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Vegetation Effects on Air Pollution: A Comprehensive Assessment for Two Italian Cities

Mihaela Mircea [1,*,†], Gino Briganti [1,*,†], Felicita Russo [1,†], Sandro Finardi [2], Camillo Silibello [2], Rossella Prandi [3], Giuseppe Carlino [3], Massimo D'Isidoro [1], Andrea Cappelletti [1] and Giuseppe Cremona [1]

1 Models and Measures for Air Quality and Climate Observation Laboratory, Italian National Agency for New Technologies, Energy and Sustainable Economic Development–ENEA, 40121 Bologna, Italy; felicita.russo@enea.it (F.R.); massimo.disidoro@enea.it (M.D.); andrea.cappelletti@enea.it (A.C.); giuseppe.cremona@enea.it (G.C.)
2 ARIANET Srl, 20128 Milano, Italy; sandro.finardi@suez.com (S.F.); camillo.silibello@suez.com (C.S.)
3 SIMULARIA Srl, Via Sant'Antonio da Padova 12, 10121 Torino, Italy; r.prandi@simularia.it (R.P.); g.carlino@simularia.it (G.C.)
* Correspondence: mihaela.mircea@enea.it (M.M.); gino.briganti@enea.it (G.B.)
† These three authors contributed equally to this work.

Abstract: The role of urban vegetation in urban air quality is usually assessed by considering only the pollutant removal capacity of the plants. This study aims to show, for the first time, the effects of vegetation on air pollutant concentrations through its effects on meteorology, separately from its biogenic emissions. It also investigates how air quality changes when only biogenic emissions are altered by using plants with different emission factors, as well as the potential effects of introducing new vegetation into urban areas. These assessments were conducted using atmospheric modelling systems currently employed for air quality forecasting and planning, configured specifically for the cities of Bologna and Milan. Simulations were performed for two representative months, July and January, to capture summer and winter conditions, respectively. The variability in air concentrations of ozone (O_3), nitrogen dioxide (NO_2), and particulate matter (PM10) within the municipal boundaries was assessed monthly. When evaluating the impact of future vegetation, changes in temperature, wind speed, and relative humidity were also considered. The results indicate that vegetation influences air quality more significantly through changes in meteorological conditions than through biogenic emissions. Changes in biogenic emissions result in similar behaviours in O_3 and PM10 concentrations, with the latter being affected by the changes in the concentrations of secondary biogenic aerosols formed in the atmosphere. Changes in NO_2 concentrations are controlled by the changes in O_3 concentrations, increasing where O_3 concentrations decrease, and vice versa, as expected in highly polluted areas. Meteorologically induced vegetation effects also play a predominant role in depositions, accounting for most of the changes; however, the concentrations remain high despite increased deposition rates. Therefore, understanding only the removal characteristics of vegetation is insufficient to quantify its effects on urban air pollution.

Keywords: urban vegetation; air pollution; urban meteorology; biogenic emissions; atmospheric modelling; concentration and deposition of air pollutants; air quality modelling system; air quality plans

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Citation: Mircea, M.; Briganti, G.; Russo, F.; Finardi, S.; Silibello, C.; Prandi, R.; Carlino, G.; D'Isidoro, M.; Cappelletti, A.; Cremona, G. Vegetation Effects on Air Pollution: A Comprehensive Assessment for Two Italian Cities. *Atmosphere* **2024**, *15*, 1511. https://doi.org/10.3390/atmos15121511

Academic Editors: Yoshizumi Kajii and Boris Igor Palella

Received: 23 October 2024
Revised: 22 November 2024
Accepted: 12 December 2024
Published: 17 December 2024

1. Introduction

The latest WHO guidelines [1] set new thresholds and limits for key air pollutants such as particulate matter (PM2.5 and PM10), ozone (O_3), and nitrogen dioxide (NO_2), which pose health risks. Improving air quality in urban areas, where most of the population resides, is particularly challenging due to the difficulty in implementing effective measures to reduce emissions from traffic, industry, energy, etc. In recent decades, phytoremediation technologies using vegetation have been proposed to clean up the air, as pollutants can deposit on leaves, be absorbed through stomata, or dissolve in the wax of trees', shrubs', and herbaceous plants' leaves [2–4]. However, vegetation also emits biogenic volatile organic compounds (BVOCs), which include isoprene, mono- and sesquiterpenes, alcohols (mainly methanol), and other volatile oxygenated compounds (mainly acetaldehyde and acetone). These emissions contribute to atmospheric chemistry and air pollution levels [5–9]. In addition to acting as both a sink and source for atmospheric pollutants, urban vegetation modifies the atmospheric flow (impacting temperature, relative humidity, wind direction and speed, etc.) [10], thereby indirectly affecting the urban air quality [11].

To date, comprehensive assessments of the overall effectiveness of vegetation (or nature-based solutions (NBSs) involving vegetation) on city-scale air quality are scarce. Yu et al. [12] used land-use classes to represent urban vegetation and demonstrated that urban greenery in the Beijing (China) area decreases the surface temperature by up to 0.45 °C. Additionally, they observed both increases and decreases in the ozone concentration on sunny and rainy days, when considering the combined impact of land-use changes and BVOC emissions (Figure S6). Similarly, for Madrid (Spain) and Bologna and Milan (Italy), D'Isidoro and Mircea et al. [10] found that urban vegetation reduced temperatures by up to 0.6 °C, 0.4 °C, and 0.8 °C, respectively, while the concentrations of O_3, NO_2, and PM10 exhibited both increases and decreases in the city area [11]. These last two studies ([10,11]) used tree inventories to enhance the description of urban vegetation and its BVOC emissions. The work was conducted within the framework of the EU-funded VEG-GAP Life project (https://www.lifeveggap.eu, accessed on 18 October 2024), with support from municipalities, between 2018 and 2022. For Paris (France), Maison et al. [13] investigated only the effects of emissions from vegetation on air quality, and they estimated an overall increase in O_3 and PM concentrations. These four studies were carried out with air quality modelling systems (AMSs) at a high spatial resolution of 1 km, allowing for a more realistic assessment of the city's characteristics in terms of atmospheric physical and chemical processes compared to coarser grid resolutions. In the last study, the effect of vegetation on meteorology was not considered.

The added value of the present study lies in its comprehensive examination of how urban vegetation impacts air pollution both directly (through BVOC emissions and deposition) and indirectly (through its influence on meteorological conditions). This is achieved by using detailed tree inventories provided by the municipalities, along with a thorough description of urban morphology for the cities of Bologna and Milan. Two sensitive tests were performed to evaluate the impact of different plant species on BVOC emissions and, consequently, on air pollution levels. To support the city planning activities, the effects of enhancing urban vegetation, down to the level of individual trees, were evaluated, considering its impacts on both meteorology and air quality, similar to the assessments conducted for existing vegetation [10,11].

2. Materials and Methods

The quantification of vegetation's effects on air quality was performed with an AMS that includes the meteorological model WRF v3.9.1.1 [14] and the chemical transport model (CTM) FARMv4.14 [15,16]. Table 1 outlines the simulations performed in this study, detailing how vegetation was treated as an input by the meteorological model (MM) and chemical transport model (CTM). More details on the configurations of the two models used here can be found in [10,11]. The simulations were conducted for July and January 2015 to represent summer and winter conditions, respectively. All simulations used the same model setup except for variations in urban vegetation characteristics, such as vegetated areas, tree species considered, and emissions factors. The VEG and NOVEG simulations discussed in the above-mentioned articles represent two scenarios: VEG reflects the state of the atmosphere considering the current vegetation, while NOVEG illustrates how the urban atmosphere would be if vegetation were completely absent from the urban area. The VEG_Uncoupled simulation uses the same meteorological fields as the VEG simulation, but without considering BVOCs emitted inside the city, as in the NOVEG simulation.

VEG_Future is the simulation in which new urban vegetation is added, and these updated vegetation data are used as inputs for both meteorological and chemical transport models. The last two simulations were designed to test the impact of emission factors; therefore, they use the current extent of vegetation, as the VEG simulation, but applying different BVOC emission factors. One simulation (VEG_CeltisAustralis) uses factors representative of Celtis Australis, which is the most common species in both cities (13.29% in Bologna and 8.42% in Milan), according to the "Guidelines on Mapping Vegetation Characteristics in Urban Areas" (https://www.lifeveggap.eu/it/index.php?q=sharer&curdir=/VEG-GAP+Guides, accessed on 18 October 2024). The other simulation (VEG_Maximum Emissions Factors) uses maximum BVOC emission factors estimated from all species included in the tree inventories of the Bologna and Milan municipalities.

Table 1. Description of the six simulations and of vegetation data in the city area used as inputs by the meteorological model (MM) and chemical transport model (CTM).

Simulation Name / Input Data	VEG	NOVEG	VEG_Uncoupled	VEG_Future	VEG_Celtis Australis	VEG_Maximum Emissions Factors
MM	Present vegetation	Without vegetation	Present vegetation	Future vegetation	Present vegetation	Present vegetation
CTM-land-use	Present vegetation	Without vegetation	Present vegetation	Future vegetation	Present vegetation	Present vegetation
CTM-BVOC emission parameters	With BVOC emissions (PSEM)	Without BVOC emissions	Without BVOC emissions	With BVOC emissions (PSEM)	With BVOC emissions using Celtis Australis emission factors	With BVOC emissions using maximum values of emission factors

For a given variable estimated by models (such as temperature, air concentration, etc.), the effects of vegetation were computed as the difference between two simulations described in Table 1. These differences are referred to as "indicators". The six indicators defined in Table 2 (REF, MET, BVOC, FUT, BVOCCA, and BVOCMAX) are analysed here to understand their associated effects: REF shows the overall effects of vegetation on air quality, incorporating both meteorology and BVOC emissions impacts. MET isolates the effects of vegetation on meteorology. BVOC focuses on the effects of BVOC emissions alone. The FUT indicator measures the impact of future vegetation, considering both meteorological and BVOC emissions effects. BVOCCA and BVOCMAX specifically assess the impact of different BVOC emission factors relative to the present vegetation (VEG simulation). Positive values for these last three indicators imply an increase in a variable due to changes in the vegetation characteristics (such as area, species, or emission factor) compared to present vegetation. Similarly, positive values of the BVOC indicator represent an increase in a variable, e.g., an air pollutant concentration, due to the current vegetation's BVOC emissions (with meteorological conditions kept unchanged). Conversely, in the case of MET, negative values (higher concentrations in the VEG_Uncoupled simulation than the NOVEG simulation) indicate an increase in concentrations due to the impact of vegetation on meteorology (without BVOC emissions inside the city). To facilitate graphical representation and analysis, MET is used to make the increase in concentration associated with positive values consistent with the other indicators. Since REF is equal to BVOC-MET, the use of MET clearly shows its contribution to REF, revealing whether vegetation's effects are "synergistic" (both positive or both negative) or "compensatory" (one positive and one negative) (see as examples Figures S1 and S2).

This approach aligns with the sign and colour conventions previously established in [10,11] for mapping vegetation's effects: positive values, showing an increase in concentration, are represented in red (non-beneficial effects), while negative values, corresponding to a decrease in concentration due to vegetation, are shown in blue (beneficial effects).

Table 2. Description of the six indicators and analysed impacts of vegetation on air pollution.

Indicator Name	REF	MET	BVOC	FUT	BVOCCA	BVOCMAX
Simulations' differences / Vegetation effect	VEG-NOVEG	NOVEG-VEG_Uncoupled	VEG-VEG_Uncoupled	VEG_Future-VEG	VEG_Celtis Australis-VEG	VEG_Maximum emissions factors-VEG
MET		X				
BVOC			X		X	X
MET and BVOC	X			X		

The leaf area index (LAI) maps used by the MM and CTM were based on LAI data at 1 km spatial resolution (https://land.copernicus.eu/global/products/lai accessed on 18 October 2024). These maps represent current vegetation and were adjusted for future vegetation (VEG_Future) by enhancing the LAI data in line with planned urban vegetation expansion. More information on the calculation of LAI and its spatial distribution in the two investigated cities for July may be found in the "Guidelines for the estimation of biogenic volatile organic compounds emissions" (https://www.lifeveggap.eu/it/index.php?q=sharer&curdir=/VEG-GAP+Guides accessed on 18 October 2024).

The two rows of Figure 1 display the spatial distribution of vegetation fraction in urban areas for both cities (Bologna and Milan, respectively). The first column (REF) shows the current vegetation, represented in shades of green. The second column (CA in REF) illustrates the distribution of Celtis Australis, a subset of the REF vegetation, indicated in shades of grey. Comparing the second column to the first, it is evident that the fraction of Celtis Australis is high in only a few cells and generally has values one order of magnitude lower than the total vegetation fraction. In both cities, the fractional vegetation cover was reconstructed from individual tree inventories available for the public green managed by the municipalities.

The third column of Figure 1, labelled NEW VEG in FUT, shows the high-resolution distribution of the planned interventions to increase urban vegetation, i.e., future vegetation scenarios for both cities. This additional vegetation, together with that represented in REF, is shown in the fourth column as future vegetation (FUT). In the case of Milan, the future vegetation includes interventions already planned for 2030 within the Air and Climate Plan (https://www.comune.milano.it/en/aree-tematiche/ambiente/aria-e-clima/piano-aria-clima, accessed on 18 October 2024) and Territorial Government Plan (PGT; https://www.comune.milano.it/en/comune/amministrazione-trasparente/pianificazione-e-governo-del-territorio, accessed on 18 October 2024). In contrast, for Bologna, an approved intervention plan was not available during the project's timeframe. Therefore, the future vegetation scenarios were developed based on information from the Fondazione Villa Ghigi and Bologna Municipality (ref. Fondazione Villa Ghigi "Il sistema del verde della Città di Bologna, ref Comune di Bologna: Progetto: Un Tram per Bologna Segreteria Capo Dipartimento Lavori Pubblici, Mobilità e Patrimonio Linea Rossa: Terminal Emilio Lepido–Terminal Fiera–Facoltà di Agraria/CAAB"). In order to make the interventions in the two cities comparable, they were divided into four categories (VEG 1 to VEG 4), and the specific content of each category is described as follows:

- The future vegetation plan for Bologna includes the following: VEG 1 (redevelopment of historic areas, indicated in blue), including those already green; VEG 2 (the greening of strategical areas for the green system of Bologna, indicated in yellow); VEG 3 (greening of disused extraction and manufacturing areas, indicated in orange); and VEG 4 (requalification of areas adjacent to motorways, indicated in red), for which there is an intentional but not yet a formally operational plan.
- The plan for Milan in 2030 includes the following: VEG 1 (infrastructure for increasing ecological performance: large areas that include already-green zones, cemeteries, and quarries with lakes, indicated in blue, where vegetation cover will be requalified and

new trees will be planted); VEG 2 (small public urban areas where new desealing and forestation projects will be developed, indicated in yellow); VEG 3 (creation of 20 new public parks, partially requalifying dismissed railway yards, indicated in orange); and VEG 4 (creation of ecological connecting corridors based on enhancing vegetation in already available roads for cyclists and pedestrians, indicated in red).

The fourth and last column of Figure 1, labelled FUT, displays the vegetation considered in the simulation VEG_Future. This includes both the current vegetation shown in REF and the additional future vegetation represented by NEW VEG in FUT. The future vegetation scenario results in an increase of up to three times in the vegetation cover compared to REF in some areas, with the greatest increases observed in the northern part of Bologna. For Bologna, in some cases, such as the parks along the river or the green areas along the ring road–motorway axis, previous projects were taken up again; however, this highlights the need for a better definition of the same or, in the case of the so-called "wooded strip", essentially putting forward different hypotheses in terms of development and physiognomy. Perhaps the most interesting and original novelty, capable of offering great opportunities, is represented by the "green inserts", which in this work appear as the main tool through which to leverage future green planning, due also to the strong urban planning implications they have, given their close connection with the urban fabric.

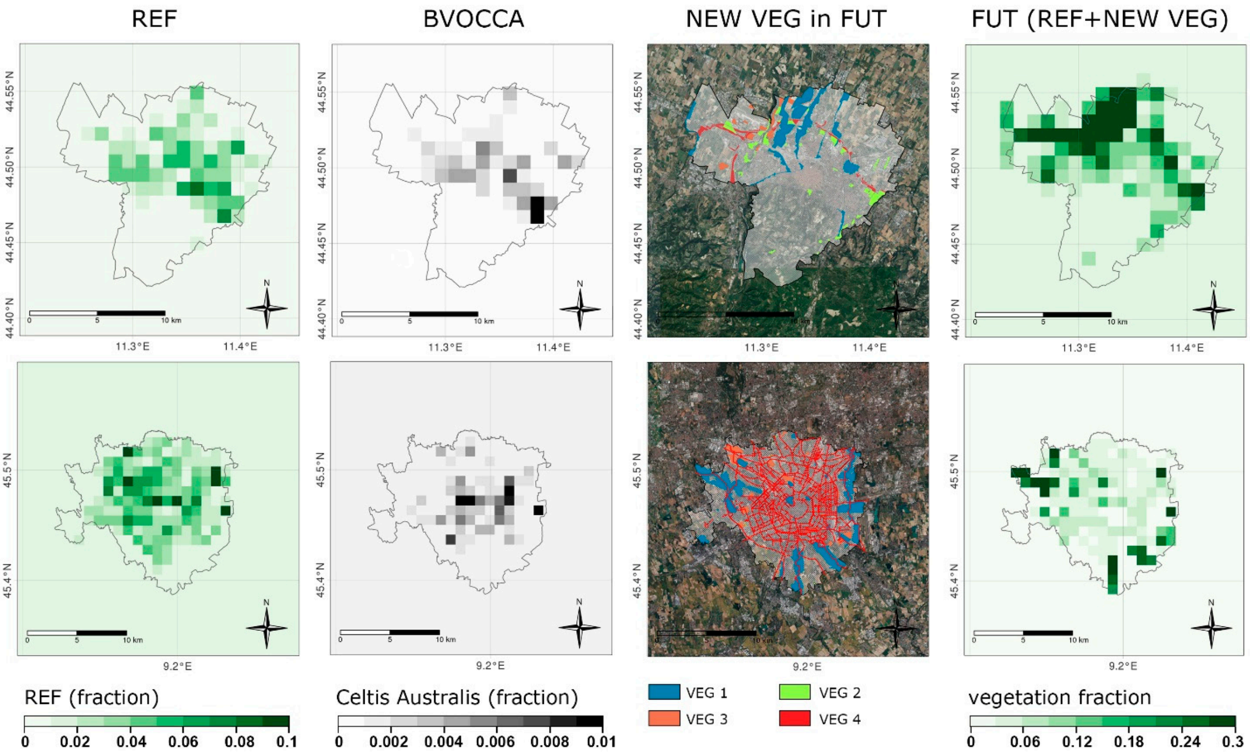


Figure 1. Distribution of urban vegetation fraction (columns, from left to right: present vegetation, present Celtis Australis, spatially detailed future added vegetation, total future vegetation on model grid; rows: Bologna (upper row), Milan (lower row)). To enhance the graphical representation and facilitate comparison between the cities, the colour scales vary by column but remain consistent within each row.

Figure 1 does not display the forested areas located south of Bologna (hilly area—Colli Bolognesi) or the agricultural area located south and west of Milan (Parco Agricolo Sud Milano; https://www.parks.it/parco.sud.milano/Eindex.php, accessed on 18 October 2024), as these regions were not modified in the simulations used by REF, BVOCCA, and FUT. These areas were excluded from the "urban vegetation" category for the purpose of this study. Similarly, vegetation outside the city borders remained unchanged and is therefore not shown in the figure.

Table 3 shows BVOC emission parameters for emissions factors used in the VEG_Celtis Australis and VEG-Maximum simulations. These parameters were estimated based on the emission factors from the PSEM model [17] and information from the tree inventories for the two cities (Guidelines on mapping vegetation characteristics in urban areas, accessed on 9 February 2024). In the VEG_CeltisAustralis simulation, Celtis Australis, a deciduous broadleaved species, was used to represent all current vegetation in both cities, as it is the predominant species. Similarly, the VEG_Maximum emissions factors simulation attributed the maximum emissions factors from the PSEM database to the present vegetation for the following BVOC compounds: isoprene (ISOP), monoterpene synthesis (MTS), monoterpene pool (MTP), sesquiterpenes (SQT), and oxygenated VOCs (OVOC).

Table 3. BVOC emission parameters for VEG_CeltisAustralis and VEG_Maximum emissions factors simulations.

Simulation Name	Foliar Dry Biomass Density (g_{dw} m^{-2})	Emission Factor (μg $g_{dw}{}^{-1}$ h^{-1})					
		Isoprene (T+L)	MTS (T+L)	MTP (T)	SQT (T)	OVOC (T+L)	Leaf Type
VEG_Celtis Australis	407	0.087	0.365	0.452	0	0.017	Deciduous
VEG_Maximum emissions factors	1340	133.05	43.507	53.825	2	10	Deciduous

3. Results

This section is divided into three parts showing the effects of vegetation on air quality, mainly on O_3, NO_2, and PM10 air concentrations, due to the following: (i) meteorology (MET) and BVOC emissions (BVOC), separately, for present vegetation (Section 3.1); (ii) changes in the BVOC emissions factors of present vegetation (BVOCCA, BVOCMAX) (Section 3.2); and (iii) addition of new vegetation (FUT) that changes both meteorology and BVOC emissions (Section 3.3). All of the effects are compared to the overall effects of present vegetation through both meteorology and BVOC emissions reconstructed by the VEG simulation, and the results are shown on a monthly basis for July 2015, with January shown only in the Supplementary Materials.

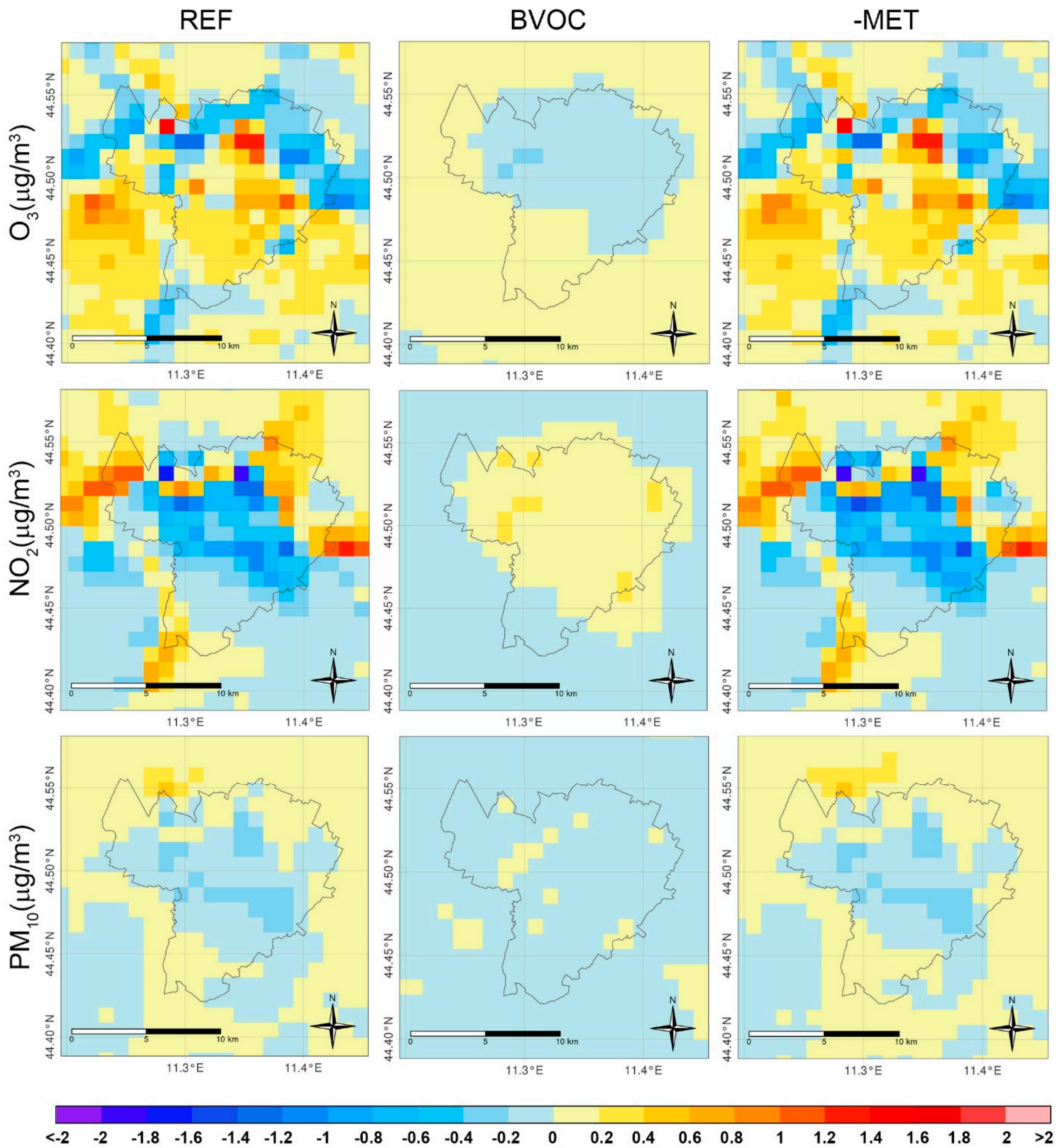
3.1. Impact of Meteorology and BVOC Emissions

Figure 2 illustrate the impact of vegetation on O_3, NO_2, and PM10 air concentrations in Bologna and Milan for July 2015. These figures show the monthly averages of the REF, BVOC, and (-MET) indicators; increases in concentrations (positive values) are depicted in red, while decreases (negative values) are shown in blue. In both cities, the meteorology (-MET) has a higher impact on concentrations compared to BVOC emissions. Specifically, the -MET values are an order of magnitude higher than the BVOC values for O_3 and NO_2. As explained in [11] by Mircea et al. (2023), the O_3 and NO_2 concentrations exhibit opposite behaviours: O_3 concentrations increase where NO_2 concentrations decrease, and vice versa. This pattern is evident across all three indicators shown.

In Milan, the (-MET) effect contributes to a decrease in O_3 almost throughout the city, with reductions of up to approximately -2.36 mg/m^3 (Table 4a). This decrease in O_3 is associated with a corresponding increase in NO_2, reaching up to 2.16 mg/m^3, due to O_3 consumption (more details in [11]).

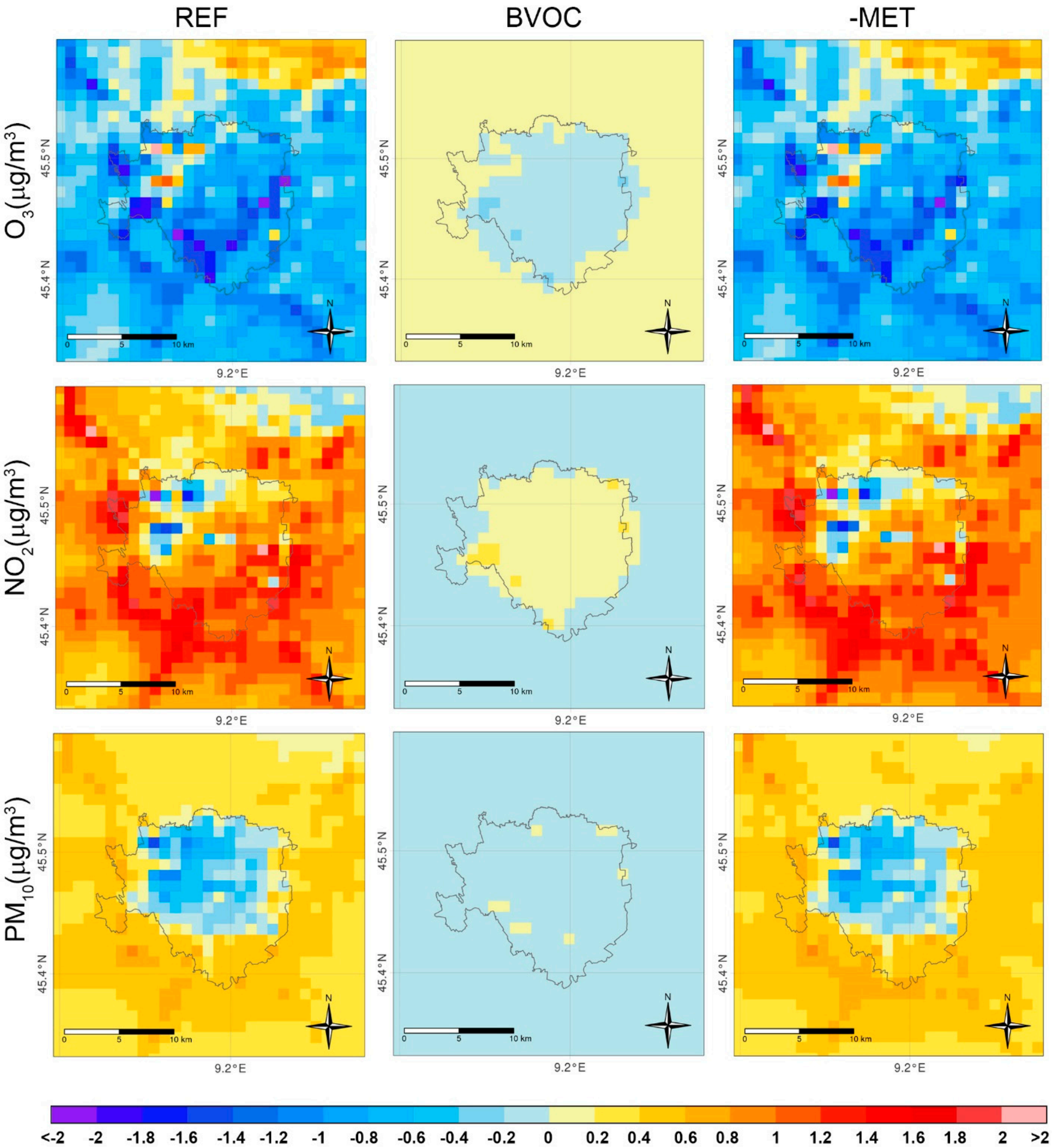
In Bologna, the decrease in ozone is observed primarily in the northern part of the city, in correspondence to the highway traffic emissions, since ozone is destroyed by NO_2 titration. The conditions most conducive to titration occur when there is weak diffusion within a thin planetary boundary layer (PBL), which allows for the accumulation of emitted pollutants. Vegetation contributes to this effect by lowering the wind speed (Figure 3 in [10]) and reducing the PBL height (Figure S3 in [11]), with these effects being more pronounced in summer than in winter, because most plants in the considered cities are deciduous broadleaved species. This phenomenon is particularly evident during summer due to the peak of vegetation abundance, which reduces soil heating and, consequently, lowers sensible heat transfer to the atmosphere, thereby mitigating the heat island effect.

Both BVOC and (-MET) show a decrease in PM10 concentrations in both cities, with a more significant impact from (-MET) and a greater reduction in Milan compared to Bologna. The meteorology has a more substantial effect on PM10 concentrations than BVOC emissions. In Milan, during July, (-MET) results in a PM10 concentration decrease of up to -1.56 mg/m^3, compared to a reduction of -0.06 from BVOC emissions (Table 4a). In January (Figure S1), the decrease in PM10 is even higher, reaching up to -3.14 mg/m^3. This happens because the effect is proportional to the concentration value, and the highest concentrations typically occur in winter in the Po Valley area ([18–21]).



(**a**)

Figure 2. *Cont.*



(**b**)

Figure 2. (**a**) Average monthly variability in O_3, NO_2, and PM10 air concentrations differences (REF, BVOC, MET) ($\mu g/m^3$) due to vegetation over the city area for July 2015 in Bologna. (**b**) As (**a**), for Milan.

In July, for all three pollutants, vegetation influences concentrations more significantly through meteorology than through BVOC emissions in both cities. Specifically, for the same meteorological conditions, BVOC emissions lead to a decrease in O_3 and PM10 concentrations of up to -0.27 mg/m^3 and -0.06 mg/m^3, respectively, and an increase in NO_2 concentrations of up to 0.34 mg/m^3. It is noteworthy that, in Bologna, the average O_3 concentration is zero despite significant variability in the city area (Table 4a). In both cities, the effect of BVOC emissions during winter (January) on the concentrations of all pollutants on a monthly basis is negligible, as shown in Table S1.

The monthly cumulated dry deposition differences are higher for (-MET) compared to BVOC for all three pollutants in both cities, regardless of the time of the year (Table 4b, Table S2). In addition, these differences are more pronounced in July than in January, mirroring the pattern observed for concentration differences (Table 4a, Table S1). This trend occurs because, by definition, the deposition is directly proportional to concentration.

Table 4. REF, BVOC, MET indicators due to vegetation over the city area for July 2015. (**a**) Average monthly variability in O_3, NO_2, and PM10 air concentration differences (µg/m^3). (**b**) Variability in O_3, NO_2, and PM10 monthly cumulated dry deposition differences (kg/km^2).

(a)

Indicator City	Pollutant Concentration (µg/m^3)	REF	-MET	BVOC	REF	-MET	BVOC	REF	-MET	BVOC
		min	avg	max	min	avg	max	min	avg	max
	O_3	−1.36	0.00	1.45	1.52	0.04	−1.30	−0.26	−0.04	0.03
Bologna	NO_2	−1.82	−0.19	1.11	1.11	−0.26	−1.98	−0.03	0.07	0.34
	PM10	−0.39	−0.07	0.13	0.17	−0.05	−0.38	−0.04	−0.01	0.01
	O_3	−2.45	−0.86	2.66	2.64	−0.82	−2.36	−0.27	−0.04	0.07
Milan	NO_2	−3.01	0.63	2.26	2.16	0.58	−3.01	−0.08	0.05	0.32
	PM10	−1.59	−0.09	0.72	0.76	−0.07	−1.56	−0.06	−0.02	0.01

(b)

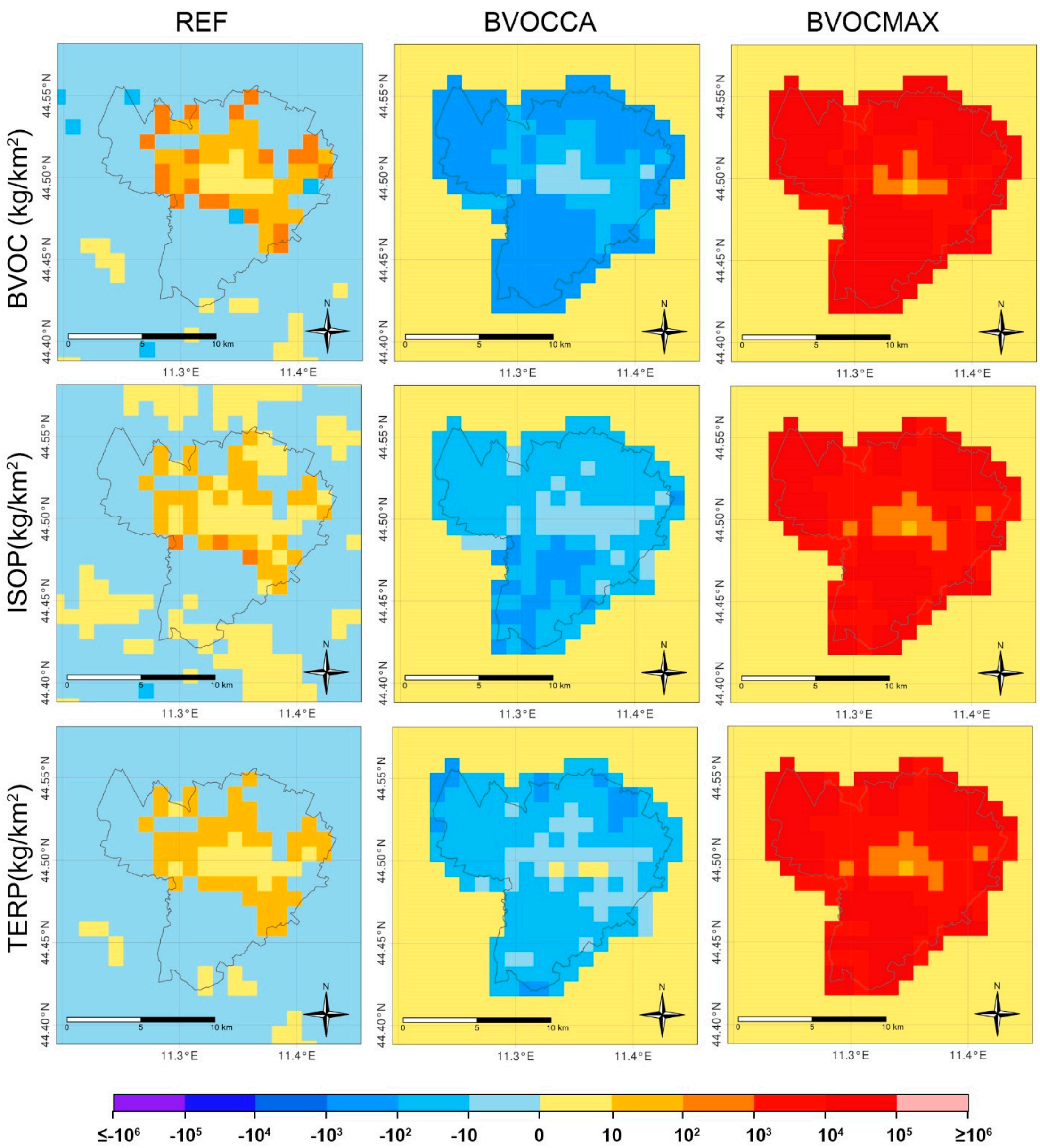
Indicator City	Pollutant Dry Deposition (kg/km^2)	REF			-MET			BVOC		
		min	avg	max	min	avg	max	min	avg	max
	O_3	−22.96	85.64	524.27	−525.38	−85.83	22.86	−1.35	−0.18	0.37
Bologna	NO_2	−3.21	18.08	132.63	−132.12	−17.87	3.52	−0.06	0.21	1.01
	PM10	−15.92	17.66	88.48	−89.50	−17.87	15.75	−1.24	−0.21	0.68
	O_3	−38.61	134.46	561.35	−563.22	−134.68	38.53	−1.86	−0.22	0.36
Milan	NO_2	−0.51	25.17	82.08	−81.86	−25.06	0.68	−0.25	0.11	1.08
	PM10	−65.44	98.63	256.62	−256.86	−98.77	65.1	−1.26	−0.14	0.7

The amount and distribution of the monthly sum of BVOC, ISOP, and TERP emissions, which contribute to changes in pollutant concentrations (Figures 2 and S1), are shown in the first two columns of Figure 1a,b [11]. Comparing Figure 1b in [11] with Figure 2, it is evident that the distribution patterns of BVOC, ISOP, and TERP emissions do not resemble the patterns of pollutant concentrations displayed in the latter, despite their high values during summer. A similar observation was made for January, comparing Figure 1a in [11] to Figure S1, although this was somewhat expected due to the significantly lower BVOC emissions during winter. Thus, on monthly basis, in both summer and winter, O_3, NO_2, and PM10 concentrations exhibit minimal variability due to vegetation emissions; the local effect of BVOC emissions is counterbalanced by physical and chemical processes. However, it is worth noting a slight increase in PM10 concentrations in the northeastern part of Bologna (Figure 2a), corresponding to an area with increased TERP emissions, more evident in January than in July: Figure 1a in [11] vs. Figure 2a.

3.2. Impact of Different BVOC Emissions

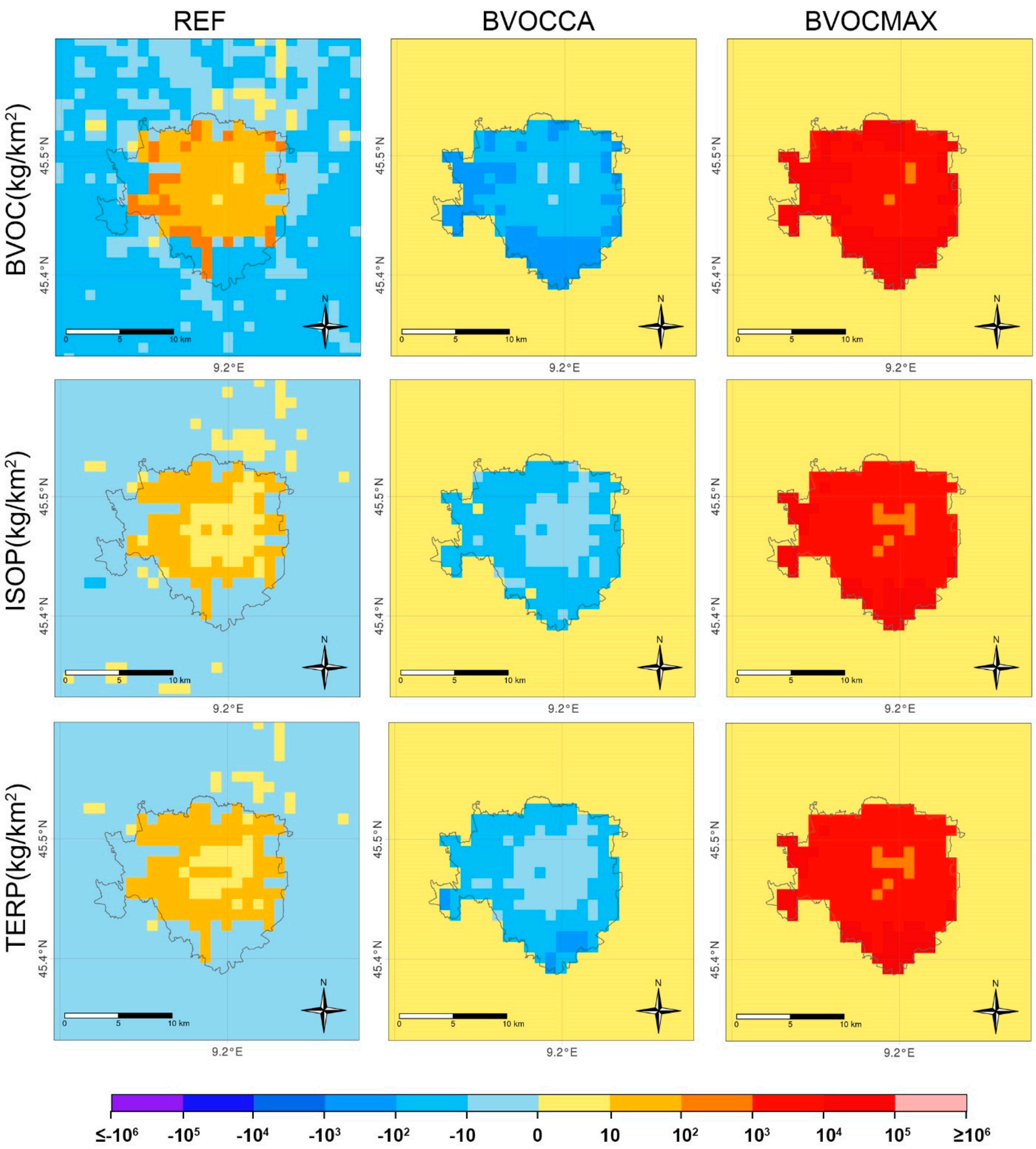
Figure 3 illustrate the monthly sum of BVOC emissions differences (expressed in kg/km^2) for July 2015 in Bologna and Milan, respectively. The three columns correspond to the three indicators presented in Table 2: REF, BVOCCA, and BVOCMAX. From top to bottom, the spatial distributions of BVOC (aggregated BVOC emissions), ISOP (isoprene), and TERP (aggregated terpene emissions) are shown. In both cities, BVOCCA generally shows negative values for all three BVOC compounds (Table S5), indicating that emissions would be lower if all vegetation was replaced by Celtis Australis compared to the actual vegetation considered in REF. This can be explained by two factors: first, Celtis Australis does not have very high emissions factors for any BVOC compound (as shown in Table 3). Second, although it is the most frequent species in both cities, Celtis Australis does not constitute a large fraction of the total vegetation (as seen in the second column of Figure 1—the BVOCCA fraction is an order of magnitude lower than the REF fraction). Consequently, the BVOCCA simulation replaces a large portion of the diverse vegetation with a single species that has lower BVOC emission factors.

In January, the BVOCCA differences for BVOC emissions are nearly negligible in both cities. However, in July, there is a significant decrease, with the total local BVOC reduction reaching up to 778.53 kg/km^2 in Milan and 708.20 kg/km^2 in Bologna (as reported in Table S5). The observed decreases (as shown in Figure 3) are minimal in the central areas of both cities and become more pronounced near the municipal borders. This pattern is evidently proportional to the vegetation fraction (Figure 2 in [10]). A similar trend can be observed for TERP and ISOP, although the decrease for these compounds is generally an order of magnitude lower than that for BVOC (as also indicated in Table S5). This suggests that while Celtis Australis contributes to a reduction in emissions, its impact varies depending on the type of BVOC and the location within the city.



(**a**)

Figure 3. *Cont*.



(**b**)

Figure 3. (**a**) Monthly sum of BVOC emissions differences (kg/km^2) for the REF (left column), BVOCCA (central column), and BVOCMAX (right column) indicators, as defined in Table 2. The rows show the total BVOC emissions (upper panel), isoprene (ISOP) (middle panel), and terpenes (TERP) (bottom panel) emissions for July 2015 in Bologna. (**b**) As (**a**), for Milan.

In contrast to BVOCCA, the BVOCMAX differences in biogenic emissions show substantial local increases in both cities. These increases are noticeable in January, when Bologna experiences a rise over 10 kg/km^2, and even more dramatically in July, with spikes of up to approximately tonnes/km^2 for total BVOC emissions. Similar to BVOCCA, the BVOCCMAX emission differences also show a distribution that varies from the city centre towards the municipal boundaries, albeit with an opposite sign, indicating an increase rather than a decrease.

Notably, the emission differences for all three compounds (BVOC, ISOP, TERP), for both BVOCCA and BVOCMAX, are up to an order of magnitude higher in Bologna compared to Milan (as shown in Table S5). This significant difference is likely due to a combination of factors. While the different meteorological conditions of each city may play a role, the larger impact is likely due to the differences in the amount of vegetation (in terms of both area and LAI). Given that these differences were produced by simulations that applied the same emission factor to a single species at a time, the variation underscores how vegetation density and distribution significantly influence BVOC emissions.

Figure 4 shows the impact of vegetation emission factors on O_3, NO_2, and PM10 air concentrations in Bologna and Milan for July 2015, presented as monthly averages for the REF, BVOCCA, and BVOCMAX indicators. At first glance, it is evident that a decrease in BVOC emissions (as shown in BVOCCA) leads to a corresponding decrease in O_3 and PM_{10} concentrations across the entire city areas. Conversely, an increase in BVOC emissions (as seen in BVOCMAX) results in an increase in these pollutant concentrations. The behaviour of NO_2 air concentrations shows distinct patterns in Milan and Bologna in response to changes in BVOC emissions. In Milan, NO_2 concentrations increase with reduced BVOC emissions (BVOCCA) and decrease with higher BVOC emissions (BVOCMAX), displaying a consistent pattern across the city. However, in Bologna, the response is more complex, with alternating areas of increased and decreased NO_2 concentrations for both indicators.

Additionally, a significant difference between BVOCCA and BVOCMAX is in the magnitude of the concentration changes. BVOCCA results in concentration differences that are two orders of magnitude lower than those observed in BVOCMAX for all three pollutants in July. This suggests that while reducing BVOC emissions has a relatively minor impact on pollutant levels, increasing BVOC emissions significantly elevates concentrations of O_3 and PM_{10}.

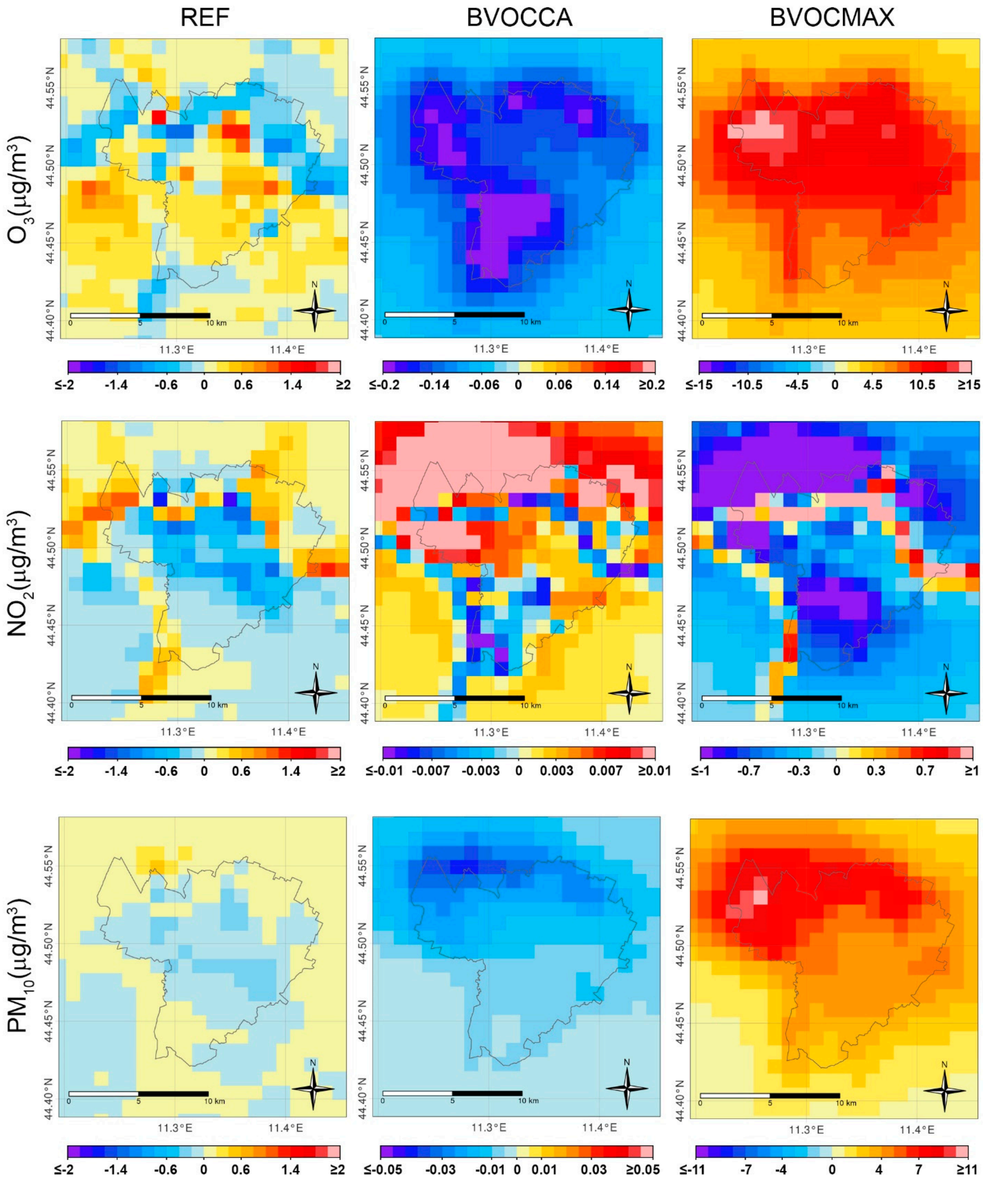
On the other hand, BVOCMAX leads to an average increase in O_3 concentrations of approximately 11.01 $\mu g/m^3$ in Bologna and 8.20 $\mu g/m^3$ in Milan (Table S6). Similarly, PM10 concentrations increase by about 5.94 $\mu g/m^3$ in Bologna and 4.36 $\mu g/m^3$ in Milan (Table S6). The higher increase in Bologna can be attributed to higher BVOC emissions in the city (Table S5). When comparing the last map in Figure 4 with Figure S4, it becomes evident that the increase in PM_{10} concentrations under BVOCMAX is primarily due to the formation of biogenic organic aerosols (AORGs), also known as secondary organic aerosols (SOAs), in the atmosphere. Conversely, BVOCCA, with reduced BVOC emissions, results in less AORG formation and, consequently, lower PM_{10} concentrations. In the REF scenario, where the combined effects of vegetation on meteorology and BVOC emissions are considered, the impact on PM_{10} concentrations via AORG formation is less clear, indicating that other factors might also play a role.

The decrease in NO_2 concentrations due to increased BVOC emissions (BVOCMAX) is considerably smaller compared to the changes observed for O_3 and PM_{10}. Specifically, NO_2 concentrations decrease by only -0.40 $\mu g/m^3$ in Bologna and -0.81 $\mu g/m^3$ in Milan under the BVOCMAX scenario.

The impact of vegetation emission factors on O_3, NO_2, and PM10 concentrations is almost negligible during January for both BVOCA and BVOCMAX in both cities. Even during July, the effects are minimal for BVOCCA (Table S6). In January, the differences in the spatial distribution of concentration changes between the pollutants within the same city are negligible, with minimal variation between the two cities for the same pollutant (Figure S4). This suggests that the influence of BVOC emissions on air quality is significantly reduced in winter, likely due to lower temperatures and reduced vegetation activity. The number of evergreen trees is very limited in both cities.

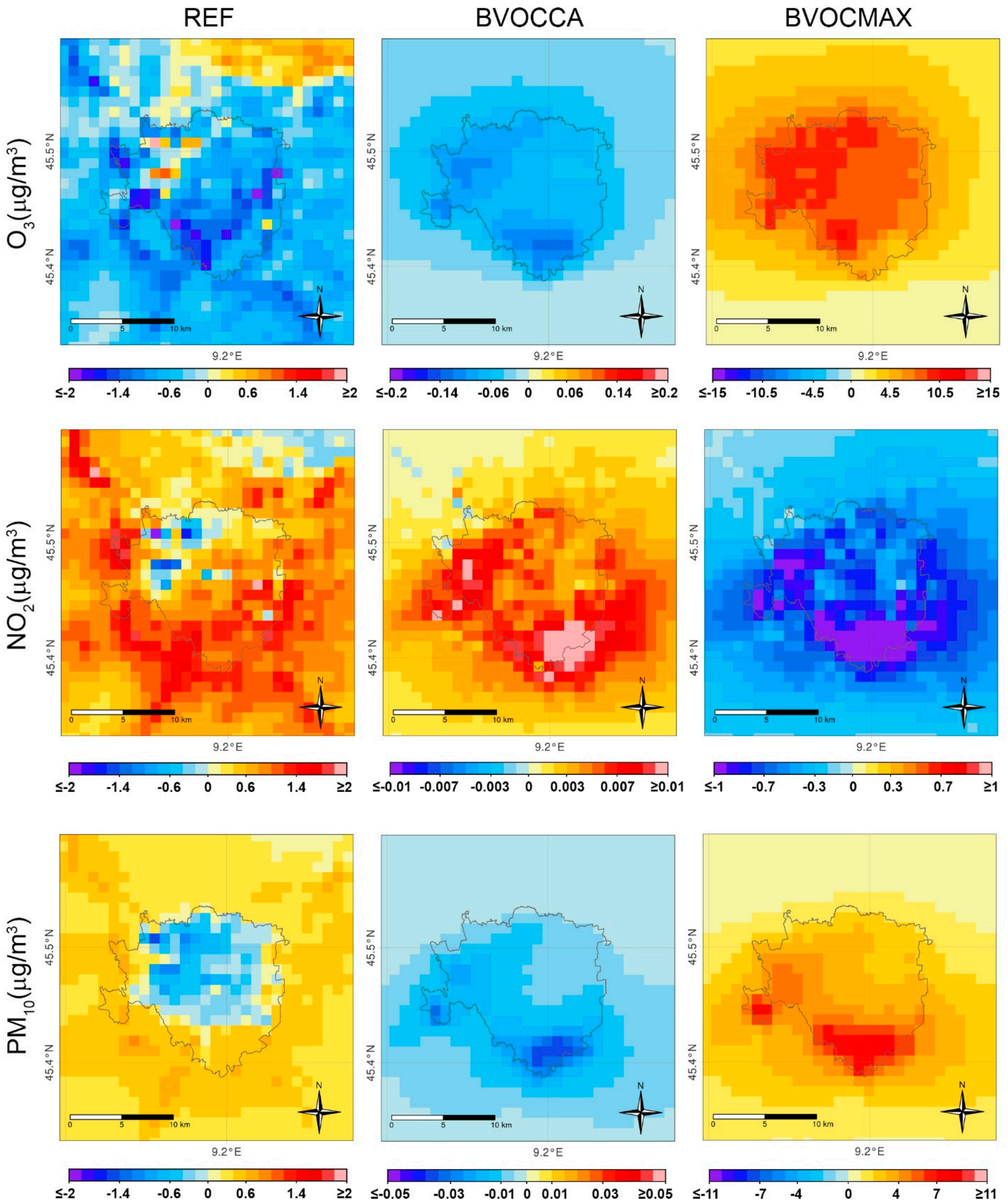
Since the depositions are strongly related to concentrations, the variability in monthly cumulated dry deposition differences (kg/km^2) for O_3, NO_2, and PM10 under the BVOCCA and BVOCMAX scenarios mirrors the patterns seen in average concentrations. Specifically, in January, both cities show almost no variability in these deposition differences, and only very low values are observed in July for BVOCCA (Table S7). In July, under the BVOCMAX scenario, while the concentration variability is highest for O_3 and PM10 (Table S6), the variability in dry deposition is highest for O_3 and NO_2. However, PM10 dry deposition still shows significant variability.

For all three pollutants, the REF scenario exhibits much higher variability in monthly cumulated dry deposition differences compared to BVOCCA and BVOCMAX. This is primarily because the REF simulation includes changes in meteorology, which has the most significant impact on deposition changes (Table 4b, Tables S1 and S2). This highlights the dominant role of meteorological conditions in driving variations in pollutant deposition, compared to the relatively minor contributions from changes in BVOC emissions alone.



(**a**)

Figure 4. *Cont.*



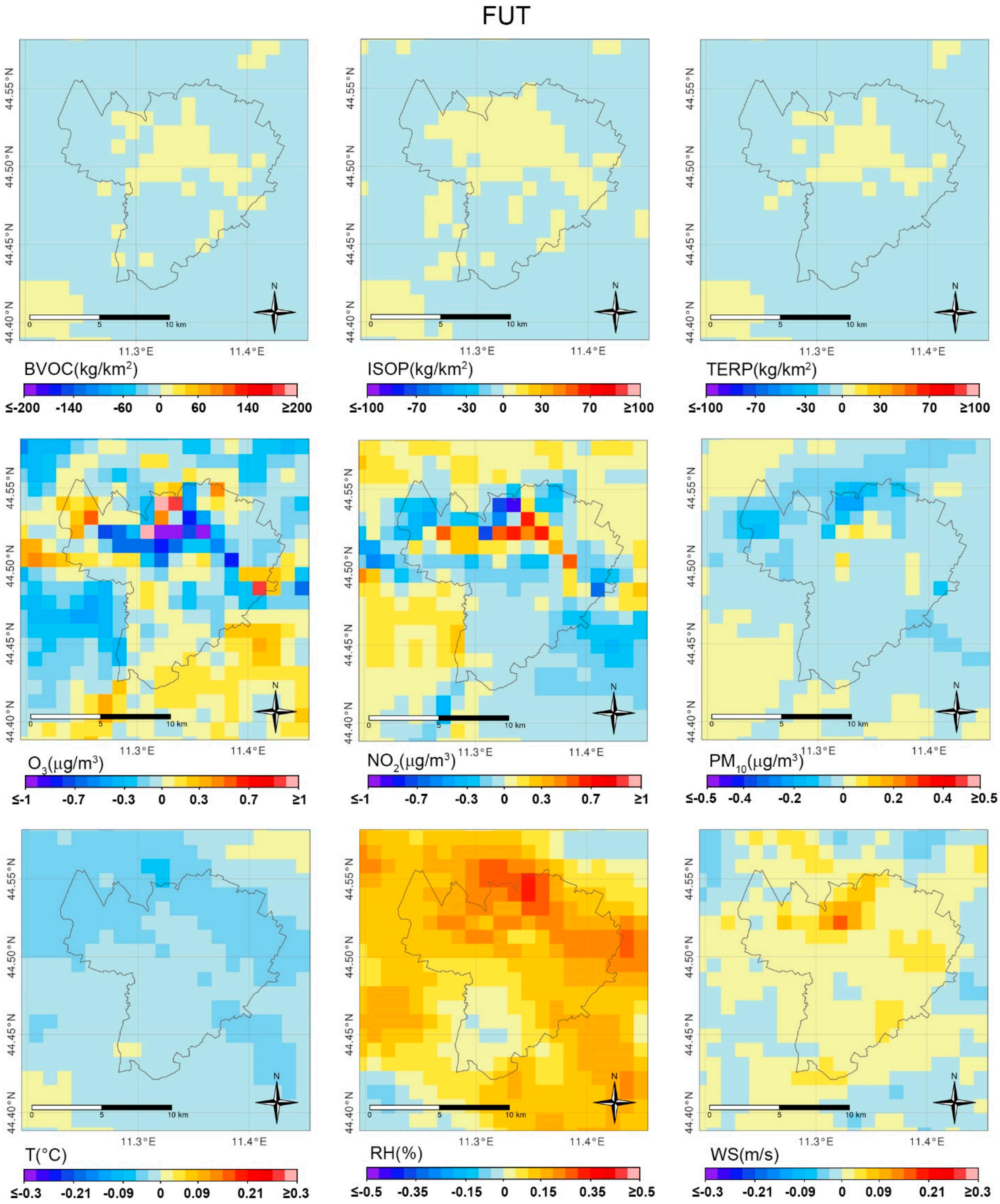
(**b**)

Figure 4. (**a**) Average monthly spatial variability in O_3, NO_2, and PM10 air concentration differences (REF, BVOCCA, BVOCMAX) (μg/m^3) due to different vegetation emission factors over the city area for July 2015 in Bologna. (**b**) As (**a**), for Milan.

3.3. Impact of Future Vegetation

Figure 5 illustrate the impact of adding new vegetation to the urban areas of Bologna and Milan in July 2015, with a focus on BVOC emissions, air pollutant concentrations, and meteorological variables. In the first row (BVOC emissions), the monthly sum of BVOC emissions differences (expressed in kg/km^2) for total BVOC compounds, isoprene (ISOP), and terpenes (TERP) is shown; the second row (air concentrations) shows the monthly averages of O_3, NO_2, and PM10 air concentration differences; the third row presents the monthly average differences in temperature (T), relative humidity (RH), and wind speed

(WS). As new vegetation, the urban vegetation fraction corresponding to FUT in Figure 1 (third column) was considered.



(**a**)

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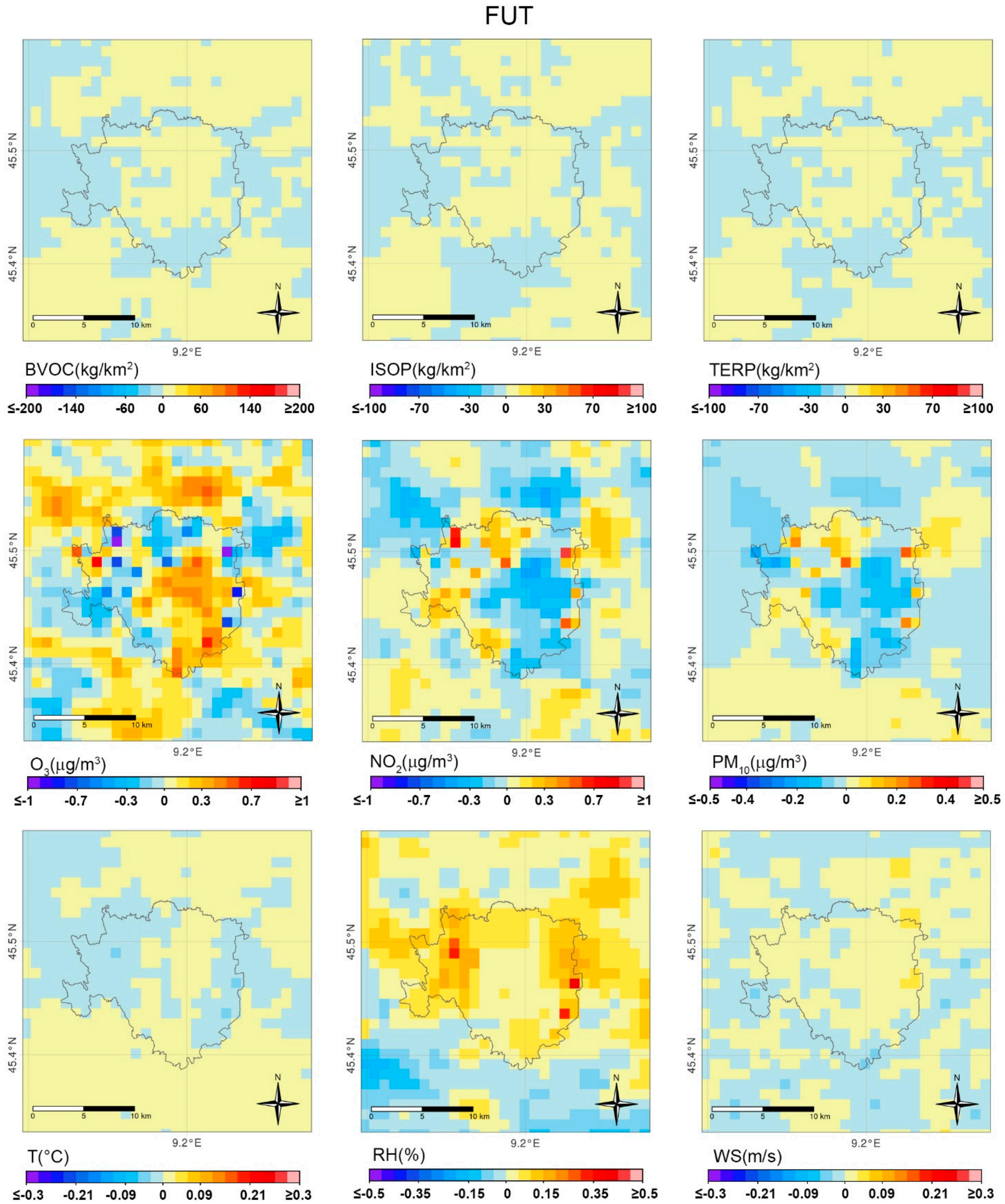

(**b**)

Figure 5. (**a**) FUT: monthly sum of emission differences for BVOC, ISOP, and TERP (kg/km^2) (upper panel); average monthly spatial variability in O_3, NO_2, and PM10 air concentrations differences (mg/m^3) (middle panel); and differences in temperature (T (C)), relative humidity (RH(%)), and wind speed (WS (m/s)) (bottom panel) for July 2015 in Bologna. (**b**) As (**a**), for Milan.

In Bologna, the highest differences in all variables shown (emissions, concentrations, and meteorology) correspond to the area designated for new vegetation in the FUT scenario, in the northern half of the city. In Milan, the impact of new vegetation is less visible inside the urban texture, particularly on meteorology, due to the limited spatial extension of the areas where new trees are planned to be planted. Effects on BVOC emissions and concentrations can be noticed over areas affected by the VEG1 intervention in the south, southeast, and northwest parts of the city. This is due to the significant extension of the areas and the number of trees to be planted there. The reduction in BVOC emissions over parts of these areas is due to the partial substitution of grass or agriculture cover with low-emission tree species.

In January, the effects of vegetation on the monthly sum of BVOC, isoprene (ISOP), and terpene (TERP) emissions in both Bologna and Milan are minimal, particularly for ISOP. However, Bologna exhibits higher emissions differences for BVOC and TERP compared to Milan (Table S8). During this month, the hypothetical FUT vegetation scenario has a more pronounced impact on temperature (T) and relative humidity (RH) in Bologna than in Milan.

When comparing the statistics of air pollutant concentrations and dry deposition differences between the two cities for a given month (as seen in Table 5 vs. Table S8), the values are generally comparable. However, the impact of vegetation on these variables is much greater in summer than in winter. This is particularly evident in the emissions differences, which are two orders of magnitude higher in summer compared to winter. This seasonal disparity underscores the heightened sensitivity of urban air quality and meteorological conditions to vegetation changes during the warmer months.

Table 5. FUT: Average monthly variability in temperature (T), relative humidity (RH), and wind speed (WS) differences; average monthly variability in concentration (c) and dry deposition (d) differences of O_3, NO_2, and PM10; monthly sum of emissions differences for BVOC, ISOP, and TERP for July 2015 in Bologna and Milan. Minimum and maximum values in the urban area are also shown, in addition to the average in bold, as min/avg/max.

City	Meteorology			BVOC Emission (kg/km^2)			Pollutant			
	T (°C)	RH(%)	WS(m/s)	BVOC	ISOP	TERP	min/avg/max	O_3	NO_2	PM10
Bologna	−0.06 **0.03** 0.00	0.01 **0.14** 0.33	0.02 **0.20** 0.15	−499.04 **−16.63** 185.24	−11.59 **11.24** 242.78	−144.63 **−6.48** 32.01	c (μg/m^3)	−1.52 **−0.07** 1.18	−0.99 **−0.05** 0.70	−0.23 **−0.03** 0.06
							d (kg/km^2)	−142.25 **12.21** 167.65	−17.73 **7.15** 65.58	−10.91 **0.38** 42.30
Milan	−0.05 **0.00** 0.02	−0.01 **0.08** 0.42	−0.04 0.01 0.05	−334.78 **−17.09** 138.86	−29.13 **−0.90** 36.20	−86.56 **−4.26** 43.63	c (μg/m^3)	−1.37 **0.05** 0.71	−0.45 **−0.03** 0.98	−0.24 **−0.03** 0.30
							d (kg/km^2)	−74.36 **7.81** 152.55	−8.20 **2.12** 30.88	−25.18 **0.64** 29.11

Overall, this monthly analysis shows that FUT's effects on meteorology are negligible (below 1 for each variable except RH in Bologna in January—Table S8) and do not substantially increase the air concentrations; on average, the differences are below 1 μg/m^3 even in July. Overall, the increase in deposition compensates for the increase in emissions (Table 5).

4. Discussion

The results shown in Section 3.1 (REF, BVOC, MET indicators), Section 3.2 (BVOCCA and BVOCMAX), and Section 3.3 (FUT) for July 2015 provide a comprehensive quantification of the effects of urban vegetation, through meteorology and atmospheric chemical and physical processes, on air pollution for Bologna and Milan. This study focuses specifically on the urban areas of the two cities, examining the effects on a monthly basis for T, RH, and WS (meteorological quantities); O_3, NO_2, and PM10 atmospheric concentrations and depositions; and BVOC, ISOP, and TERP emissions (chemical and physical quantities). The same analysis was performed for January 2015 and is shown in the Supplementary Materials.

The comparison between the BVOC, BVOCCA, and BVOCMAX simulations illustrates the effects of varying vegetation emission factors for existing vegetation (BVOC), the assumption that all vegetation is Celtis Australis (BVOCCA), and the hypothesis that all vegetation emits BVOCs at the maximum levels recorded in the database (BVOCMAX). The vegetation extent and distribution within the city remain consistent across all three indicators, as do the meteorological data. As anticipated, reducing the emission factors (from BVOC to BVOCCA) results in a decrease in biogenic emissions (see Table S5). This reduction in emissions leads to a corresponding decrease in the atmospheric concentrations of O_3 and PM10, while the effect on NO_2 concentrations is negligible on average (see Table S6), particularly in Bologna. This reduction is comparable to the decrease observed with BVOC (Table 4a), suggesting a benefit in the widespread use of Celtis Australis in urban green projects, even if only effects due to emissions are considered in the BVOCCA simulation. In contrast, BVOCMAX leads to a significant increase in O_3 and PM10 concentrations in both cities, but this effect is only notable in July (Table S6). Changes in emission factors in BVOCCA and BVOCMAX do not affect air pollutant concentrations in January, since vegetation activity is reduced during winter, and because most plants in the considered cities are deciduous broadleaved species. The relationship between O_3 concentration and vegetation emission factors is more pronounced during summer due to higher biogenic emissions and the more intense O_3 formation processes, which are strongly influenced by sunlight intensity and air temperature. Reactions of BVOCs with oxygen radicals (·OH and $\cdot O_2$) generate radicals that enhance O_3 production in the presence of urban NO_X. However, the reduction in NO_2 concentrations is significantly lower than the increase in O_3 for BVOCMAX, while it is comparable for BVOC and BVOCCA.

A similar pattern can be observed for PM10, as the amount of SOAs formed is directly related to the amount of BVOC emissions.

Using the same meteorological conditions, Maison et al. [13] simulated the air quality in Paris during June–July, incorporating BVOC emissions from a detailed tree inventory. Their simulations revealed that changes in BVOC emissions led to an increase in SOAs of up to approximately 0.5 $\mu g/m^3$ (Figure 10 in Maison et al. [13]), and in O_3 concentrations of up to about 1 $\mu g/m^3$ (Figure 12 in Maison et al. [13]). Conceptually, these results are directly comparable to those obtained with BVOCCA and BVOCMAX, which also utilised the same REF meteorology. However, the effects of vegetation on PM10, SOAs, and O_3 differ due to variations in the emission factors used (more details in Section 2). Nonetheless, BVOCMAX confirms that increased BVOC emissions lead to higher PM10 levels, through increased SOA formation (Figure S4), and elevated O_3 concentrations across both cities (Figure 4). Therefore, a more comprehensive understanding of tree species and their emission factors is crucial for accurately estimating air pollutant concentrations in urban areas.

The effects of vegetation on air concentrations through meteorology are embedded in the REF and FUT indicators and are explicitly illustrated by the (-MET) indicator. As demonstrated in Table 4a, Figures 2 and 6, (-MET) is the main indicator responsible for the variability in pollutant concentrations observed in the REF indicator across the city areas, as monthly averages, in both Bologna and Milan ((-MET) is almost equal to REF). It is noteworthy that the variability in O_3, NO_2, and PM10 concentrations for FUT is comparable with that observed in REF for Bologna, whereas it is significantly lower in Milan. This disparity may be attributed to the nature of the planned interventions, suggesting that the impact of the city's characteristics in Milan is similar to that in Bologna when comparing the meteorological effects of vegetation: (-MET) vs. REF. These results confirm the established significance of meteorology in influencing air quality [22] and highlight the critical role of vegetation in meteorological models [10,23,24]. While vegetation typically has a lower albedo compared to bare soil, leading to greater absorption of sunlight and surface warming, the overall effect can be cooling. This is due to the processes of diurnal transpiration and evapotranspiration, which absorb latent heat and release water vapour into the atmosphere. From the perspective of atmospheric diffusion, this implies a reduced capacity for atmospheric dispersion, leading to higher concentrations of PM and NO_2, especially during summertime daylight hours. Conversely, during nighttime under clear sky conditions, the release of latent heat from condensation within the canopy enhances atmospheric diffusivity, which, in turn, reduces the concentrations of NO_2 and PM. The presence of trees modifies surface roughness, increasing mechanical turbulence and thereby enhancing dry deposition fluxes. In essence, vegetation influences air quality locally through various meteorological processes, particularly altering turbulence, wind patterns, and the exchange of heat and moisture. The net effect of vegetation on air quality can sometimes be ambiguous, as two opposing phenomena may occur: for instance, during periods of strong insulation, the vegetation can reduce atmospheric diffusivity, leading to higher pollutant concentrations; on the other hand, the presence of vegetation can enhance dry deposition effectiveness due to increased surface roughness, thereby reducing concentrations. Additionally, vegetation induces non-local effects by altering atmospheric circulation patterns, such as modifying the urban heat island. The variability in meteorological conditions within the urban areas of the two cities investigated was discussed in detail in [10] and is further presented here in Section 3.3 for the FUT scenarios. The variability observed between grid cells arises from differences in vegetation characteristics and city morphology, affecting local microclimates (such as temperature, humidity, and wind conditions), and from transport processes between the cells, influenced by larger-scale atmospheric circulation.

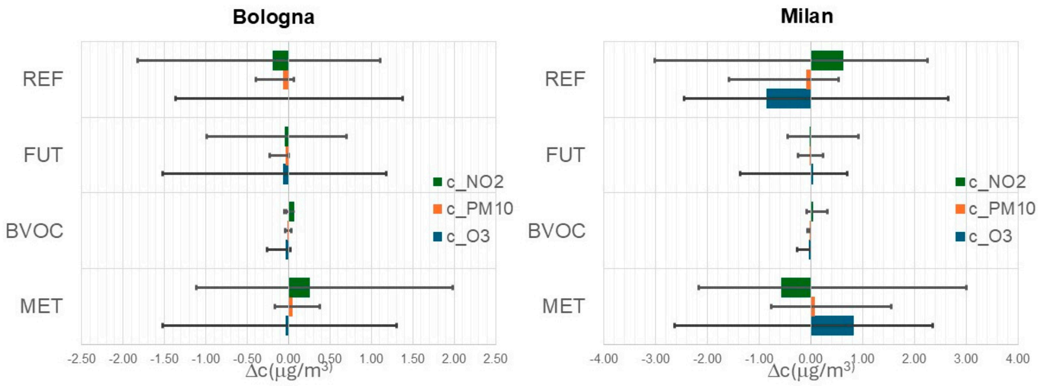

Figure 6. Intercomparison of average monthly variability in O_3, NO_2, and PM10 air concentration differences ($\mu g/m^3$) for the REF, FUT, BVOC, and MET indicators in the two cities for July 2015.

Changes in air pollutant concentrations affect dry deposition rates: higher concentrations generally lead to higher depositions, provided the meteorological conditions remain unchanged. However, when considering the effects of vegetation on meteorology, the increase in pollutant concentrations due to additional BVOC emissions may be partially balanced by enhanced removal processes associated with vegetation. Therefore, the average concentrations of pollutants, both temporally (over a month) and spatially (over the whole city area), can either increase or decrease despite changes in dry deposition rates. For example, an increase in NO_2 concentrations is observed in Milan, while a decrease is observed in Bologna, even though the dry deposition rates rise (Table 4a,b—REF). Similarly, an increase in O_3 concentrations is noted in Milan despite an increase in deposition (Table 5—FUT). The contrasting effects of urban vegetation on air quality have been analysed by Maison et al. [25] for the city of Paris, confirming a prevailing effect of the vegetation impact, mediated by its effects on atmospheric circulation and meteorology, from the city to street scales.

In addition to the findings presented in Section 3.1, the comparison between FUT and REF (Figure 6) highlights the significant role of vegetation in influencing air quality through meteorological changes. Despite the vegetation fraction increase in FUT being substantially smaller than the existing vegetation fraction in REF (Figure 1), FUT exhibits comparable variability for all three pollutants investigated in both cities. Furthermore, FUT shows enhanced pollutant removal through dry deposition, as shown by the differences between Tables 4b and 5.

Furthermore, achieving effects comparable with BVOC and MET would require the selection and planting of tree species with exceptionally high emission factors and foliar biomass densities, which may not even be available. Nevertheless, during the planning phase of urban greenery, conducting a meteo-diffusive study could be highly beneficial. Such a study could assess the impact of vegetation on local-scale meteorology and air quality, enabling the optimisation of planting distribution based on urban land-use characteristics. This approach could enhance overall urban air quality and contribute to promoting a better quality of life.

All of the results presented here demonstrate that relying solely on an average value to describe urban air quality is insufficient due to the significant variability in city characteristics and their effects on the urban atmosphere.

5. Conclusions

This study separately and collectively evaluated the effects of vegetation on air pollutant concentrations through BVOC emissions (BVOC, BVOCCA, and BVOCMAX indicators) and through meteorology (REF, FUT, and (-MET) indicators) in Bologna and Milan, for July and January 2015, representing the summer and winter seasons, respectively.

For each indicator and season, the results are generally similar qualitatively for both cities, although there are differences in the magnitude and spatial distribution of changes in air pollutant concentrations (for example, NO_2 decreased for REF and (-MET) in Figure 2).

The BVOCCA and BVOCMAX indicators demonstrate that altering emission factors by selecting plants with either lower or higher BVOC emission factors than the current vegetation can lead to a decrease or increase in O_3 concentrations, respectively. The extent of these changes depends on both the magnitude of BVOC emissions and the city's morphological characteristics. A similar behaviour can be observed for PM10 concentrations, as BVOC emissions directly contribute to the formation of SOAs. Therefore, when selecting urban vegetation, it is crucial to consider the BVOC emission factors of different plant species. Choosing plants with lower BVOC emissions can help mitigate air quality issues; alternatively, using highly emissive plants in small areas can maintain lower local BVOC emissions.

Disentangling the effects of meteorology (-MET) and BVOC emissions (BVOC) within the REF indicator showed that meteorological factors have a more significant impact on air pollutant concentrations than BVOC emissions. Assessing the effects of vegetation on air quality without explicitly considering its influence on meteorology can lead to misguided measures for improving air quality.

The FUT indicator shows that introducing new vegetation can both improve and worsen air quality in the city area compared to REF, and this is crucial for sustainable city planning considering the time required for trees to grow. Both REF and FUT highlight that, while vegetation can increase pollutant deposition, relying solely on the removal effect of vegetation is insufficient. An increase in deposition does not always translate to a reduction in air pollutant concentration, underscoring the need for a comprehensive approach that considers both the benefits and limitations of vegetation in urban air quality management.

Generally, all indicators and quantities evaluated here exhibit more significant changes in summer than in winter, as anticipated; however, when the effects on meteorology are also considered, as with the REF and FUT indicators, the changes during winter are not negligible.

The significantly variability in meteorology and chemistry across the city area (and over time, as shown in [10,11]) revealed in this study underscores the need for a more localised approach, rather than relying on city-wide average values for relevant quantities. Adopting a city-area-based approach is crucial to avoid potentially negative impacts on human health and vegetation, which could arise from further urban development or shifts in emission patterns due to the implementation of new technologies. Moreover, a combination of city-scale and street-level analysis is needed to identify the urban circulation and air quality changes induced by urban greening policies, and to complement them with the assessment of local impacts of the species planted within the street canyons, modifying local shading and dispersion conditions at a resolution that is not achievable for models covering the whole urban area.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/atmos15121511/s1: Figure S1 (as Figure 2) (a). Average monthly variability of O_3, NO_2, and PM10 air concentrations differences (REF, BVOC, MET) (µg/m^3) due to vegetation over the city area for January 2015 in Bologna. (b). As (a) for Milano; Figure S2 (as Figure 3) Monthly sum of BVOC emissions differences for REF (left column), BVOCCA (central column) and BVOCMAX (right column) indicators as defined in Table 2. The rows show the total BVOC emissions (upper panel), isoprene—ISOP (middle panel) and terpenes—TERP (bottom panel) emissions for January 2015 in Bologna. (b). As (a) for Milan; Figure S3 (as Figure 4) (a). Average monthly variability of O_3, NO_2, and PM10 air concentrations differences (REF, BVOCCA, BVOCMAX) (µg/m^3) due to vegetation over the city area for January 2015 in Bologna. (b). As (a) for Milano; Figure S4 Average monthly variability of aerosol organic (AORG) concentrations differences (REF, BVOCCA, BVOCMAX) (µg/m^3) due to vegetation over the city area for July 2015 in Bologna (top row) and Milan (bottom row); Figure S5 (as Figure 5) (a FUT: monthly sum of emissions differences for BVOC, ISOP and TERP (upper panel); average monthly variability of O_3, NO_2, and PM10 air concentrations differences (µg/m^3) (middle panel), and difference of temperature (T (C)), relative humidity(RH(%)) and wind speed (WS(m/s)) (bottom panel) for January 2015 in Bologna. (b). As (a) for Milano; Figure S6 FUT: monthly sum of BVOC emissions differences (BVOC, ISOP, TERP) (kg/km^2) for Bologna (top row) and Milan (bottom row), for January (a) and July (b) 2015; Table S1 Average monthly variability of O_3, NO_2, and PM10 air concentrations differences (µg/m^3) for REF, BVOC, MET indicators due to vegetation over the city area for January 2015; Table S2 Variability of O_3, NO_2, and PM10 monthly cumulated dry deposition differences (kg/km^2) for REF, BVOC, MET indicators due to vegetation over the city area for January 2015; Table S3. Average monthly standard deviation of O_3, NO_2, and PM10 air concentrations differences (µg/m^3) for REF, BVOC, MET indicators due to vegetation over the city area for July 2015; Table S4. Standard deviation of O_3, NO_2, and PM10 monthly cumulated dry deposition differences (kg/km^2) for REF, BVOC, MET indicators due to vegetation over the city area for July 2015; Table S5 Variability of monthly sum of BVOC, ISOP and TERP emission differences (REF, BVOCCA, BVOCMAX) (kg/km^2) for January and July 2015 in Bologna and Milan; Table S6 Average monthly variability of O3, NO2, and PM10 air concentrations differences (REF, BVOCCA, BVOCMAX) (µg/m^3) due to vegetation over the city area for January and July 2015; Table S7 Variability of O_3, NO_2, and PM10 monthly cumulated dry deposition differences (kg/km^2) for REF, BVOCCA and BVOCMAX indicators due to vegetation over the city area for January and July 2015; Table S8. FUT: Average monthly variability of temperature (T), relative humidity (RH) and wind speed (WS) differences; average monthly variability of concentrations (c) and dry depositions (d) differences of O_3, NO_2, and PM10; monthly sum of emissions differences for BVOC, ISOP and TERP for January 2015 in Bologna and Milan. Minimum and maximum values in the urban area are also shown in addition to the average in bold as min/avg/max.

Author Contributions: Conceptualisation, G.B. and M.M.; methodology, G.B. and M.M.; software, A.C., G.B., G.C. (Giuseppe Carlino), G.C. (Giuseppe Cremona), M.D., S.F., R.P., F.R. and C.S.; formal analysis, G.B. and M.M.; investigation, G.B., G.C. (Giuseppe Carlino), M.D., M.M., S.F., R.P., F.R. and C.S.; resources, G.C. (Giuseppe Cremona), M.D., S.F., M.M., F.R. and C.S.; data curation, G.B., M.D., M.M. and F.R.; writing—original draft preparation, M.M.; writing, G.B., M.D., M.M. and F.R.; review and editing, all authors; visualisation, F.R.; supervision, M.M.; project administration, M.M.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This study was developed under the project Life VEG-GAP (https://www.lifeveggap.eu/ accessed on 18 October 2024) and funded by the European Union Life Program in 2018; Grant Number: LIFE18 PRE IT 003.

Institutional Review Board Statement: No ethical approval required.

Informed Consent Statement: It doesn't involve humans.

Data Availability Statement: The datasets and/or analysis generated during the current study are not publicly available due to the high volume of data, but they are available from the corresponding

author upon reasonable request. Data analysis products are available on the information platform: https://veggaplatform.enea.it (accessed on 18 October 2024).

Acknowledgments: We acknowledge the support of Milan Municipality and the Metropolitan City of Bologna in the acquisition of present and future tree datasets in the framework of the Life VEG-GAP project (www.lifeveggap.eu, accessed on 18 October 2024). The computing resources and the related technical support used for this work were provided by the CRESCO/ENEAGRID High-Performance Computing infrastructure and its staff. The CRESCO/ENEAGRID High-Performance Computing infrastructure is funded by ENEA, the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development, and by Italian and European research programmes; see http://www.cresco.enea.it/english (accessed on 14 May 2024) for information. We also acknowledge the Regional Agency for Prevention, Environment, and Energy of Emilia-Romagna, and of Lombardy, for providing the anthropogenic emission inventories for Bologna and Milan; TNO (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek) for providing the European anthropogenic emissions CAMS-REG-AP_v2.2.1; and the ECMWF (European Centre for Medium-Range Weather Forecasts) for providing European meteorological data (DSC-9674 Permission to use IFS data).

Conflicts of Interest: The Authors Sandro Finardi and Camillo Silibello were employed by ARIANET S.r.l. and authors Rossella Prandi and Giuseppe Carlino were employed by SIMULARIA S.r.l. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Available online: https://www.who.int/publications/i/item/9789240034228 (accessed on 22 November 2024).
2. Vashist, M.; Kumar, T.V.; Singh, S.K. A Comprehensive Review of Urban Vegetation as a Nature-Based Solution for Sustainable Management of Particulate Matter in Ambient Air. *Environ. Sci. Pollut. Res.* **2024**, *31*, 26480–26496. [CrossRef] [PubMed]
3. Han, Y.; Lee, J.; Haiping, G.; Kim, K.-H.; Wanxi, P.; Bhardwaj, N.; Oh, J.-M.; Brown, R.J.C. Plant-Based Remediation of Air Pollution: A Review. *J. Environ. Manag.* **2022**, *301*, 113860. [CrossRef] [PubMed]
4. Wróblewska, K.; Jeong, B.R. Effectiveness of Plants and Green Infrastructure Utilization in Ambient Particulate Matter Removal. *Environ. Sci. Eur.* **2021**, *33*, 110. [CrossRef]
5. Wang, H.; Liu, X.; Wu, C.; Lin, G. Regional to Global Distributions, Trends, and Drivers of Biogenic Volatile Organic Compound Emission from 2001 to 2020. *Atmos. Chem. Phys.* **2024**, *24*, 3309–3328. [CrossRef]
6. Hata, H.; Hoshino, S.; Fujita, M.; Tonokura, K. Atmospheric Impact of Isoprene-Derived Criegee Intermediates and Isoprene Hydroxy Hydroperoxide on Sulfate Aerosol Formation in the Asian Region. *Atmos. Environ. X* **2023**, *20*, 100226. [CrossRef]
7. Carlsson, P.T.M.; Vereecken, L.; Novelli, A.; Bernard, F.; Brown, S.S.; Brownwood, B.; Cho, C.; Crowley, J.N.; Dewald, P.; Edwards, P.M.; et al. Comparison of Isoprene Chemical Mechanisms under Atmospheric Night-Time Conditions in Chamber Experiments: Evidence of Hydroperoxy Aldehydes and Epoxy Products from NO_3 Oxidation. *Atmos. Chem. Phys.* **2023**, *23*, 3147–3180. [CrossRef]
8. Zhang, X.; Wang, S.; Apel, E.C.; Schwantes, R.H.; Hornbrook, R.S.; Hills, A.J.; DeMarsh, K.E.; Moo, Z.; Ortega, J.; Brune, W.H.; et al. Probing Isoprene Photochemistry at Atmospherically Relevant Nitric Oxide Levels. *Chem* **2022**, *8*, 3225–3240. [CrossRef]
9. Ma, F.; Guo, X.; Xia, D.; Xie, H.-B.; Wang, Y.; Elm, J.; Chen, J.; Niu, J. Atmospheric Chemistry of Allylic Radicals from Isoprene: A Successive Cyclization-Driven Autoxidation Mechanism. *Environ. Sci. Technol.* **2021**, *55*, 4399–4409. [CrossRef]
10. D'Isidoro, M.; Mircea, M.; Borge, R.; Finardi, S.; de la Paz, D.; Briganti, G.; Russo, F.; Cremona, G.; Villani, M.G.; Adani, M.; et al. The Role of Vegetation on Urban Atmosphere of Three European Cities—Part 1: Evaluation of Vegetation Impact on Meteorological Conditions. *Forests* **2023**, *14*, 1235. [CrossRef]
11. Mircea, M.; Borge, R.; Finardi, S.; Briganti, G.; Russo, F.; de la Paz, D.; D'Isidoro, M.; Cremona, G.; Villani, M.G.; Cappelletti, A.; et al. The Role of Vegetation on Urban Atmosphere of Three European Cities. Part 2: Evaluation of Vegetation Impact on Air Pollutant Concentrations and Depositions. *Forests* **2023**, *14*, 1255. [CrossRef]
12. Yu, M.; Zhou, W.; Zhao, X.; Liang, X.; Wang, Y.; Tang, G. Is Urban Greening an Effective Solution to Enhance Environmental Comfort and Improve Air Quality? *Environ. Sci. Technol.* **2022**, *56*, 5390–5397. [CrossRef] [PubMed]
13. Maison, A.; Lugon, L.; Park, S.-J.; Baudic, A.; Cantrell, C.; Couvidat, F.; D'Anna, B.; Di Biagio, C.; Gratien, A.; Gros, V.; et al. Significant Impact of Urban Tree Biogenic Emissions on Air Quality Estimated by a Bottom-up Inventory and Chemistry Transport Modeling. *Atmos. Chem. Phys.* **2024**, *24*, 6011–6046. [CrossRef]
14. Skamarock, W.C.; Klemp, J.B.; Dudhia, J.; Gill, D.O.; Barker, D.; Duda, M.G.; Huang, X.-Y.; Wang, W.; Powers, J.J. *A Description of the Advanced Research WRF Version 3*; Technical Note, NCAR/TN–475+STR; National Center for Atmospheric Research: Boulder, CO, USA, 2008.

15. Mircea, M.; Ciancarella, L.; Briganti, G.; Calori, G.; Cappelletti, A.; Cionni, I.; Costa, M.; Cremona, G.; D'Isidoro, M.; Finardi, S.; et al. Assessment of the AMS-MINNI System Capabilities to Simulate Air Quality over Italy for the Calendar Year 2005. *Atmos. Environ.* **2014**, *84*, 178–188. [CrossRef]
16. Mircea, M.; Grigoras, G.; D'Isidoro, M.; Righini, G.; Adani, M.; Briganti, G.; Ciancarella, L.; Cappelletti, A.; Calori, G.; Cionni, I.; et al. Impact of Grid Resolution on Aerosol Predictions: A Case Study over Italy. *Aerosol Air Qual. Res.* **2016**, *16*, 1253–1267. [CrossRef]
17. Ciccioli, P.; Silibello, C.; Finardi, S.; Pepe, N.; Ciccioli, P.; Rapparini, F.; Neri, L.; Fares, S.; Brilli, F.; Mircea, M.; et al. The Potential Impact of Biogenic Volatile Organic Compounds (BVOCs) from Terrestrial Vegetation on a Mediterranean Area Using Two Different Emission Models. *Agric. For. Meteorol.* **2023**, *328*, 109255. [CrossRef]
18. Stafoggia, M.; Schwartz, J.; Badaloni, C.; Bellander, T.; Alessandrini, E.; Cattani, G.; de' Donato, F.; Gaeta, A.; Leone, G.; Lyapustin, A.; et al. Estimation of Daily PM10 Concentrations in Italy (2006–2012) Using Finely Resolved Satellite Data, Land Use Variables and Meteorology. *Environ. Int.* **2017**, *99*, 234–244. [CrossRef] [PubMed]
19. D'Elia, I.; Briganti, G.; Vitali, L.; Piersanti, A.; Righini, G.; D'Isidoro, M.; Cappelletti, A.; Mircea, M.; Adani, M.; Zanini, G.; et al. Measured and Modelled Air Quality Trends in Italy over the Period 2003–2010. *Atmos. Chem. Phys.* **2021**, *21*, 10825–10849. [CrossRef]
20. Fioravanti, G.; Martino, S.; Cameletti, M.; Cattani, G. Spatio-Temporal Modelling of PM10 Daily Concentrations in Italy Using the SPDE Approach. *Atmos. Environ.* **2021**, *248*, 118192. [CrossRef]
21. Messina, P.; Ung, A.; Meleux, F.; Raux, B.; Colette, A. Annual Air Quality Assessment Report 2021. Copernicus Atmosphere Monitoring Service Policy Support. 2023. Available online: https://atmosphere.copernicus.eu/sites/default/files/publications/CAMS2_71_2023SC1-1_D1.2.1-2021_202401_V1.pdf (accessed on 11 December 2024). [CrossRef]
22. Colette, A.; Solberg, S.; Beauchamp, M.; Bessagnet, B.; Malherbe, L.; Guerreiro, C. *Long Term Air Quality Trends in Europe. Contribution of Meteorological Variability, Natural Factors and Emissions*; ETC/ACM Technical Paper, 2016/7; European Topic Centre on Air Pollution and Climate Change Mitigation: Bilthoven, The Netherlands, 2017; p. 97. Available online: https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etcacm_tp_2016_7_aqtrendseurope/@@download/file/ETCACM_TP_2016_7_AQTrendsEurope.pdf (accessed on 11 December 2024).
23. Lu, B.; Zhong, J.; Wang, W.; Tang, S.; Zheng, Z. Influence of Near Real-Time Green Vegetation Fraction Data on Numerical Weather Prediction by WRF over North China. *J. Meteorol. Res.* **2021**, *35*, 505–520. [CrossRef]
24. Gómez, I.; Caselles, V.; Estrela, M.J. Improving RAMS and WRF Mesoscale Forecasts over Two Distinct Vegetation Covers Using an Appropriate Thermal Roughness Length Parameterization. *Agric. For. Meteorol.* **2020**, *280*, 107791. [CrossRef]
25. Maison, A.; Lugon, L.; Park, S.-J.; Boissard, C.; Faucheux, A.; Gros, V.; Kalalian, C.; Kim, Y.; Leymarie, J.; Petit, J.-E.; et al. Contrasting Effects of Urban Trees on Air Quality: From the Aerodynamic Effects in Streets to Impacts of Biogenic Emissions in Cities. *Sci. Total Environ.* **2024**, *946*, 174116. [CrossRef] [PubMed]