish word for a thicket of live oak. The chaparral is particularly dominant in the hills around Los Angeles and San Diego.[49] While there is variation among oak species, oaks tend to emit large amounts of biogenic VOCs. For example, native oaks emit 700 times more VOCs than the London planetree, ones of the species included in Denver's tree planting initiative.[50] Thus, efforts to replace exotic trees and shrubs in the cities of

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42. Calfapietra et al., *supra* note 18, at 75.

43. Thomas W. Kimmerer & Theodore T. Kozlowski, *Ethylene, Ethane, Acetaldehyde, and Ethanol Production by Plants Under Stress*, 69 PLANT PHYSIOLOGY 840, 844–46 (1982); Thomas W. Kimmerer & Robert C. MacDonald, *Acetaldehyde and Ethanol Biosynthesis in Leaves of Plants*, 84 PLANT PHYSIOLOGY 1204, 1208 (1987).

44. Kesselmeier & Staudt, *supra* note 8, at 46.

45. *See e.g.* THOMAS LEO OGREN, THE ALLERGY FIGHTING GARDEN (2015); Email from Thomas Leo Ogren to author (Apr. 27, 2019) (on file with author).

46. T.R. Duhl, D. Helmig & A. Guenther, *Sesquiterpene Emissions from Loblolly Pine and their Potential Contribution to Biogenic Aerosol Formation in the Southeastern US*, 40 ATMOSPHERIC ENV'T. 761, 764, 772 (2006).

47. ROBERT P. SCHULTZ, LOBLOLLY PINE: THE ECOLOGY AND CULTURE OF LOBLOLLY PINE, U.S. FOREST SERVICE, AGRICULTURAL HANDBOOK 713, at 1–3 (1997).

48. ALLAN A SCHOENHERR, A NATURAL HISTORY OF CALIFORNIA 224–27, 266 (2d ed. 2017).

49. *Id.*

50. Abigale J. Curtis, Detlev Helmig, C.J. Baroch, Ronan Daly & Simon P. Davis, *Biogenic Volatile Organic Compound Emissions from Nine Tree Species Used in an Urban Tree-Planting Program*, 95 ATMOSPHERIC ENV'T 634, 639, 642 (2014).

southern California with native plants could worsen the already polluted air because native species emit large amounts of VOCs.[51]

There are many species of oak and not all are large emitters of isoprene. While all North American oaks emit isoprene, some European oaks do not.[52] American oaks and loblolly pine are not the only offenders. Spruce, sycamore, willow, aspen, acacia, locust, and gum trees are heavy emitters of biogenic VOCs.[53] Biogenic VOC emissions are not merely a function of the natural biome, even where commercial forestry has favored one native species over another. Introducing trees outside their native range has impacts on local air quality. Several commonly planted exotic trees are significant emitters of biogenic VOCs. Widely planted outside its native Australia, the eucalyptus emits volatile terpenoids.[54] The Blue Mountains east of Sydney are covered in eucalyptus; the terpenoids create a blue-tinged haze, giving the mountains their name.[55] Large commercial forests of eucalyptus have been planted around the globe because the tree grows quickly. Eucalyptus is also planted in cities because it grows tall, while requiring little water.[56] Planted in California, the eucalyptus contributes to poor urban air quality.[57]

But, several widely planted trees actually consume more biogenic VOCs than the trees emit.[58] These net consumers of biogenic VOCs have the potential to clean the air. Ash, dogwood, holly, juniper, and maple all consume more biogenic VOCs than they emit. In addition, many fruit trees remove biogenic VOCs from the atmosphere, at least on a net basis. These species of air-cleaning fruit trees include apricot, cherry, nectarine, orange, peach, pear, persimmon, plum, and pomegranate.[59]

The relative absence of VOCs in urban areas can limit the formation of ground-level ozone. Cities with more biogenic VOC-emitting trees will have worse pollution than a city with similar human-caused pollution but fewer or different trees.[60] In addition to California, many cities in the Mediterranean have the same combination sunlight and temperature without rain that produce smog and ground-level ozone. Studies in Barcelona have found that many of the most common trees are among the largest VOCs emitters.[61]

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51. SCHOENHERR, *supra* note 48, 290–291. Fire is a natural part of the chaparral biome. Thus, native plants tend to burn, while some exotics do not. Replacing exotic plants with native plants can mean surrounding a house with tinder in a climate where fire is common. *Id.*

52. Saskia Welter, Araceli Bracho-Nuñez, Céline Mir, Ina Zimmer, Jürgen Kesselmeier, Roselyne Lumaret, Jörg-Peter Schnitzler & Michael Staudt, *The Diversification of Terpene Emissions in Mediterranean Oaks: Lessons from a Study of Quercus suber, Quercus canariensis and its Hybrid Quercus afares*, 32 TREE PHYSIOLOGY 1082, 1086–87 (2012).

53. THOMAS LEO OGREN, SAFE SEX IN THE GARDEN 169 (2003).

54. Guenther et al., *supra* note 21, at 3189; John F. Karlik et al., *A Survey of California Plant Species with a Portable VOC Analyzer for Biogenic Emission Inventory Development*, 39 ATMOSPHERIC ENV'T. 5221, 5230–31.

55. Went, *supra* note 13, at 641.

56. FOOD & AGRIC. ORG., FORESTRY SERIES NO. 11: EUCALYPTS FOR PLANTING 51–119 (1979) http://www.fao.org/3/ac459e/ac459e.pdf [https://perma.cc/JP9G-4XEJ].

57. *Id.* at 137.

58. OGREN, *supra* note 53, at 170–71.

59. *Id.*

60. Calfapietra et al., *supra* note 18, at 73.

61. *Id.*

The cumulative impact of planting the right (or wrong) trees can be significant. The city and the county of Denver have announced the goal of planting one million trees.[62] If Denver plants one million English Oak trees, those trees will generate 1.2 million kilograms of VOCs. That figure of 1.2 million kilograms is equivalent to the emissions of 500,000 cars.[63] In contrast, if Denver plants the same number of low-emitting trees, those trees will emit only 19,000 kilograms of VOCs, equivalent to the emissions of only 8200 cars.[64] Planting the right trees instead of the wrong trees would have the same air quality impact as taking almost a half-million cars off the road in Denver alone. That impact is roughly similar to the entire impact of all of Denver's public transportation.[65] While the entire metro area has 2.9 million people, only 678,000 live in the city and county of Denver. Note that the air quality improvement is merely the result of choosing to plant the right trees; planting one million trees is already something that Denver has decided to do.[66]

Denver is not the only city that has decided to increase its tree cover. Many cities have adopted tree planting for environmental and quality of life reasons.[67] Trees can sequester carbon, improve air quality, reduce the urban heat island effect (reducing cooling), and shelter buildings (reducing heating). Yet some of the trees that cities are planting release biogenic VOCs, which contribute to pollution.[68] Trees that emit less or even consume VOCs will provide similar benefits of carbon sequestration, reduced heating and cooling, and improved quality of life.

## III. PLANTING THE RIGHT TREES TO REDUCE VOC EMISSIONS

Improving air quality by planting the right trees is inherently local. The right tree for Southern California is not the right tree for Ontario. In addition to pairing the trees to the climate, the specifics of local pollution determine whether trees can contribute to better air quality. During the summer, VOCs combine with $NO_x$ to form ozone and smog. Sunlight and high temperatures prompt trees to emit more biogenic VOCs and also accelerate the photochemical reactions that form both ground-level ozone and smog.[69] Thus, southern California and many eastern cities can improve its air quality by planting trees that will consume biogenic VOCs, starving the photochemical reactions in the atmosphere that produce both smog and ground-level ozone.

In contrast, many mountain cities have worse air quality in winter. In Salt Lake City, for example, planting the right trees will have very little impact on air quality.

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62. Curtis et al., *supra* note 50, at 640.

63. *Id.*

64. *Id.*

65. *Id.*

66 *Id.*

67. *See generally* E. Gregory McPherson, James R. Simpson, Qingfe Xiao & Chunxia Wu, *Million Trees Los Angeles Canopy Cover and Benefit Assessment*, 99 LANDSCAPE & URBAN PLANNING 40 (2011) (reporting on Los Angeles's tree-planting plan).

68. Arianna Morani, David J. Nowak, Satoshi Hirabayashi & Carlo Calfapietra, *How To Select the Best Tree Planting Locations to Enhance Air Pollution Removal in the MillionTreesNYC Initiative*, 159 ENVTL. POLLUTION 1040, 1040–41, 1045 (2011).

69. Carter, *supra* note 16 at 1094.

During winter, thermal inversion traps polluted air against the Wasatch Front.[70] During winter, trees produce little to no biogenic VOCs; only in the early spring do trees begin to flower, overlapping with some winter weather. Also, photochemical reactions that depend on heat and light do not produce smog or ground-level ozone in winter with its cold weather, short days, and weak sunlight.[71] Because the "wrong" trees do not contribute to poor air quality, planting the "right" ones will have little impact. Unfortunately for Salt Lake City and other cities with poor winter air quality, there is little benefit to planting the right trees. Those cities need to reduce emissions from buildings, industry, and transportation because thermal inversions cannot be prevented.

Where summer air quality is poor, the right trees can reduce air pollution. In many places, government can improve air quality by regulating tree planting. At the very least, government should only plant trees in parks or other city property that contribute to good air quality. When government decides which trees to plant, it should not decide to worsen air quality. For the government that plans to plant trees anyway, like Denver, choosing different species is essentially free. For local governments, choosing the right tree is the cheapest way to improve local air quality.

Government can do more than control which trees are planted on public land. Many cities already restrict which trees landowners can plant on private property because many trees are not appropriate for the city. Several cities restrict the planting of allergenic trees.[72] Other cities restrict planting unsafe trees. For example, Tempe, Arizona does not allow planting specific species of tree that cannot safely be grown in thin desert soils.[73] Elsewhere, cities restrict trees with spreading roots that can damage sidewalks.[74]

New York City is fairly typical. The Department of Parks & Recreation maintains a list of trees that may be planted within the public right of way, including sidewalks and lawns.[75] Unfortunately, the current list includes several species that produce large amounts of biogenic VOCs. In fact, New York City allows planting seventeen different species of oak.[76] Where the government already dictates which trees private landowners can plant, government should tailor its dictates to improve air quality. New York City, for example, should not allow the planting of oak, sweetgum, or

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70. *See* John D. Beard, Celeste Beck, Randall Graham, Steven C. Packham, Monica Traphagan, Rebecca T. Giles & John G. Morgan, *Winter Temperature Inversions and Emergency Department Visits for Asthma in Salt Lake County, Utah, 2003–2008*, 120 ENVTL. HEALTH PERSPECTIVES 1385 (2012).

71. Carter, *supra* note 16 at 1094.

72. *E.g.*, PHOENIX, ARIZ., CODE § 39-9 (2017); CLARK COUNTY, NEV., AIR QUALITY REG. § 44 (2017).

73. *E.g.*, TEMPE, ARIZ. ZONING & DEV. CODE § 4-702 (2017).

74. Larry Gordon, *Ficus' Shady Reputation Prompts Change in Scenery*, L.A. TIMES (Mar. 13, 1996), https://www.latimes.com/archives/la-xpm-1996-03-13-mn-46502-story.html https://perma.cc/MJF8-97PP].

75. NEW YORK CITY APPROVED STREET TREES, NEW YORK CITY (2016), https://www.nycgovparks.org/pagefiles/52/Street-Trees-List-For-Permits.pdf [https://perma.cc/M553-66U8].

76. *Id.* at 2–3.

locust. Additionally, New York City suggests that maple should be planted "[s]paringly," which it should revise.[77]

Cities that do not currently restrict which trees private landowners can plant should consider doing so. Where biogenic VOCs contribute to the formation of smog and ground-level ozone, the impact on human health is large. Requiring landowners to choose a tree that cleans the air rather than contributes to its pollution is a small price.

Already those same city residents are restricted in their choice of heating, cooling, and transportation to improve air quality. Even cities where central heating is not strictly necessary require it, specifying heating requirements in minute detail.[78] If the heating source is electric, detailed aspects of the building code relating to electricity must be followed.[79] If the heating fuel is a hydrocarbon, more rules are imposed, including the types of fuel permitted and how the exhaust is removed from the dwelling.[80] Even when more polluting types of heating are permitted, like fireplaces, cities often impose no-burn days when the air quality is poor.[81] Cooling is similarly limited, especially because certain refrigerants are banned and others are highly regulated. Even the technicians who work on systems are regulated.[82] Similarly, Americans are limited in transportation fuels. Vehicles must use specific fuels and burn those fuels in specific ways.[83] Already, government at all levels regulates behavior with a high degree of specificity to protect air quality.[84] Restricting the planting a few tree species is a small imposition.

If cities choose to improve air quality through controlling the trees planted within the city, there are several regulatory options. All regulation falls into one of three categories: information, prices, and mandates. Information and prices would do little, while mandates will produce large changes at little cost.

Information is already disfavored in the regulation of air quality. While the EPA requires some disclosures from vehicle makers, the heavy lifting is done by mandates.[85] Informational labels on nursery trees will do little. Some people may not read labels; others might ignore the information. Although it is true that some trees contribute to air pollution, it does not *seem* true. A small tag on a sapling at the nursery is the wrong place to teach atmospheric chemistry. Professional landscapers should be better positioned to incorporate information into their choice of tree mix. Information about the allergy potential of trees, which varies considerably between species, has been available for decades, and landscapers appear to be making no

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77. *Id.* at 6.

78. Phoenix requires central heating; portable heaters are not sufficient. PHOENIX, ARIZ., BUILDING CONSTR. CODE § 1203.1 (2018).

79. *See* NAT'L FIRE PROT. ASSOC., NATIONAL ELECTRICAL CODE (2017).

80. *See e.g.,* PHOENIX, ARIZ., BUILDING CONSTR. CODE § 101.4 (2018) (requiring compliance with gas and mechanical codes).

81. *See e.g*., BAY AREA, CAL. AIR QUALITY MANAGEMENT DISTRICT § 6-3 (2015).

82. 40 C.F.R. § 82.161 (2018).

83. *See* 40 C.F.R. pts. 80, 86 (2018).

84. *See supra* notes 67–74.

85. Compare the light burden of 40 C.F.R. § 600.301 (2018) (fuel economy and environment label) with the onerous requirements under 40 C.F.R. §86.101–213 (2018) (emission regulation).

changes in response.[86] If anything, the allergic potential of new plantings is higher, indicating that other considerations predominate, and suggesting that air quality regulation should not rely on informing landscapers.

The second alternative is prices, either through taxation or less direct schemes, like cap-and-trade. Taxing pollution has seen great success in certain contexts[87] and cap-and-trade has had some achievements.[88] There are several reasons why using the price mechanism here is inappropriate. On any given parcel, trees are planted infrequently. Homeowners may not compare prices, blunting the impact of tax on VOC-emitting trees. Professional landscapers may be more sensitive to price changes, but it will depend on both competition in the industry, their own pricing practices, and how their customers decide how much to spend. If landscapers charge their own customers according to some variant of cost-plus, increasing input prices might even be attractive to them, if the increased mark-up does not encourage consumers to cut back on their spending on landscaping.

Mandates are most appropriate, given that information and prices are unlikely to have the desired impact on homeowners making decisions in the chaos of a nursery or garden center on the weekend. There are a variety of ways to mandate better tree choices. Already, cities use a variety of different legal regimes. In some cities, the zoning code proscribes planting specific trees.[89] In other cities, the planting and sale of offending trees is prohibited.[90] Restricting sale is the better strategy than relying on notoriously dense zoning codes: If nurseries continue to sell banned trees, landowners will continue to plant them.

Whether to plant a tree that cleans the air instead of one that pollutes the air is an easy question. There are several more difficult questions. Firstly, should cities remove existing trees? And secondly, should government try to influence which trees are planted outside of cities?

In most cases, it will not make environmental sense to replace a healthy tree. VOC emission is only one aspect of a tree's contribution to air quality. Replacing a mature tree with a sapling will reduce shade, which increases energy use and hence emissions.[91] In some regions, the physical effect of urban trees on ozone may be

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86. *See e.g.*, OGREN, *supra* note 45. Even in 2000, much of the information included in Ogren's earlier book was not new; some was widely-known. *See* THOMAS LEO OGREN, THE ALLERGY-FREE GARDEN: THE REVOLUTIONARY GUIDE TO HEALTHY LANDSCAPING (2000). Ogren reports that nurseries and landscapers have shown very little interest in reduced allergy landscapes. Email from Thomas Leo Ogren to author (Apr. 27, 2019) (on file with author).

87. *See generally* Frank Convery, Simon McDonnell & Susana Ferreira, *The Most Popular Tax in Europe? Lessons from the Irish Plastic Bags Levy*, 38 ENVTL. RESOURCE ECON. 1 (2007) (analyzing the success of the Irish plastic bag levy).

88. The U.S. Environmental Protection Agency established a market in pollution credits in the Acid Rain Program under the authority of the Clean Air Act Amendments of 1990. 42 U.S.C. § 7651 (2017); *see e.g.*, *The Invisible Green Hand*, ECONOMIST (July 4, 2002), https://www.economist.com/special-report/2002/07/04/the-invisible-green-hand [https://perma.cc/63CN-PLLS] (calling the Acid Rain Program the "greatest green success story of the past decade"). But, other schemes have been less successful. *See* Brian Sawers, *Covariant Risk and Nutrient Credit Trading*, 77 MD. L. REV. ENDNOTES 1, 16 (2018).

89. *E.g.*, TEMPE, ARIZ., ZONING & DEV. CODE § 4-702 (2017).

90. *E.g.*, ALBUQUERQUE, N.M., CITY ORDINANCES § 9-12 (2017).

91. *See generally* David J. Nowak, Kevin L. Civerolo, S. Trivikrama Rao, Gopal Sistla, Christopher J. Luley & Daniel E. Crane, *A Modeling Study of the Impact of Urban Trees on*

greater than the effect of biogenic VOCs.[92] A sapling traps fewer particulates because its bark and leaf area is smaller.[93] Thus, replacing a mature tree that emits biogenic VOCs with a sapling that does not could worsen air quality. It would not be appropriate to replace a healthy mature tree, regardless of species. Given the slow pace of tree growth and replacement, choosing the right trees should be understood as a way to very gradually improve air quality. Thus, tree regulation cannot replace other efforts to clean the air.

Replanting tree plantations after harvest with another species that emits less biogenic VOCs can improve air quality. In almost all cases, it is not appropriate or feasible to replant wild areas to replace net emitters. The chaparral that covers the hills and mountains of southern California includes several species of oak. Even if every urban tree in southern California removed VOC from the air, wild trees and shrubs would contribute VOCs to the atmosphere.[94] While replacing urban trees is part of cleaning southern California's air, it cannot be a replacement for reducing $NO_x$ emissions from transportation, industry, and even yardwork.

## CONCLUSION

VOCs combine with $NO_x$ and carbon monoxide to form smog and produce ground-level pollution. One large source of VOCs is trees, although different species produce very different amounts. In parts of the United States, like California, the natural predominance of certain species of tree contributes to poor air quality. In other parts, like the Southeast, tree plantations worsen air quality. But, many species of trees consume more VOC than they emit. Thus, government should encourage the planting of trees that will clean the air and discourage the planting of trees that worsen air pollution. In many cities, the impact of planting the right trees would be significant—greater than any short-term change in transportation. Because many cities have already decided to plant more trees, the cost is essentially zero, but the impact on air quality is large.

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*Ozone*, 34 Atmospheric Env't. 1601 (2000).

92. *Id.*

93. David J. Nowak, Daniel E. Crane & Jack C. Stevens, *Air Pollution Removal by Urban Trees and Shrubs in the United States*, 4 URBAN FORESTRY & URBAN GREENING 115, 121 (2006).

94. *See generally* SCHOENHERR, *supra* note 48 (discussing California's natural history).