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Receptor-Scale Isoprene Contribution and Daylight Ozone Control in Bologna Urban Green Infrastructure

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Abstract

While urban greening can enhance thermal comfort, public space quality and ecological continuity, the impact of daylight ozone formation hinges on the composition of tree species, local transport system and chemical reactions involving nitrogen oxide. For this analysis, Bologna's tree population-specific canopy renewal target has been calculated with ten broadleaf species as $P_i = f_i E_i$, pollutant-response coefficient and receptor attenuation threshold using their isoprene emission potentials, statistics, ozone and nitrogen oxide response rates and daylight ozone increment for Irnerio, Montagnola, University Gardens and Berti Pichat receptors. Isoprene production is highly concentrated in Bologna's assemblage with *Platanus* × *acerifolia*, contributing 57.90% of normalized isoprene potential, and *Sophora japonica* making up for additional 21.08%. The two species contribute together 78.98% of normalized isoprene emission potential with first five species providing 99.25%. Ozone has a stronger response rate compared to that of nitrogen oxides (K_{O_3}=0.783 versus K_{NO_x}=0.257). As such, daylight ozone increment may be adopted as the managed endpoint in canopy management. University Gardens receptor is controlled by the daylight ozone increment of 6.7% while those of Irnerio, Montagnola and Berti Pichat are 2.3%, 1.9% and 0.8%, respectively. Within the constraint of 2% daylight ozone increment, University Gardens needs to have the reduction of 70.1% isoprene production potential while Irnerio only 13.0%. Replacing completely *Platanus* × *acerifolia* and *Sophora japonica* results in the University Gardens' residual daylight ozone increment of about 1.41%.

Keywords: urban vegetation; isoprene; ozone; Bologna; tree-species composition; canopy renewal; biogenic volatile organic compounds

1. Introduction

Urban tree plantings have gained increasing recognition as part of urban infrastructure, because they mitigate heat island effects and contribute to pedestrian comfort, particle interception and use of public spaces. Such advantages of urban vegetation have been proven in numerous studies on the tree, street and city level. However, tree plantings can also affect urban air quality by modifying wind speed, particle deposition or biogenic volatile organic compound emissions [1, 17, 19]. It means that the air quality value of a tree assemblage is not solely dependent on canopy cover but also includes crown porosity, street geometry, proximity of traffic, and tree-emitted compounds [12, 22, 28, 30].

Isoprene stands out as the key compound in that regard, since it is highly reactive and capable of promoting

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ozone production when in contact with nitrogen oxides, radicals and solar radiation [3, 23, 25]. However, the photochemistry leading to ozone formation is a complex process, involving nitrogen oxide regimes, oxidative capacity, mixing ratios, deposition and meteorology. The significance of isoprene as a biogenic hydrocarbon still makes its consideration relevant for assessing urban photochemical load, especially in dense urban settings, which combine tree emissions and vehicle-derived nitrogen oxides [5, 6].

Different tree species vary in their ability to emit isoprene. Several regional or continental inventories of biogenic emissions show that plant species composition plays a critical role, while studies on the physiology of tree isoprene emission point out that temperature, light exposure and leaf condition also matter [9–11, 14, 24]. That implies that the importance of a given species is determined not by emission rate per se, but rather by its frequency and the normalized emission rate. Assessments of urban vegetation based purely on canopy area and stem counts do not address that factor.

The compact nature of the Bologna district allows identifying four receptors that differ from each other in terms of street exposure, garden enclosure, built-up boundary, open traffic corridors and vegetation. An averaged citywide value would not reflect those distinctions. The purpose of this calculation is to find, based on the values from Bologna, what taxa contain high isoprene leverage and what receptor needs reduction to reach a 2% increase in daylight ozone levels. The calculations will rely on frequency and normalized emissions only.

The analysis is practical and diagnostic rather than prescriptive in its approach. Tree removal will not be considered as a solution to the air-quality issue. The results will be interpreted with regard to species-weighted emissions, receptor-specific sensitivity and pollutant reduction requirements to suggest a strategy for targeted canopy renewal.

2. Literature Background

Urban greening has traditionally relied on various environmental benefits, such as air pollution mitigation, urban cooling and improvements of public-space quality. Those remain important in the discussion on urban planning, but they depend on spatial scales and particular circumstances. Vegetation can help cities to remove pollutants and adapt to warming temperatures. Moreover, the effect can extend beyond the pollutant and climate issues. Tree crowns affect air circulation and pollutant concentration along streets [17, 19, 22]. This aspect is particularly relevant to a city like Bologna, which consists of several receptors located near each other yet showing different ozone increment responses.

A growing body of literature emphasizes that urban vegetation does not guarantee improvements in every case, especially regarding air quality. Dense tree crowns may impede pollutant dispersion and even cause particulate trapping, whereas other types of canopy configuration and placement might create better exposure conditions [1, 12, 30]. That does not diminish the positive effect of vegetation on air quality, but rather underscores the need for species-specific greening. The same canopy cover can mean different things depending on road design, atmospheric stability and distance from the source. The Bologna values follow that approach by focusing on species and receptors separately.

Biogenic volatile organic compounds constitute another factor of interest in this study, given that isoprene affects photochemical reactions and ozone formation. Emission depends on plant species, exposure to light, temperature, age and leaf status [15, 16, 24]. The significant contribution of vegetation emissions into atmospheric reactivity has been confirmed by inventories and models developed for European or global scales. To perform an urban study on air quality, however, it is necessary to quantify the reactive potential of planted tree species [2, 11, 26, 27]. This is precisely what the Bologna values provide by including both species frequency and normalized isoprene potential.

Ozone regulation in an urban environment should also account for the fact that VOC control does not lead to ozone suppression under all conditions. Depending on the pollutant regime and interaction between gases, there might be a positive response, while negative response can be observed if conditions allow for nitrogen oxides to be titrated [3, 13, 25]. The purpose of pollutant-evaluation coefficient in this study is not solving the whole problem of chemical regimes. Rather, it will compare ozone and nitrogen oxide concentrations to see which one dominates and define receptor thresholds. The threshold for the dominant pollutant will be then applied for species-specific assessment of isoprene reduction.

Previous urban studies have established that the choice of tree species can be significant for mitigating urban photochemical pollution [4, 5, 8]. This study follows that principle but introduces a new dimension – local specificity of receptor and plant assemblage. A generic conclusion that some trees emit more isoprene than others is not helpful for planting design. What is needed for that is a local evaluation, including the assessment of whether the receptor response to isoprene is driven by one species, a couple of species, or a number of plants. In Bologna, the latter is observed for the University Gardens receptor.

3. Bologna Receptors and Analytical Procedure

3.1. Receptor Sites and Pollutant Variables

There are four receptors in Bologna, all having distinct combinations of street form, vegetation exposure and traffic proximity. Irnerio is a street-edge receptor surrounded by buildings and located near vegetation. Montagnola is a park, which is enclosed by nearby vegetation. University Gardens are densely vegetated, pedestrian-accessible spaces, providing the highest daylight ozone response. Finally, Berti Pichat is an adjacent to traffic receptor with the lowest daylight ozone increment in the evaluated set. Each receptor is analysed separately, since daylight ozone response differs across those receptors despite compact setting of Bologna.

Figure 1 illustrates the visual setting of those receptor sites. It helps to keep receptor definitions clear before numerical calculations begin. This is important, since receptor-specific thresholds are not determined by the type of green space. Despite being vegetated spaces, Montagnola and University Gardens exhibit a sharp difference in daylight ozone increments, which makes it possible to justify retaining those increments as a separate variable.

The pollutants include day time ozone increase, building nitrogen oxide difference, and vegetation nitrogen oxide difference. The latter two quantities are maintained in the equation since ozone formation, depletion, and reaction cycles depend on the available amounts of nitrogen oxides [13, 23]. By doing this, the calculation will not make the result of ozone response dependent on the trees' composition.

3.2. Species-Weighted Isoprene Potential

There are ten species of broadleaved tree in this assemblage: *Platanus × acerifolia*, *Sophora japonica*, *Quercus robur*, *Populus alba*, *Populus nigra*, *Quercus rubra*, *Quercus ilex*, *Celtis australis*, *Aesculus hippocastanum* and *Tilia intermedia*. The sum of their frequency amounts to 50.3 percent points. No information is estimated regarding other trees. This comparison is done to evaluate the relative impact of the reported Bologna tree assemblage in terms of isoprene potential.

For each species i, normalized isoprene potential is calculated as

$$P_i = f_i E_i, \tag{1}$$

where f_i is the listed frequency percentage and E_i is the normalized isoprene emission factor in $\mu\text{g}\ \text{g}_{\text{dw}}^{-1}\ \text{h}^{-1}$. The contribution share of species i is then

$$\ell_i = \frac{P_i}{\sum_{j=1}^{n} P_j}. \tag{2}$$

The weighted calculation is transparently based on the planting choices. This determines which taxa contribute most to the chemical potential once frequency and emission are both considered. The formula provides equal treatment of high-frequency taxa and high-emission taxa. Both are scaled on the same axis through multiplication of the two quantities.

The computation works well for filtering due to its use of quantities that are straightforwardly obtainable from a species inventory. It is not a leaf-scale emissions estimator. It does not include crown volume, leaf area, canopy

(a) Irnerio **(b)** Montagnola **(c)** University Gardens

(d) Berti Pichat **(e)** Receptor map

Figure 1. Bologna receptor setting.

temperature, and daily irradiance in the calculation; however, the Bologna values are sufficient to determine whether there is a strong isoprene emitter concentration or diffusion. In the case of emitter concentration, canopy renewal may be effective; for emitter diffusion, there would need to be species turnover.

3.3. Pollutant Response Coefficient

The pollutant-evaluation coefficient allows a comparison of ozone and nitrogen oxides' representation using the same Bologna evaluation set. The q-th pollutant response coefficient is defined as

$$K_q = \frac{\mathrm{Fac2}_q(1 - |F_{b,q}|)\max(r_q, 0)}{1 + \mathrm{NMSE}_q}, \quad (3)$$

where Fac2 denotes the two-fold agreement statistic, F_b is fractional bias, NMSE is the normalized mean square error and r is the Pearson correlation coefficient. High agreement, low fractional bias, high positive correlation and low normalized mean square error increase the value of the coefficient. This expression is utilized for comparison within the Bologna data here, but not as an universal validation procedure.

The pollutant coefficient has an interpretation consistent with the simple ozone-evaluation paradigm. The pollutants are chemically related, but not inter-changeable management targets [29]. While nitrogen oxide levels have great variability due to traffic-related and built-form-related fluctuations, the daylight photoreaction product is what matters concerning the ozone attenuation threshold. Consequently, a high ozone response coefficient favors the use of ozone in the receptor attenuation computation, while nitrogen oxide differences can aid in interpreting the pollution context.

3.4. Receptor Attenuation Calculation

The initial ozone increment at location p is $O_{p,0}$. An attenuation fraction $m_i \in [0,1]$ is attributed to each taxon in species-management. An attenuation fraction of zero leaves the taxon's normalized contribution intact, while an attenuation fraction of one indicates functional substitution for the taxon by a lower emitter in the normalized comparison. The total normalized reduction is

$$A = \sum_{i=1}^{n} \ell_i m_i. \tag{4}$$

The residual daylight ozone increment is estimated as

$$O_p(A) = O_{p,0}(1 - A). \tag{5}$$

For an operational limit τ, the minimum required reduction is

$$A_p^* = \max\left(0, 1 - \frac{\tau}{O_{p,0}}\right). \tag{6}$$

This analysis takes $\tau = 2\%$ as the main limiting criterion, but also considers 1% and 3% thresholds for the purpose of testing sensitivity.

It should be noted that the proportional residual represents only an approximate planning value because of the non-linearity of ozone production. The response function may vary depending on the availability of nitrogen oxides, chemistry of radicals, or deposition/mixing processes [3, 23, 25]. As far as the present case is concerned, the value is purely diagnostic rather than predictive. It is used to express the shares of individual species contributions as proportional reductions.

4. Results

4.1. Proportional Isoprene Contributions

The isoprene emission distribution for the Bologna group is extremely concentrated. The table presents frequency, normalized emission factor, calculated potential, relative contribution and cumulative contribution for each entry. The sum of normalized potentials equals 626.32. *Platanus* × *acerifolia* occurs with a frequency of 19.6%. Its emission factor is 18.5 and calculated potential 362.60. This one taxon provides a proportional 57.90% of all normalized emissions despite ranking below other entries in the list.

Sophora japonica ranks second in terms of relative proportion. The occurrence rate is 4.0%, while normalized emission factor is 33.0. The normalized potential comes out at 132.00, yielding a relative share of 21.08%. Thus, two species, *Platanus* × *acerifolia* and *Sophora japonica*, account for a combined 78.98%. The sum of relative shares for five contributors amounts to 99.25%.

Table 1. Species-level normalized isoprene potential.

Species	Frequency (%)	E_i	$P_i = f_i E_i$	Share (%)	Cumulative (%)
Platanus × acerifolia	19.6	18.5	362.60	57.90	57.90
Sophora japonica	4.0	33.0	132.00	21.08	78.98
Quercus robur	0.8	70.0	56.00	8.94	87.92
Populus alba	0.6	60.0	36.00	5.75	93.67
Populus nigra	0.5	70.0	35.00	5.59	99.25
Quercus rubra	0.1	35.0	3.50	0.56	99.81
Quercus ilex	6.9	0.1	0.69	0.11	99.92
Celtis australis	5.3	0.1	0.53	0.08	100.00
Aesculus hippocastanum	6.8	0.0	0.00	0.00	100.00
Tilia intermedia	5.7	0.0	0.00	0.00	100.00
Total	50.3	–	626.32	100.00	–

The values presented in Table 1 explain why both frequency and emission factor should be considered simultaneously. The high emission factor for species like *Quercus robur*, *Populus alba* and *Populus nigra* does not imply a large impact since their combined influence is smaller than that of *Sophora japonica*. On the other hand, *Aesculus hippocastanum* and *Tilia intermedia* constitute 12.5 percentages of frequency but make zero contribution to the normalized isoprene emission. *Quercus ilex* and *Celtis australis* comprise 12.2 percentages of frequency and give a contribution of only 0.19%. Therefore, even a low-isoprene forest may consist of an appreciable proportion of the total tree community.

This conclusion is corroborated by the graph shown in Figure 2 without appealing to the values of Table 1. In particular, one sees from the contribution panel the extreme domination of the first two species; from the ranking panel, the separation between the two largest species and the near-zero group; and from the cumulation panel, that the top five contributors make up almost all normalized potential. The last point is especially important since it means that the most contributing species is not necessarily the species with the highest emission factor.

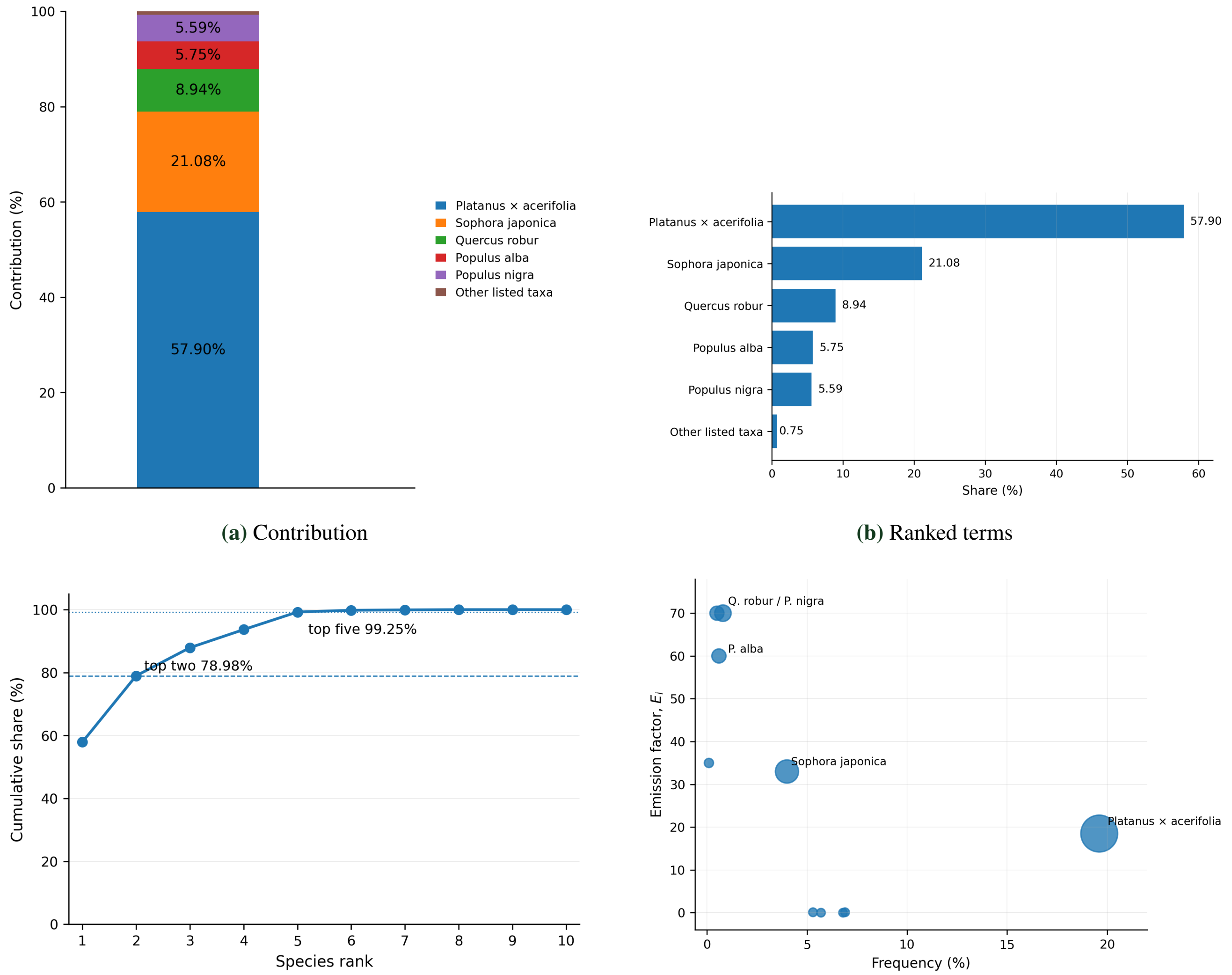
The frequency-emission plane in Figure 3 provides a second check on the contribution calculation. *Platanus × acerifolia* appears as the dominant term because it combines the highest frequency with a non-zero emission factor. *Sophora japonica* has lower frequency but stronger emission, making it the second major term. The high-emission low-frequency taxa occupy a different part of the plane, while low- and zero-emitting taxa remain close to the bottom axis. This visual separation supports the decision to target the dominant contribution terms rather than using a simple list of high emission factors.

The pattern of a focused contribution facilitates targeted renewal. Otherwise, in the case where the pattern was spread out among many taxa, the effect of targeted renewal could have been insignificant. But in this case, we can see from the values obtained in Bologna that a small fraction of taxa influences the normalized isoprene potential. Therefore, a receptor-specific attenuation technique requires this condition.

4.2. Selection of Pollutant Response

From the values presented in Table 2, one can see that ozone represents the strongest response for the threshold. The mean simulated and observed values of nitrogen oxide concentrations equal 18 $\mu g\, m^{-3}$. The mean simulated and observed concentrations of ozone are equal to 77 $\mu g\, m^{-3}$ and 78 $\mu g\, m^{-3}$ respectively. Fractional biases for these pollutants are also relatively low; they are 0.02 for nitrogen oxides and -0.01 for ozone.

The sharper distinction appears in agreement, error and correlation. Ozone has a Fac2 value of 0.97, NMSE of 0.03 and Pearson correlation of 0.84. Nitrogen oxides have a lower Fac2 value of 0.77, a larger NMSE of 0.41 and a weaker correlation of 0.48. The resulting coefficient is 0.783 for ozone and 0.257 for nitrogen oxides. Ozone is therefore about three times stronger by this coefficient, which justifies using daylight ozone increment as the direct attenuation endpoint.



(a) Contribution (b) Ranked terms

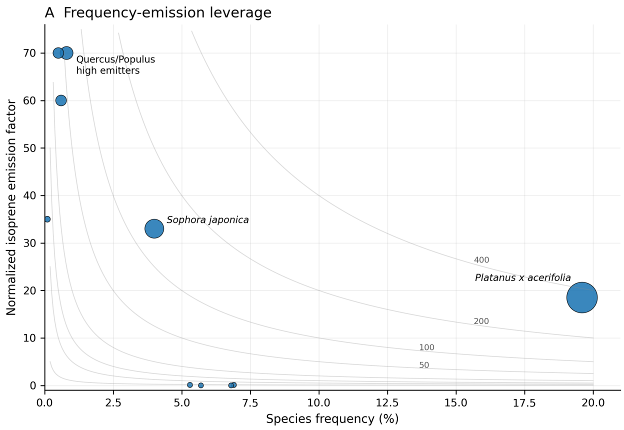
(c) Cumulative share (d) Input values

Figure 2. Species contribution pattern.

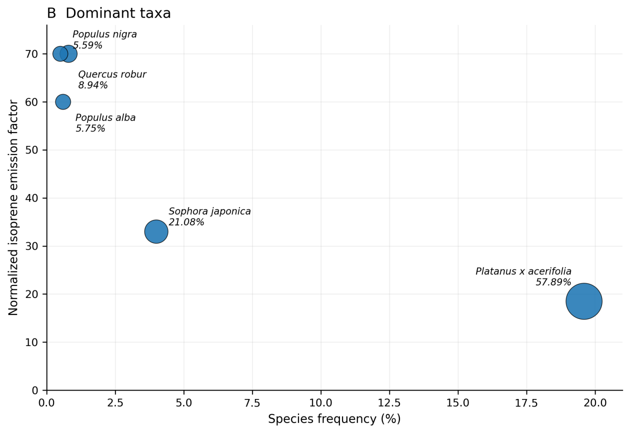
Table 2. Pollutant-evaluation values.

Statistic	NO_x	O_3
Mean simulated concentration ($\mu g\,m^{-3}$)	18	77
Mean observed concentration ($\mu g\,m^{-3}$)	18	78
Simulated standard deviation ($\mu g\,m^{-3}$)	12	23
Observed standard deviation ($\mu g\,m^{-3}$)	10	25
Fac2	0.77	0.97
Fractional bias	0.02	-0.01
NMSE	0.41	0.03
Pearson r	0.48	0.84
K_q from Eq. (3)	0.257	0.783

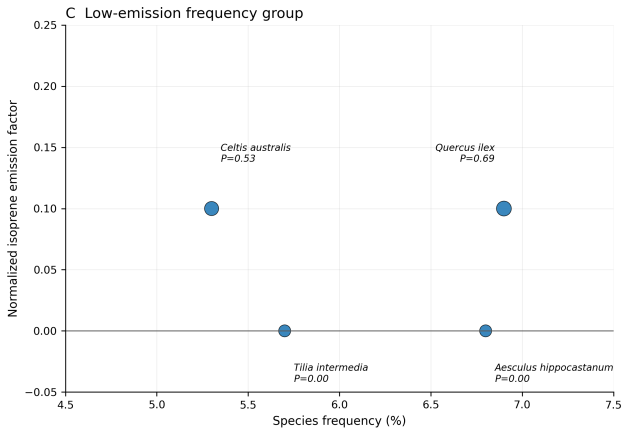
The panels in Figure 4 make the same comparison visually. The concentration panel shows that the two pollutants are not separated primarily by mean mismatch. The component panel indicates that ozone is consistently stronger across agreement, correlation and error terms. The coefficient panel compresses those terms into one comparison, while the receptor panel links the pollutant decision to the location-specific values used later in the analysis. This



(a) All taxa



(b) Dominant taxa



(c) Low-emission group

Figure 3. Frequency-emission contribution plane.

sequence strengthens the logic of the Bologna calculation: nitrogen oxides remain chemically necessary, but ozone provides the response value used for the receptor thresholds.

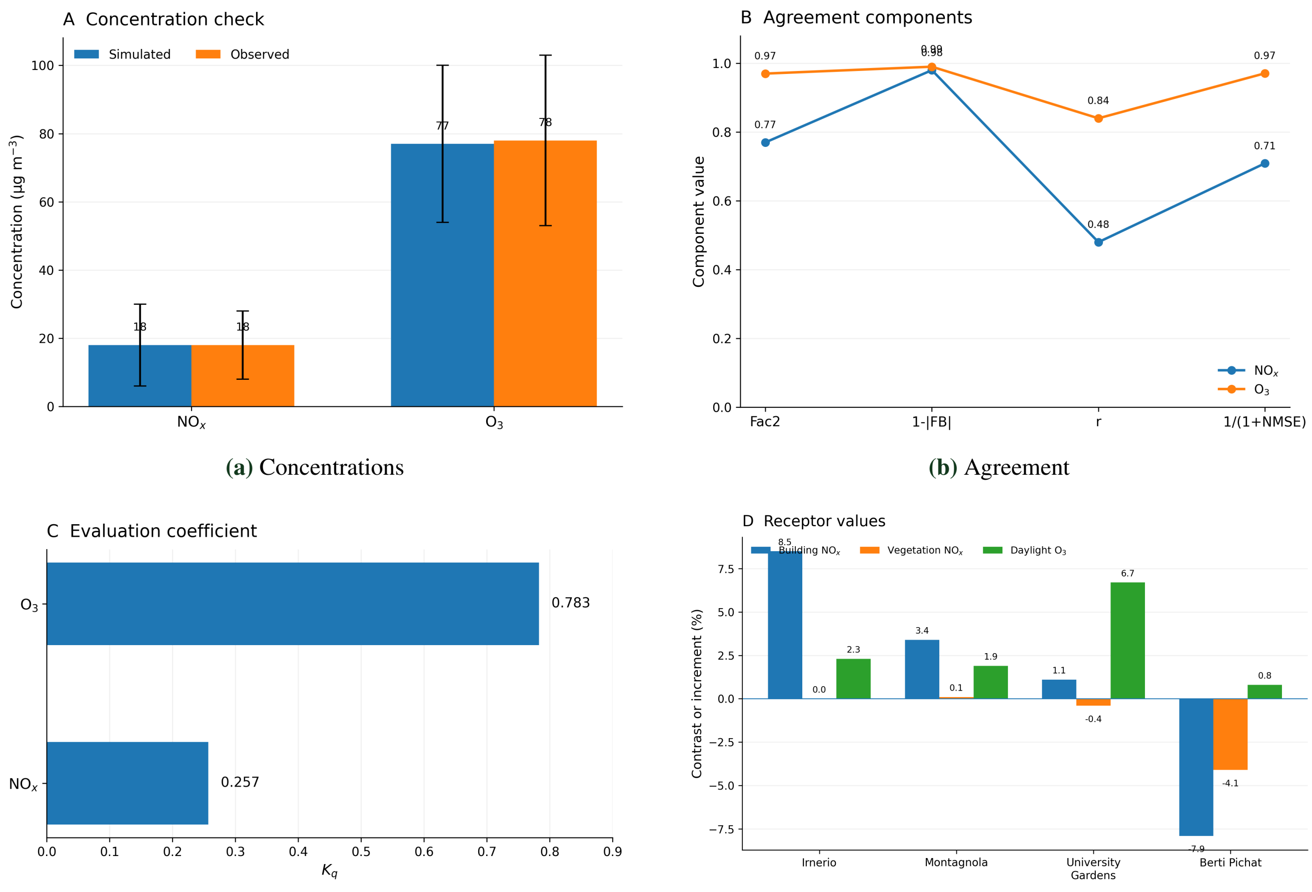
The result also clarifies why nitrogen oxide contrasts are not discarded. Ozone chemistry is formed by the interaction of reactive organics and nitrogen oxides, and the local nitrogen oxide regime can decide whether volatile organic compound reduction has a strong or weak ozone effect [3, 25]. The coefficient only determines which pollutant is used as the managed response in this calculation.

4.3. Receptor Ozone Increments

The receptor values in Table 3 show that University Gardens has the largest daylight ozone increment, 6.7%. Irnerio follows at 2.3%, Montagnola is slightly below the main limit at 1.9%, and Berti Pichat is lowest at 0.8%. These values immediately separate the receptors into different management positions. University Gardens is far above the 2% limit, Irnerio is slightly above it, and the other two receptors remain below it.

Table 3. Receptor pollutant contrasts.

Location	Building-related NO_x contrast (%)	Vegetation-related NO_x contrast (%)	Daylight O_3 increment, $O_{p,0}$ (%)
Irnerio	8.5	0.0	2.3
Montagnola	3.4	0.1	1.9
University Gardens	1.1	-0.4	6.7
Berti Pichat	-7.9	-4.1	0.8



(a) Concentrations **(b)** Agreement

(c) Coefficient **(d)** Receptor values

Figure 4. Pollutant evaluation and receptor values.

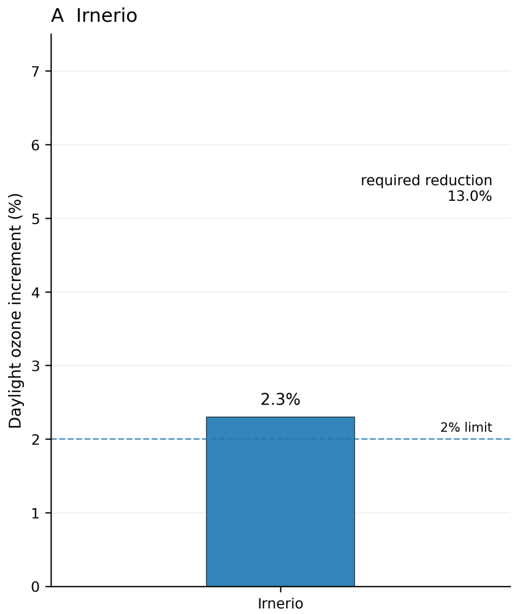
The nitrogen oxide contrasts help interpret the spatial differentiation. Irnerio has the highest building-related nitrogen oxide contrast, 8.5%, but its daylight ozone increment is much smaller than University Gardens. Berti Pichat has negative nitrogen oxide contrasts and the lowest ozone increment. University Gardens has only a small building-related nitrogen oxide contrast of 1.1% and a vegetation-related contrast of -0.4%, yet it has the strongest ozone response. The receptor outcome is therefore not reducible to nitrogen oxide contrast alone. It reflects local chemistry, ventilation, sunlight, residence time and the contribution of reactive organics.

The threshold panels in Figure 5 place the four receptors on the same 2% reference line. University Gardens is clearly the limiting receptor because the distance between 6.7% and the operational limit is large. Irnerio is only slightly above the line and can be brought below it by a modest reduction. Montagnola and Berti Pichat do not require immediate isoprene reduction under this limit. The figure therefore turns the receptor table into a practical priority order.

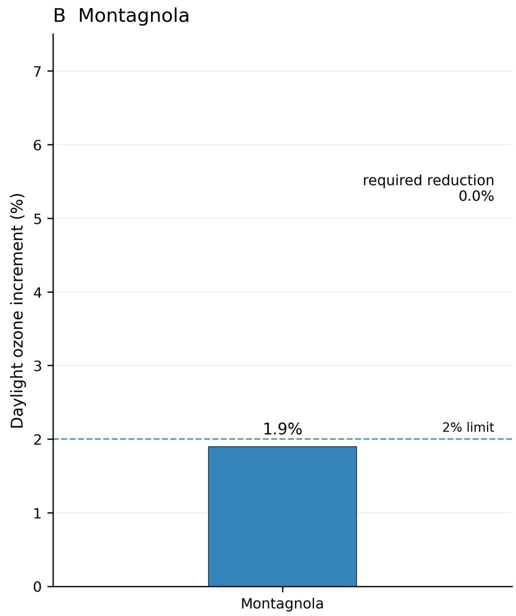
The contrast between Montagnola and University Gardens is especially important. Both are green locations, but their ozone increments differ by 4.8 percentage points. This shows that a planting recommendation cannot be based only on whether a receptor is a garden or a street. The receptor-level increment determines how much species-composition change is needed.

4.4. Required Reductions at the 2% Limit

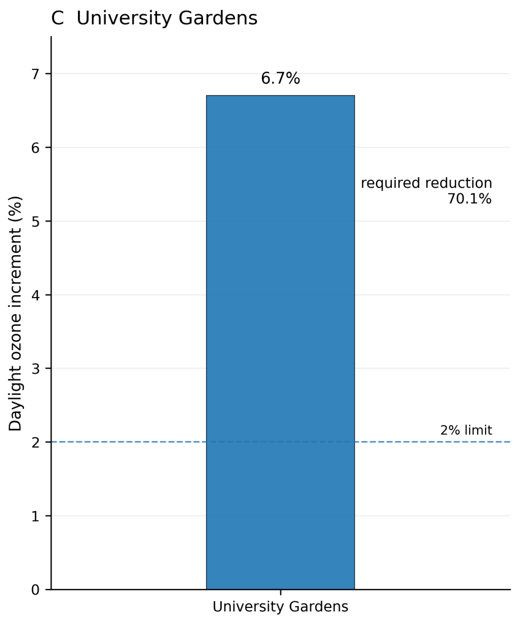
The partial replacement values in Table 4 use the species shares to estimate residual ozone increments under two reduction levels. A 50% reduction of the two dominant terms removes 39.49% of total normalized potential because the pair accounts for 78.98%. A 50% reduction of the first five contributors removes 49.62% because those taxa account for 99.25%. The values apply Eq. (5) to the calculated contribution shares.



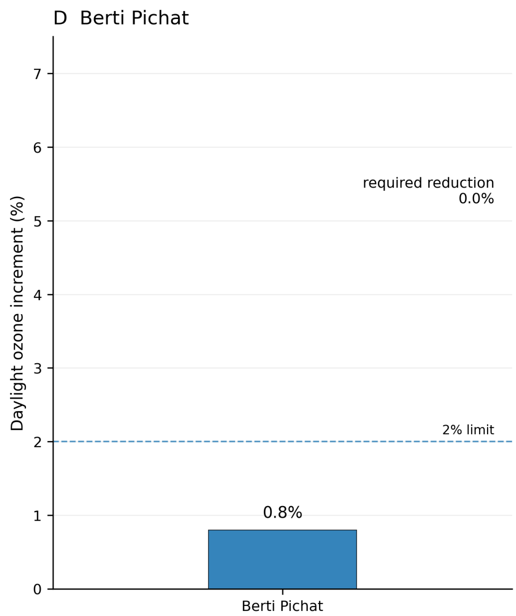
(a) Irnerio



(b) Montagnola



(c) University Gardens



(d) Berti Pichat

Figure 5. Daylight ozone increments.

Table 4. Residual increments after partial reduction.

Location	Initial $O_{p,0}$ (%)	Required A_p^* (%)	Top-two 50% residual (%)	Top-five 50% residual (%)
Irnerio	2.3	13.0	1.39	1.16
Montagnola	1.9	0.0	1.15	0.96
University Gardens	6.7	70.1	4.05	3.38
Berti Pichat	0.8	0.0	0.48	0.40

The table splits the receptors into four positions. Irnerio would only require 13.0% reduction to fulfill the 2% reduction criterion. The residual after the top-two 50% test is 1.39%, while that from the top-five 50% test is 1.16%. Hence, it becomes clear that management of the Irnerio receptor can be achieved through progressive preference against the dominant pair.

University Gardens, on the other hand, requires a completely different approach. The required reduction here is 70.1%. However, the residual after the top-two 50% test would be 4.05%, while that of the top-five 50% test would be 3.38%. Both values are above the operational limits of 2%. It follows that moderate reduction alone would not solve the issue at this receptor. Instead, most of the normalized potential must be addressed, and this means focusing on the dominant pair.

As for Montagnola and Berti Pichat receptors, they already satisfy the 2% reduction criterion. Hence, no reduction in their respective contributions is needed for them to become compliant with the limits set. Nevertheless, it is still useful to estimate the margins that would result in case of reduction of the high-contribution species. In case of Montagnola, this margin is relevant since the starting value is 1.9%, which is near the 2% threshold. The task at this location is preventive.

4.5. University Gardens Substitution and Limit Sensitivity

From Table 5, the complete substitution analysis reveals the threshold-crossing target for the University Gardens receptor. Removal of the high contribution from only *Platanus* × *acerifolia* reduces the residue by about 3.88%, resulting in a new residual increment of 2.82%, above the target value of 2%. However, substituting both the *Platanus* × *acerifolia* and *Sophora japonica* contributions would lower this residual increment to 1.41%.

Table 5. Residual increments after complete substitution.

Location	Initial $O_{p,0}$ (%)	Complete top-one residual (%)	Complete top-two residual (%)	Complete top-five residual (%)
Irnerio	2.3	0.97	0.48	0.02
Montagnola	1.9	0.80	0.40	0.01
University Gardens	6.7	2.82	1.41	0.05
Berti Pichat	0.8	0.34	0.17	0.01

The same complete substitution has different practical meaning across receptors. At Irnerio, substituting the top species alone would lower the residual to 0.97%, already below the 2% limit. At Montagnola and Berti Pichat, the same operation would reduce values that are already acceptable under the main limit. University Gardens is the only receptor where the top-one case remains insufficient. This confirms that the planting decision must be receptor-specific even when the species ranking is the same.

The University Gardens panels in Figure 6 isolate the threshold crossing. The residual-increment panel shows that the top-one case remains above 2%, while the dominant-pair case falls below the limit. The substitution-share panel shows why: the dominant pair removes 78.98% of normalized potential, which exceeds the required 70.1%. The dominant-species panel identifies the exact taxa responsible for the crossing, and the distance-from-limit panel indicates that the top-five case would create a much larger margin than the dominant-pair case. The dominant pair is therefore sufficient but not excessive in the calculation.

The sensitivity values in Table 6 test how much the result depends on the selected limit. Under a strict 1% limit, University Gardens requires 85.1% reduction, Irnerio requires 56.5% and Montagnola requires 47.4%. Under the 2% limit, University Gardens requires 70.1% and Irnerio requires 13.0%, while Montagnola and Berti Pichat require no reduction. Under a 3% limit, University Gardens still requires 55.2%, and all other receptors require no reduction.

The cap sensitivity confirms that University Gardens is not an artifact of the 2% limit. It remains active even when the limit is relaxed to 3%. The secondary receptors are more sensitive to the selected tolerance. Irnerio shifts from active reduction at 2% to no required reduction at 3%, while Montagnola requires action only under the 1% limit. Berti Pichat remains below all evaluated limits. These values support a graded planting policy rather than a uniform species rule for every receptor.

The separated cap panels in Figure 7 make that graded policy visible. University Gardens remains farthest to the right in each panel, indicating the largest required reduction. Irnerio and Montagnola move leftward as the limit

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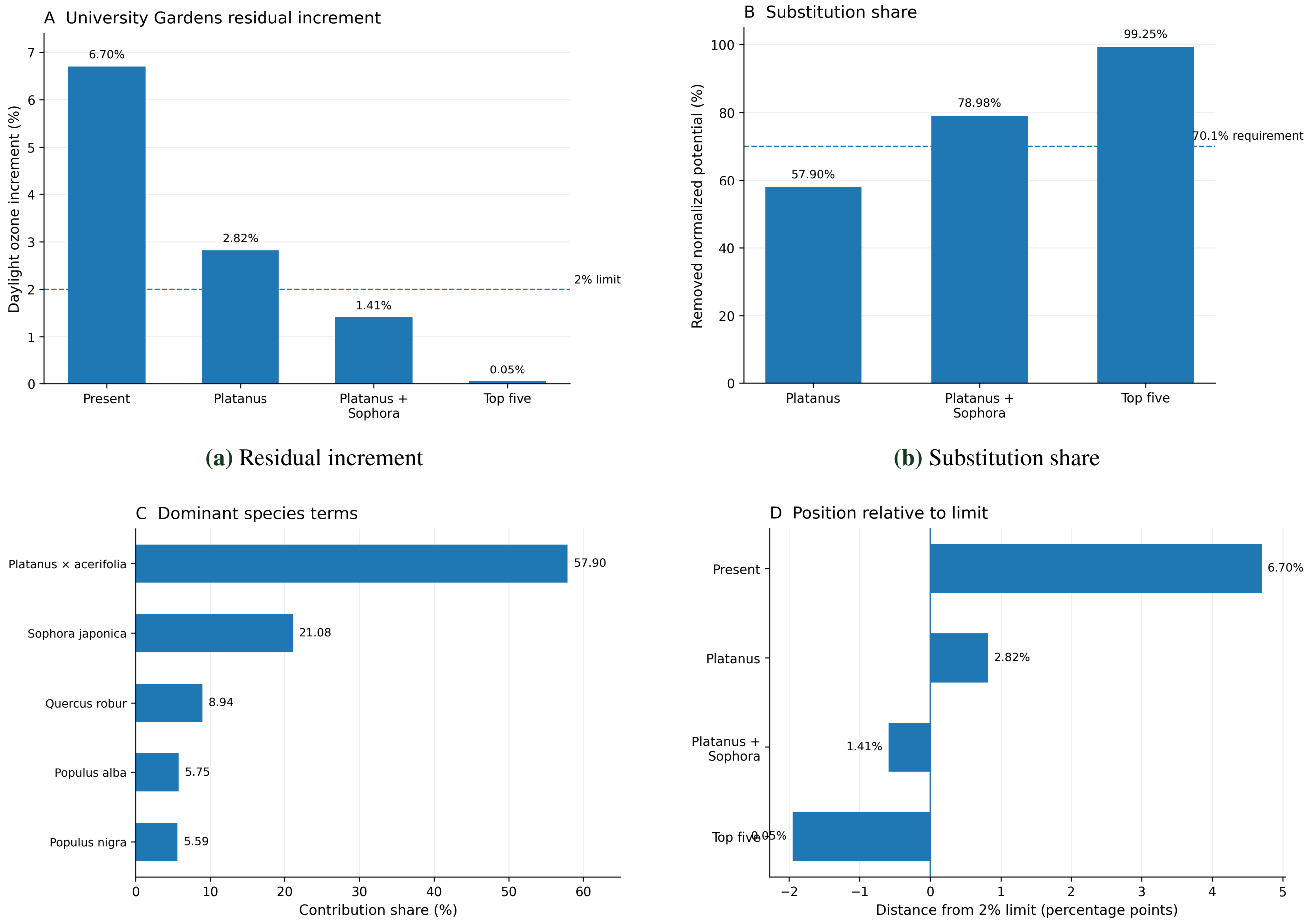


(a) Residual increment **(b)** Substitution share

(c) Dominant terms **(d)** Limit position

Figure 6. University Gardens substitution response.

Table 6. Required reduction under alternative limits.

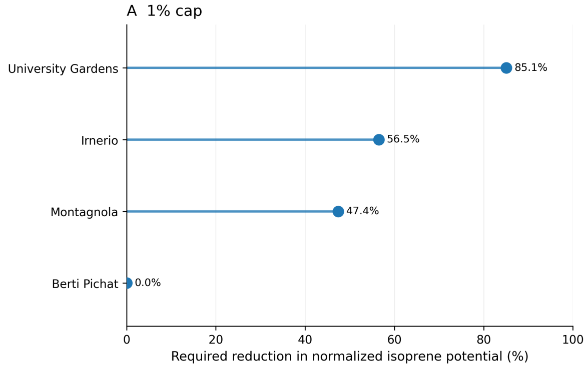
Location	1% limit (%)	2% limit (%)	3% limit (%)
Irnerio	56.5	13.0	0.0
Montagnola	47.4	0.0	0.0
University Gardens	85.1	70.1	55.2
Berti Pichat	0.0	0.0	0.0

relaxes, and Berti Pichat remains at zero. The figure therefore shows that the calculation is robust in identifying the primary receptor but flexible in assigning secondary priorities.

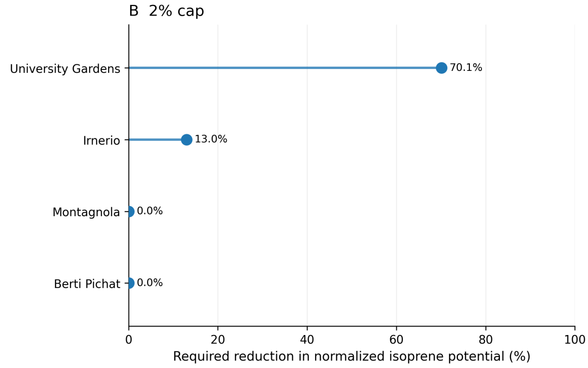
4.6. Bologna Evidence Synthesis

Species, pollutant and receptor evaluations all lead to the same conclusion from different angles. The species assessment confirms that normalized potential is concentrated in two dominant taxa; the pollutant evaluation confirms that ozone will be the response with the greatest relative strength; and the receptor evaluation confirms that University Gardens is the site requiring the greatest isoprene increment reduction to meet the threshold condition. These results taken alone would not be sufficient; a species analysis identifies high-contribution taxa but cannot pinpoint where renewed emphasis should occur; and a receptor table can identify University Gardens as the sensitive receptor but not determine which taxa should be subject to management reduction.

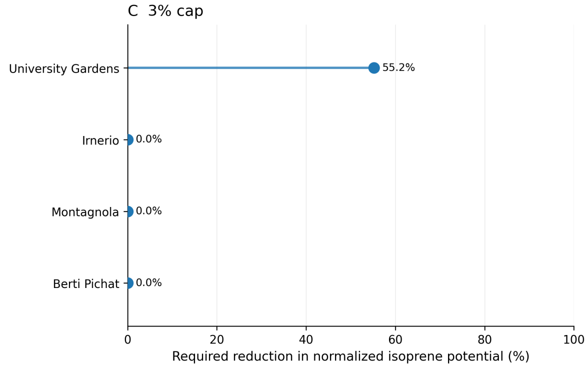
The distinction between contribution share and management sufficiency is critical to interpreting results. The



(a) 1% limit



(b) 2% limit



(c) 3% limit

Figure 7. Limit sensitivity.

dominant two taxa contribute 78.98% of normalized potential, but the importance of that statistic becomes operational only when compared against receptor requirements. University Gardens requires a reduction of 70.1%, thus making it possible. However, if the threshold is set as 1%, the required reduction rises to 85.1%. Even then, dominant-pair reduction would be insufficient. Irnerio, in contrast, requires only 13.0%; therefore, reduction of the dominant pair is more than sufficient. In this respect, the species ordering is important for determining action priority, while receptor increment is relevant for determining management intensity.

The partial and full substitution analysis also separates operational sufficiency from planning foresight. Montagnola and Berti Pichat satisfy the 2% threshold, but in different ways. Montagnola meets the threshold by 0.1%, while Berti Pichat meets it by 0.8%. For Montagnola, the limited excess over the limit means that even the slightest accumulation of dominant-pair taxa could cause a future violation. For Berti Pichat, there is ample margin below the threshold; therefore, preventative substitution is less of a priority. This important distinction would have been overlooked if the receptors were classified solely as either above or below the limit.

This distinction is reflected in the final list of recommended taxa. High-contributing assemblage members include those listed but also those with zero or low normalized values. Species such as *Aesculus hippocastanum*, *Tilia intermedia*, *Quercus ilex*, and *Celtis australis* show how greening targets can be met with minimal isoprene contribution. Urban canopy and shade can thus be preserved with lower-emission replacement strategies without abandoning greening ambition. This is particularly relevant for Bologna because public spaces can retain heat-moderating capacity and pedestrian amenity value.

5. Discussion

5.1. The Dominant Two Taxa as the Species Renewal Targets

Results show that high-emission component of the Bologna assemblage is not distributed evenly within the total. This conclusion is significant because many urban-forest assessments consider canopy quantity or tree numbers as proxies for environmental benefits [17, 19]. Such proxy variables are useful, but they do not represent the chemical reactivity of the canopy. As the Bologna values show, the chemically active fraction of the canopy can concentrate in just two taxa.

The concentration of chemical potential in a dominant pair is particularly useful because it precludes the possibility of overgeneralizing results. One should not assume that *Platanus* × *acerifolia* is a high emitter; it is a dominant contributor because of frequency. The emission potential of *Quercus robur*, *Populus alba* and *Populus nigra* is greater, but their infrequency renders them less harmful to Bologna's photochemistry. The reason why Bologna calculations outperform species lists lies precisely here.

Low-emission taxa also play an interpretative role. *Aesculus hippocastanum*, *Tilia intermedia*, *Quercus ilex* and *Celtis australis* prove that high-frequency canopy can coexist with zero or low isoprene potential. Designers should still assess heat tolerance, drought resilience, pest resistance, soil suitability and allergy risk for planting. The photochemistry-based calculation is merely a screening tool, which does not pick replacement species on its own.

In this way, it contributes positively to the existing research. Literature frequently emphasizes the relationship between canopy design and street geometry or between tree planting and photochemical responses [1, 28, 30]. The calculation turns abstract principles into operational priorities. It shows that chemical contribution does not reside uniformly within the canopy, but in two dominant taxa. This interpretation of results enhances the defensibility of planting recommendations, since it does not demand canopy elimination or broad-scale avoidance of high-reactive assemblage components.

The same principle allows reconciling climate change adaptation and ozone mitigation efforts. Tree loss is undesirable in dense urban areas, since vegetation reduces heat islands. However, canopy loss may also help reduce the photochemically active fraction of the assemblage. Gradual substitution through renewal will allow maintaining tree cooling effects while slowly reducing normalized isoprene contribution. From this perspective, Bologna results provide a framework for managing species composition, not urban greening per se.

5.2. University Gardens as the Receptor Threshold Boundary Point

It is worth repeating that the dominant role of University Gardens derives from its high ozone increment and the high required reduction. Its 6.7% increment is nearly three times greater than the chosen operational limit. A 50% reduction of the dominant pair still leaves the residual contribution at 4.05%; even if the contribution of the first five taxa is cut in half, the residual will remain at 3.38%. Both scenarios demonstrate that reduction of a moderate size is not enough to meet the threshold.

Montagnola is perhaps the best example of internal variation among receptors. It, like University Gardens, belongs to the green receptor category. However, its ozone increment is 1.9%, which makes it a bit below the chosen operational limit. This example proves once again that the issue of ozone production is not the presence or absence of trees in a green receptor. Photochemical contribution depends on species composition, sensitivity and receptor type. As numerous studies on canopy and street geometry suggest [1, 18, 20, 21], urban canopy effects are complex.

Irnerio is in a similar situation to University Gardens except for increment. Being slightly above the operational limit, it requires a 13.0% reduction. In this case, small changes in dominant-pair contribution would suffice to meet the chosen limit. Berti Pichat is located in the lowest ozone-increment category and therefore does not require a species substitution at any level under the evaluated operational limits. Overall, this internal differentiation results in four categories of management intensity: one requiring substantial, one medium and one prevention, and the last no isoprene-driven reduction.

5.3. Isoprene Management Without Tree Removal

The species evaluation makes canopy renewal a better strategy than canopy removal. Trees in a densely planted street provide numerous benefits beyond isoprene production. Removing them may make pedestrians more exposed to heat island conditions. Instead, the Bologna calculation supports a gradual substitution approach. As trees grow old and become a safety hazard, they should be substituted with less reactive alternatives. Similarly, any planting opportunity due to public space redesign should favor taxa with low-normalized emission potential.

University Gardens requires gradual dominance shift toward species with low isoprene contribution. The evaluation shows that substitution of *Platanus* × *acerifolia* alone would leave normalized isoprene above 2%. However, substitution of the dominant pair will reduce it to approximately 1.41%. Thus, a new species list for urban greening can be built based on this threshold criterion. Only the dominant pair contributes above 2%.

Irnerio, in contrast to University Gardens, has a 2.3% increment, making a small reduction sufficient for meeting the 2% limit. New planting should focus on preserving street ventilation without increasing dominant-pair frequency. Montagnola should be classified as a receptor requiring prevention, as it is already very close to the limit; it needs further study to identify appropriate species substitutions. Berti Pichat does not need any isoprene-specific species interventions for meeting the chosen threshold criterion.

As demonstrated in Figure 8, planting panels reflect this differentiated approach. The panels do not impose the same decision on each receptor. For example, University Gardens requires the most intensive action; Irnerio, a moderate; Montagnola, preventative actions, and Berti Pichat, none of them.

The management interpretation should continue to be conservatively horticultural. A low normalized isoprene potential is not sufficient information to pick a tree to grow on narrow Bologna streets or gardens. The candidate trees must be able to withstand a limited root zone, hot summer temperatures, droughts, pests, soil compaction, and utility maintenance limitations. As such, the calculation is a screening tool within a much larger process. The purpose of the calculation is to understand what should be decreased and not necessarily how many trees need to be replaced across the city.

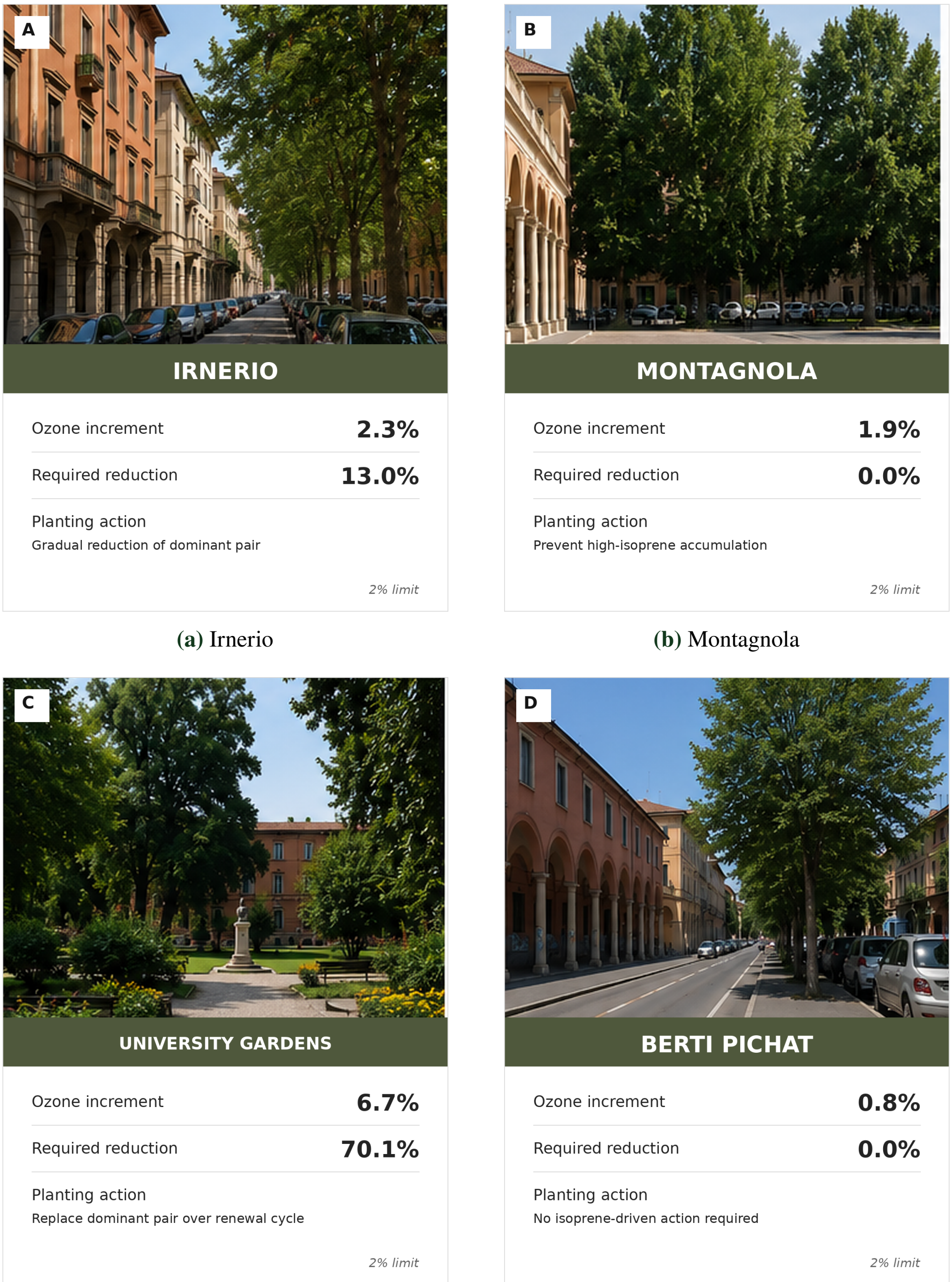
5.4. Uncertainty and Applicability

The primary constraint is that frequency is used rather than leaf mass, crown mass or leaf-area index. While frequency is clear and easily comparable, a mature individual of a certain species can provide more canopy area than younger individuals of the same type. Including crown mass and leaf area measurements, temperature, phenology and solar exposure can improve this calculation. The improved Bologna calculation will retain the same underlying rationale but include more parameters to make a better estimate.

The second constraint relates to the proportional residual relationship assumption. Ozone responses can change non-linearly due to shifts in the chemistry of radicals and nitrogen oxides. Depending on the situation, a particular decrease in the normalized isoprene potential may lead to a smaller or larger decrease in ozone. It should thus be considered a planning tool that can show how easy or difficult achieving the chosen goal can be. The proportional calculation helps to identify the magnitude of the required reduction.

The third constraint lies in using the ozone reduction as one of the urban-forest criteria. Planting trees should not necessarily mean reducing ozone levels in Bologna. Reducing air temperature, ensuring shading, promoting biodiversity, satisfying preferences, maintaining tree structure and performing proper maintenance are some of the important goals that cannot be ignored. The value of Bologna results thus lies in combining this criterion with the others.

The additional interpretive constraint is related to timing. The calculations do not indicate how often isoprene reduction needs to occur. The implementation strategy based on these calculations can use the results to create the timeline for planting activities, which can take into account the species' health and safety. Slow and gradual reduction allows not only testing the success but also avoiding sudden canopy decreases that could lead to negative effects on residents.



(a) Irnerio **(b)** Montagnola

(c) University Gardens **(d)** Berti Pichat

Figure 8. Planting priorities.

The calculation results can also inform the choice of monitoring sites. University Gardens receives the highest number of measurements due to being the limiting receptor for all limits tested. Irnerio should receive monitoring attention due to proximity to the limit and sensitivity to changes. Montagnola is another receptor that should be monitored for composition changes, but not at the expense of Berti Pichat. This recommendation is driven solely by the results of this calculation.

6. Conclusion

The Bologna species and receptor values define the exact canopy renewal target to achieve an ozone reduction without decreasing urban vegetation in general. It consists in reducing high-normalized species composition, which leads to the highest daylight ozone increment value.

Firstly, the species component shows an exceptionally high concentration. *Platanus × acerifolia* is responsible for 57.90% of normalized isoprene potential and together with *Sophora japonica* brings up the total contribution to 78.98%. The first five taxa account for 99.25%, while the contribution of several common species is marginal. Such composition makes targeted renewal possible, as the majority of the chemical leverage lies with a few taxa.

Secondly, the pollutant component supports ozone as the management endpoint, while the proportion of nitrogen oxide contribution is 0.783. The coefficient for ozone is higher and has less error in comparison with the coefficient of nitrogen oxides in the evaluated values. While it is still necessary to know the proportion, the receptor-specific attenuation threshold should be estimated based on daylight ozone increment.

Finally, the receptor component provides the critical information. University Gardens has the highest initial daylight ozone increment – 6.7% – and requires a 70.1% decrease to reach the 2% limit. Irnerio requires 13.0% decrement, and no decrement is needed for Montagnola and Berti Pichat within the same limit. Even complete substitution of *Platanus × acerifolia* in University Gardens keeps ozone at approximately 2.82%. Complete substitution of both *Platanus × acerifolia* and *Sophora japonica* reduces ozone increment to about 1.41%, indicating that the dominating species are the minimum required threshold-crossing renewal target for University Gardens in this case.

The conclusion regarding Bologna urban-forest planning thus is receptor-specific canopy renewal. University Gardens is the priority receptor, and efforts should be taken to reduce the dominating pair of species gradually. Irnerio should also be guided towards avoiding a further increase in the dominating species population. Montagnola should be protected from isoprene accumulation since it is close to the 2% limit. Berti Pichat does not require any ozone-increasing interventions under the evaluated limits.

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