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Traffic-related air pollution biomonitoring with *Tradescantia pallida* (Rose) Hunt. cv. *purpurea* Boom in Brazil

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Abstract This study aimed to verify the capacity of *Tradescantia pallida* in the biomonitoring of air pollution in urban areas with different traffic intensities and under varying environmental conditions. Experiments were carried out in Ribeirão Preto, in the Southeastern Brazil, with more than 660,000 inhabitants and a fleet of more than 485,000 motor vehicles. Ten seedlings of *T. pallida* were exposed in three areas in the city, differing in traffic vehicle flow, in two seasons (wet and dry). At the end of each sampling period, which lasted 4 months, samples of leaves were collected, and the content of As, Ba, Ca, Cd, Cr, Cu, Fe, Hg, Mg, Mn, P, Pb, S, and Zn was determined by inductively coupled plasma mass spectroscopy (ICP-MS). The same elements were determined in soil samples for a seasonal characterization in conjunction with secondary data of environmental parameters. Additionally, micronucleus assay with early pollen tetrad cells of *Tradescantia* (Trad-MN) was conducted by collecting flower buds and analyzing the micronuclei frequencies in pollen mother cells. Although pollutant levels in air were below the Brazilian legal limits, plants exposed in the high-traffic flow area presented higher concentrations of elements related to vehicle emissions, especially under dry conditions, and higher micronuclei frequency in pollen mother cells. These results show the sensitivity of *T. pallida* to low-level urban air pollution and its suitability as bioindicator for trace elements. This alternative tool for biomonitoring can serve as a support methodology for the adoption of more restrictive public environmental policies in Brazil and extendible to other developing countries.

Keywords Air pollution · Metals · Biomonitoring · Vehicle emissions · Air quality management · *Tradescantia pallida*

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Introduction

Ambient air pollution has been associated with several cardiovascular diseases, being also considered a potentially modifiable risk factor for lung cancer (Fajersztajn et al. 2013). The uncontrolled growth of large urban centers, especially in developing countries, has contributed to increasing emissions of polluting gases, resulting in damage to the natural environment and human health. The most important source of urban air pollution, motor vehicle emissions, has rapidly risen in Brazil in recent years. According to statistics supplied by the National Department of Transit, Brazil has currently about 85 million motor vehicles, of which 30 % are concentrated in the São Paulo state (Denatran 2014).

Common airborne pollutants produced from dense traffic include carbon monoxide, sulfur dioxide (in motor vehicles powered by diesel), nitrogen dioxide (considered an indicator of vehicle emissions), and particulate matter, composed of a mixture of organic and inorganic chemicals, such as trace elements, hydrocarbons, and microorganisms (Samara and Voutsa 2005; Fajersztajn et al. 2013). In urban regions, vehicle-related emissions greatly contribute to the increase of trace elements in aerosol particles, especially fine sized, which can be deeply inhaled into lungs, thus increasing health risks (Song and Gao 2011). Despite technological developments in the production of less polluting fuels, motor vehicles are still considered an important mobile source of air pollution, difficult to monitor and control. In this scenario, biomonitoring can be used as a practical management tool in detecting and assessing air pollution, complementing physical and chemical methods (Crispim et al. 2012). This alternative is especially useful when analyzing the accumulation of compounds with known carcinogenic potential, such as some polycyclic aromatic hydrocarbons and trace elements, which are not routinely measured by environmental agencies (Fajersztajn et al. 2013).

Besides the low cost and easy handling of plants, the response of them to pollutants provides a reliable indication of the quality and characteristics of the environment. The use of plant biomonitoring can provide important information on the risk associated with exposure to air pollution for other organisms, including humans (Mulgrew and Williams 2000). Several species of plants are used as bioindicators of air pollution or as cumulative and sensitive biomonitors, depending on the type of study, either qualitative or quantitative assessment (Arndt and Schweizer 1991).

Lichens, mosses, and epiphytic plants are common organisms used as air pollution biomonitors, since they obtain nutrients from the atmosphere (Mulgrew and Williams 2000; Wannaz et al. 2012). In contrast, vascular plants get their nutrients from the substratum, therefore not only intercepting pollutants from atmospheric deposition but also accumulating aerial metals from the soil via their root system and translocating them to other parts of the plant, such as leaves or bark (Guéguen et al. 2012). The vascular plant *Tradescantia pallida* (Rose) Hunt. cv. *purpurea* Boom is an ornamental herbaceous, with a wide distribution in many countries. Several studies have used this species as an air quality biomonitor, especially for its genetic characteristics favorable for genotoxic analyses, more specific to mutation in the DNA of pollen mother cells, through micronucleus bioassay (micronucleus assay with Tradescantia pollen tetrads (Trad-MN)) (Batalha et al. 1999; Carreras et al. 2009; Mariani et al. 2009; Alves et al. 2011; Crispim et al. 2012). However, only few of them have used *T. pallida* as a bioaccumulator of trace elements from urban air pollution (Saiki et al. 2003; Sumita et al. 2003).

Air pollution is an important challenge for environmental managers and decision-making stakeholders, especially in industrial regions and megacities of emerging countries, where annual average concentrations of PM_{10} can easily reach up to 200 $\mu g\ m^{-3}$, ten times greater than the World Health Organization's (WHO) air quality guidelines (WHO 2011). For various reasons, including economic viability, most of these countries have standards for air quality with limits above those recommended by the WHO. In Brazil, according to several epidemiological studies, it is proven that, even under conditions that are compliant with the National Air Quality Standards, the concentration of atmospheric pollutants causes adverse effects on human health (Roseiro and Takayanagui 2006; Mariani et al. 2009; Olmo et al. 2011; Nicolussi et al. 2014). In this context, the objective of the present study was to verify the capacity of *T. pallida* for air pollution biomonitoring in urban areas with different traffic intensity and under varying environmental conditions.

For that purpose, the levels of some traffic-related elements were determined in samples of *T. pallida* collected in different exposure areas of Ribeirão Preto, Brazil. Same elements were determined in soil samples for a seasonal characterization in conjunction with secondary data of environmental parameters. As a verification method, the Trad-MN bioassay was applied.

Materials and methods

Study site

This study was carried out in the city of Ribeirão Preto, located in São Paulo state, in Southeastern Brazil. The city has approximately 660,000 inhabitants, with more than 99 % of them living in urban areas (IBGE 2014). The climate in this region is tropical and wet, characterized by rainy summers and dry winters (Cetesb 2012), with prevailing winds blowing from east and southeast, according to Ribeirão Preto air quality assessment (Cetesb 2007). Ribeirão Preto is the eighth largest city in the state of São Paulo, and a large number of vehicles move around the city every day. There are more than 485,000 vehicles registered in the city, representing an annual increase of 4 % (Denatran 2014).

Plant exposure

Samples of *T. pallida* were cultivated in uniform uncontaminated soil. Water supply was provided by suction from water reservoirs along nylon wicks, which contained nutritive solution, prepared according to Hoagland and Arnon (1950), at dilutions of 1:4 (Fig. 1a–c). The nutritive solution in each box reservoir was replaced fortnightly. Healthy plants of the same age, height, and number of leaves were maintained for 1 month under similar conditions of lighting, substrate, water, and nutrients, before exposure to air pollution. The experiments were carried out in three areas in the city, with no industry but different intensities of vehicle flow.

The first area was the campus of the University of São Paulo (USP), located 6 km from the central region, with pathways of local circulation with low traffic flow (LT). This site is 1.5 km away from the nearest main avenue, following the direction of prevailing winds that has maximum capacity around 1200 vehicles per hour (Ribeirão Preto 2014).

The second area was at a state school located in a residential neighborhood in the West region of the city, 3 km distant from the central region, with moderate traffic flow (MT). The streets in this area are intended for light traffic, with cargo transport only for local supplies and some public transportation. Following the direction of the prevailing winds, the air quality in this area may be affected by an avenue 1.5 km away, with maximum capacity around 1,800 vehicles per hour (Ribeirão Preto 2014).

Finally, the third area was at a state school in the central region, with high traffic flow (HT). This region is crossed by avenues with general traffic, with some load restrictions and prioritized public transportation. Following the direction of the prevailing winds, the nearest main avenue is less than 600 m away, with maximum capacity around 3600 vehicles per hour (Ribeirão Preto 2014).

At each area, ten seedlings of *T. pallida* were exposed during two consecutive periods of 4 months each, with seasonal variability. The first exposure period was from March to June 2011 and the second one from July to October 2011.

Sampling and analysis

Two sampling campaigns were done at the end of each exposure period by collecting leaves from each area (LT,

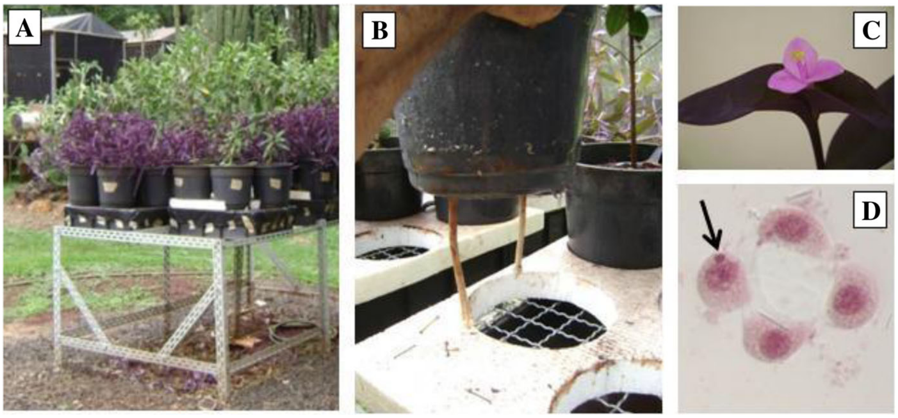

Fig. 1 Exposure of *Tradescantia pallida* (**a**–**c**). Pollen mother cell (tetrad) with an *arrow* pointing a micronucleus (**d**)

MT, and HT). Leaf samples were dried at 70 °C until reaching a constant weight, and approximately, 0.25 g of them was digested in a Teflon bomb with nitric acid (65 % Suprapur, Merck, Darmstadt, Germany) for 16 h (8 h at room temperature and 8 h at 80 °C). After filtration, the samples were diluted to 25 ml with Milli-Q water in volumetric flasks. Soil samples from the HT area, with approximately 0.5 g, were collected under dry and wet conditions and prepared following the same procedures used with leaf samples (Rovira et al. 2014).

Concentrations of arsenic (As), barium (Ba), calcium (Ca), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), magnesium (Mg), manganese (Mn), phosphorus (P), lead (Pb), sulfur (S), and zinc (Zn) were determined by inductively coupled plasma mass spectrometry (ICP-MS, PerkinElmer Elan 6000). The limits of detection (LDs) in leaves were the following: 0.0005 $\mu g\ g^{-1}$ for Cd and Pb; 0.001 $\mu g\ g^{-1}$ for Ba and Mn; 0.002 $\mu g\ g^{-1}$ for As, Cu, and Hg; 0.005 $\mu g\ g^{-1}$ for Cr and Zn; 1.0 $\mu g\ g^{-1}$ for Fe and Mg; 2.0 $\mu g\ g^{-1}$ for S; and 5.0 $\mu g\ g^{-1}$ for Ca and P. In turn, the LDs in soil were the following: 0.00006 $\mu g\ g^{-1}$ for Cd and Pb; 0.0001 $\mu g\ g^{-1}$ for Ba and Mn; 0.0002 $\mu g\ g^{-1}$ for As, Cu, and Hg; 0.0006 $\mu g\ g^{-1}$ for Cr and Zn; 0.125 $\mu g\ g^{-1}$ for Fe and Mg; 0.25 $\mu g\ g^{-1}$ for S; and 0.625 $\mu g\ g^{-1}$ for Ca and P.

Inflorescences of five samples of *T. pallida* were collected at the LT, MT, and HT areas, during the plant exposure for analysis of micronuclei frequency, following the procedure for *Tradescantia* clone 4430, described by Ma (1981). Young flower buds were dissected and smashed onto a glass slide with acetic carmine dye. At least ten slides were prepared for each area of exposure, and 300 tetrads (pollen mother cells) were counted on each slide. They were analyzed using a ×40 objective light binocular microscope (Fig. 1d), and frequency of micronuclei was expressed in percentages (number of micronuclei per 100 tetrads).

Environmental parameters

Monthly average data for temperature, rainfall, and concentration of air pollutants (i.e., particulate matter with diameter <10 μm (PM_{10}) and nitrogen dioxide (NO_2)) were obtained from the São Paulo State Environment Agency (Cetesb 2014). These data were used to characterize the environmental conditions of each area in each sampling campaign.

Statistical analysis

The results of multielemental concentrations were compared between the three areas of plant exposure (LT, MT, and HT) and between the two sampling environmental conditions (dry and wet) through analysis of variance (two-way ANOVA), with a significance level of 5 % and multiple comparisons of the Tukey test. Soil element concentrations were compared between the two sampling conditions (dry and wet) by the Student's *t* test or the Mann-Whitney test, depending on whether the data had a parametric distribution or not, respectively. ANOVA and Tukey tests were also used to compare micronuclei frequencies between the areas of plant exposure. The relationship between spatial variation trends of related traffic elements and micronuclei frequency in *T. pallida* were performed based on Pearson's correlation coefficient and principal component analysis (PCA).

Results and discussion

Spatial variation of air pollutants in plants

Leaf concentrations of elements related to vehicle emissions and essential elements to plant physiology are summarized in Table 1, highlighting the exposure area (LT, MT, or HT) and the sampling conditions (dry or wet). The spatial study showed variations for some elements in *T. pallida* during the dry season only. Some elements related to air pollution by vehicle emissions (Fe, Pb, and Zn) showed higher concentrations in leaf samples collected in the HT area. Although Ba, Cd, Cu, Cr, and S showed no significant differences according to the area of plant exposure, there was a clear increasing trend in the same HT area. This zone is characterized by intense traffic, with many cars and vehicles for public transportation. Furthermore, it is topographically depressed with high buildings, and therefore, the dispersion of pollutants is hindered.

The environmental presence of metals in urban areas is related to density traffic flow (Guéguen et al. 2012; Maher et al. 2008; Monaci et al. 2000; Samara and Voutsa 2005; Song and Gao 2011). Barium and Mn are mainly released from fuel combustion; Cd and Zn from tire wear; and Cr, Cu, and Fe from the wear of metallic parts (Monaci et al. 2000). According to Song and Gao (2011), another source of Fe can be the

Table 1 Concentration of elements (μg g^{-1} dw) in leaves of *Tradescantia pallida*, collected under dry or wet conditions, at three areas of Ribeirão Preto, SP, Southeastern Brazil, differing in traffic flow of vehicles

Sampling conditions		Study area			ANOVA
		LT	MT	HT	
Traffic-related elements					
Ba	Dry	9.9±1.0 Aa	10.5±1.1 Aa	12.0±0.8 Aa	F_{A}=0.8 ns
	Wet	4.5±0.5 Ab	3.1±0.1 Ab	3.5±0.2 Ab	F_{C}=150.7**
					F_{AxC}=2.4 ns
Cd	Dry	0.004±0.001 Aa	0.004±0.001 Aa	0.008±0.001 Aa	F_{A}=0.7 ns
	Wet	0.005±0.002 Aa	0.006±0.001 Aa	0.005±0.002 Aa	F_{C}=0.01 ns
					F_{AxC}=0.9 ns
Cr	Dry	0.127±0.006 ABa	0.116±0.006 Aa	0.137±0.006 Ba	F_{A}=0.5 ns
	Wet	0.149±0.003 Ab	0.149±0.007 Ab	0.131±0.005 Aa	F_{C}=12.3**
					F_{AxC}=6.0*
Cu	Dry	0.9±0.1 Aa	1.2±0.2 Aa	1.4±0.1 Aa	F_{A}=2.2 ns
	Wet	1.2±0.2 Aa	1.4±0.1 Aa	1.2±0.1 Aa	F_{C}=2.0 ns
					F_{AxC}=2.8 ns
Fe	Dry	39.3±4.0 Aa	57.2±8.2 Ba	58.5±5.3 Ba	F_{A}=4.3*
	Wet	17.0±2.0 Ab	25.2±3.3 Ab	16.8±1.5 Ab	F_{C}=71.9**
					F_{AxC}=2.2 ns
Mn	Dry	26.7±2.6 Aa	24.1±2.9 Aa	16.5±3.3 Ba	F_{A}=3.3*
	Wet	3.1±0.5 Ab	2.7±0.3 Ab	2.9±0.4 Ab	F_{C}=130.1**
					F_{AxC}=3.2*
Pb	Dry	0.07±0.01 Aa	0.16±0.04 Ba	0.13±0.01 ABa	F_{A}=4.0*
	Wet	0.04±0.01 Aa	0.07±0.01 Ab	0.05±0.01 Ab	F_{C}=18.4**
					F_{AxC}=1.3 ns
Zn	Dry	5.9±0.3 Aa	8.4±0.7 Ba	7.0±0.8 ABa	F_{A}=5.2*
	Wet	3.4±0.2 Ab	4.0±0.3 Ab	3.8±0.2 Ab	F_{C}=70.0**
					F_{AxC}=1.9 ns
Essential elements					
Ca	Dry	2,848.6±185.7 Aa	3,142.8±219.8 Aa	3,094.1±172.1 Aa	F_{A}=1.1 ns
	Wet	3,441.0±219.2 Ab	3,731.5±132.4 Ab	3,526.7±216.2 Aa	F_{C}=11.6**
					F_{AxC}=0.1 ns
Mg	Dry	710.7±50.9 Aa	640.9±24.0 Aa	586.9±21.8 Aa	F_{A}=0.4 ns
	Wet	777.9±50.0 Aa	808.2±35.6 Ab	828.8±43.4 Ab	F_{C}=24.4**
					F_{AxC}=2.5 ns
P	Dry	237.8±17.8 Aa	288.5±23.8 Aa	433.4±25.0 Ba	F_{A}=12.2**
	Wet	337.6±17.1 Ab	408.9±28.7 Ab	372.0±25.1 Aa	F_{C}=7.8*
					F_{AxC}=0.1**
S	Dry	223.1±19.2 Aa	225.1±11.0 Aa	236.1±18.7 Aa	F_{A}=1.3 ns
	Wet	255.4±11.5 Aa	301.5±20.5 Ab	284.0±14.4 Ab	F_{C}=15.3**
					F_{AxC}=0.9 ns

Average concentration±standard deviation. Small letters compare the statistical results according to sampling season, while capital letters compare the results according to the area. Values followed by same letter do not differ by Tukey test. ANOVA results for area (A) and data collection conditions (C), as well as the interaction between these factors (AxC), are presented for each element analyzed. N=10

LT low traffic flow, *MT* moderate traffic flow, *HT* high traffic flow

*$0.05 > P > 0.001$; **$P < 0.001$; *ns* not significant ($P > 0.05$)

resuspension of soil dust. The occurrence of Cd, Cr, and Pb in the leaves is directly related to the deposition of particles, as they are nonessential elements for plants (Mulgrew and Williams 2000).

Lead in gasoline has been banned in many countries since the 1980s for its toxicological effects on health and environment (Landrigan 2002), but it can still be found in some types of fuel with additives, aircraft fuel and, in trace amounts, in recycled tires, metallic alloys, and batteries. With the prohibition of tetraethyl lead in Brazilian gasoline in 1989, anhydrous alcohol has been used as a substitute additive, in a limit of 25 %.

In general terms, the plants exposed in the MT area had intermediate or similar concentrations of elements related to vehicle emissions, compared to the plants at the HT area, regarding Fe, Pb, and Zn. All elements related to vehicle emissions were less concentrated in plants exposed in the LT area, located at the campus of the USP in Ribeirão Preto, where there is low vehicle flow and abundant vegetation. The high number of trees and other small plants in this area can somehow have a phytoremediation effect, accumulating trace elements from the atmosphere in leaves, bark, and other parts of the plant.

Significant spatial differences in the results of the Trad-MN bioassay were also observed according to traffic intensity (Fig. 2). The inflorescences from the HT area had higher frequencies of micronuclei (3.7 % on average) compared to others (1.8 % on average). Figure 3 illustrates the results of the Pearson's correlation coefficient and PCA calculated for spatial variation of micronuclei frequency and traffic-related elements in leaves. The first component explained about 68 % of the variation in the data. The analysis showed positive correlation between micronuclei frequency and most of elements across the tree exposure areas, especially with leaf concentration of Ba, Cd, and Cu (r=0.992; 0.989 and 0.901, respectively).

Although the results of Trad-MN have a general character and it is not possible to link effects with a particular pollutant, this bioassay allows relating exposure to air pollutants with genotoxic effects in plants. In this study, we did the Trad-MN bioassays as a verification method, and the results indicated that air pollutions related to vehicular emissions, in the HT area, were able to interfere in the production of *T. pallida* male gametes, inducing the formation of micronuclei.

Micronuclei frequency in this species is broadly used as air pollution indicator and sometimes can be correlated to human exposure. Mariani et al. (2009), for example, correlated Trad-MN results with the prevalence of cardiovascular disease and mortality rates caused by cancer in an industrial region of São Paulo city, Brazil. If the outcomes of the Trad-MN bioassays are analyzed jointly with the physicochemical analyses of pollutants and weather conditions of the studied area, micronuclei frequencies can be a useful environmental management tool. On this basis, Trad-MN bioassays have been included in the routine of the State Health Department of Mato Grosso, a Brazilian state, as one of the parameters of their air quality monitoring program (Lira et al. 2008).

Both spatial and seasonal variation of air pollutants should be optimized by a complete monitoring program, within available resource constraints (Sajani et al. 2004). In São Paulo state, Cetesb prioritizes the implementation

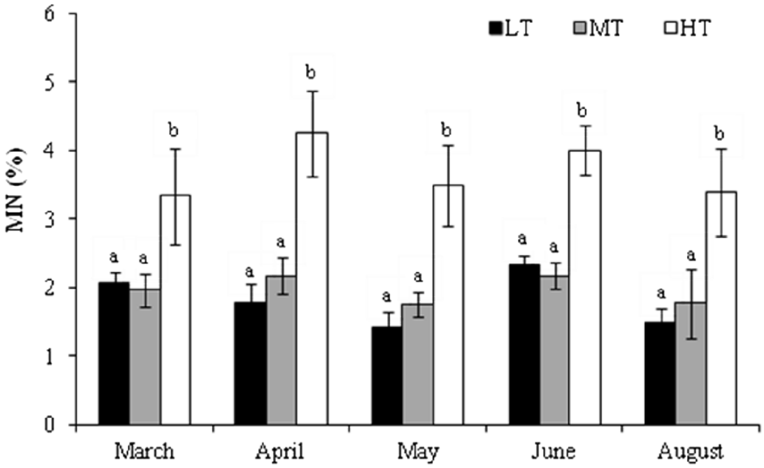

Fig. 2 Frequency of micronuclei (MN) (%) in inflorescences of *Tradescantia pallida* collected at three areas of Ribeirão Preto, SP, Southeastern Brazil, differing in traffic flow of vehicles. *LT* low traffic flow, *MT* moderate traffic flow, *HT* high traffic flow. Data are presented as mean and standard error (*bars*). *Different superscripts* indicate significant differences between exposure areas (P≤0.05, n=10)

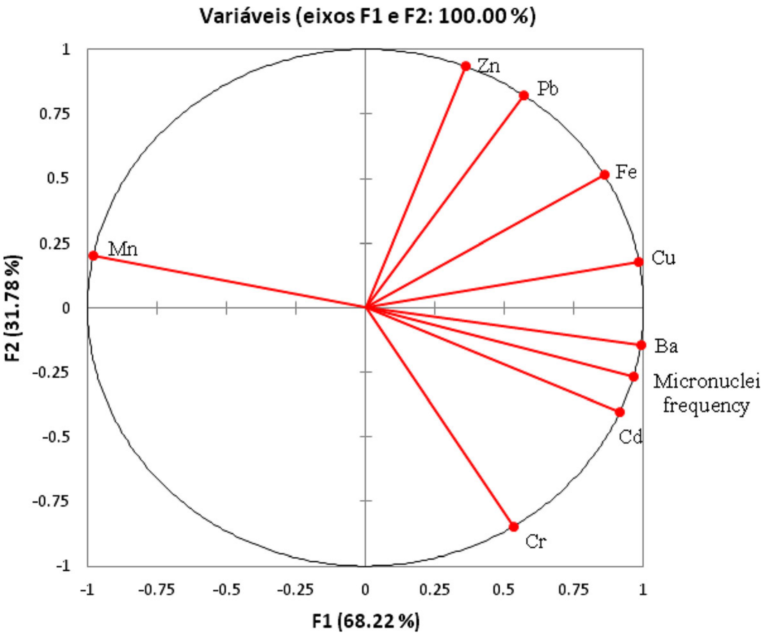

Fig. 3 Principal component analysis (PCA) for leaf concentration of related traffic elements and micronuclei frequency in *T. pallida*, across three exposure areas with different intensity of vehicle flow, at Ribeirão Preto, SP, Southeastern Brazil

of monitoring fixed stations in areas with less interference from vehicle emissions, seeking more spatial representativeness of pollutant data for urban air quality analysis and comparison with other cities.

However, the large spatial variability of air pollution within the urban sites implies the impossibility of obtaining a real air quality assessment and the population exposure levels, with the data from fixed stations alone (Sajani et al. 2004). Different points of the city, including heavily polluted areas, can be monitored with complement methods as *T. pallida* biomonitoring, used in this work. Besides some studies show that $PM_{2.5}$ and PM_{10} concentrations tend to be uniformly distributed within an urban environment, main air pollutants emitted by vehicle have high spatial variability (Maher et al. 2008; Song and Gao 2011). The results of a systematic air pollutant biomonitoring can be correlated to fixed-stations data by regression functions. This kind of analysis, combined with the use of passive samplers, can provide a better understanding of the variability of air pollutants in urban areas, with more versatility and greater cost-effectiveness in long- and short-term measurements (Sajani et al. 2004; Wannaz et al. 2012).

Seasonal variation of air pollutants in plants

The environmental conditions, regarding rainfall patterns, may explain the different concentrations of traffic-related elements in *T. pallida* leaves and soil samples. Regardless of the traffic flow intensity, results showed average concentrations of Ba, Fe, Mn, Pb, and Zn higher in leaf samples collected under dry conditions (Table 1). Although the difference was not statistically significant, the concentrations of Cd, Cr, and Cu tended to be higher in leaves collected under dry conditions, especially from the HT area.

Higher deposition of PM_{10} on leaf surfaces was in the first sampling, under dry conditions. At that time, there was a decrease in the monthly average rainfall, together with a decrease in temperature (Fig. 4). These factors, which usually take place as a consequence of the high frequency of thermal inversions (Cetesb 2014), do not facilitate the dispersion of air pollutants. Data collected under dry conditions correspond to the elemental content of the leaf tissue as well as the surface accumulation from deposition of particulate matter. On the other hand, data collected under wet conditions, in late October, correspond mainly to the content of leaf elements. Distribution of rainfall during the experimental periods had a similar role to washing procedures in the sample preparation followed in some studies (Mulgrew and Williams 2000; Saiki et al. 2003). The rain washes deposited particles into the soil, which can be translocated to the leaves through their root systems.

Calcium, Mg, P, and S showed lower concentrations in leaf samples of *T. pallida* collected under dry

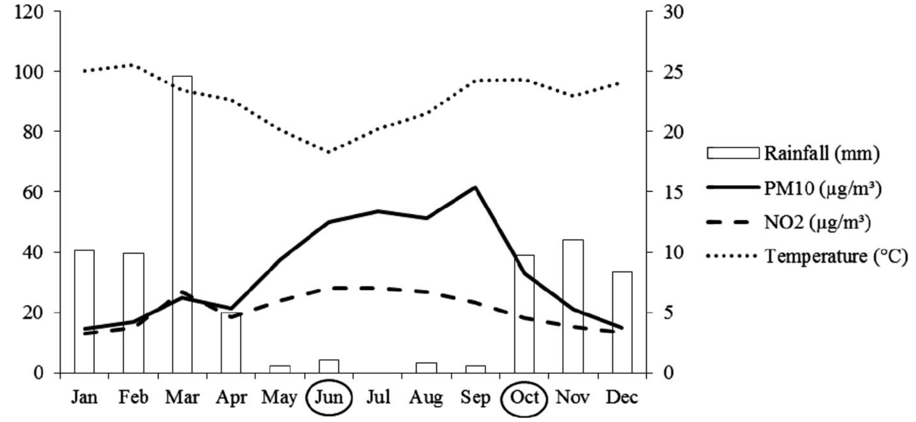

Fig. 4 Monthly average of rainfall, temperature, and concentration of particulate matter with 10 µm or less in diameter (PM_{10}) and nitrogen dioxide (NO_2), at Ribeirão Preto, SP, Southeastern Brazil, pointing out the periods of data collection (dry and wet conditions)

conditions (Table 1). These elements are essential to plant physiology, being important constituents of the cell wall (Ca), chlorophylls (Mg), energy compounds (P) and proteins (S) (Taiz and Zeiger 2010). Usually, these nutrients are obtained from the soil, but the main source of S in the atmosphere is still fuel burning. Although it is essential for plants, S can be toxic at high concentrations, being SO_2 an important indicator of pollution by diesel vehicles. Considering that the availability of water and nutrients was similar throughout the exposure periods, the lowest concentrations of these elements in samples collected under dry conditions may indicate a result of physiological damage to the plants, leading to a possible reduction in the photosynthesis rate and, consequently, less biomass allocation. The exposure to air pollutants can cause several effects in plants, such as alterations on the production of metabolites and hormones related to oxidative stress (Meletiou-Christou et al. 2011), enzymatic (Tripathi and Gautam 2007), genetic (Klumpp et al. 2006), physiologic (Moraes et al. 2000, 2004), or anatomic alterations (Alves et al. 2001), which may result in leaf chlorosis and necrosis.

Similarly to leaves, all soil samples presented values of As and Hg below their respective LDs (0.002 $\mu g\ g^{-1}$). About 38 % of the analyzed elements in soil showed significant differences between the two samplings (dry and wet conditions). The concentrations of Cd, Fe, Mn, P, and Pb were, on average, 96.4 % higher in the soil samples collected under dry conditions. In turn, the other analyzed elements (Ba, Ca, Cr, Cu, Mg, Na, S, and Zn) showed no significant differences between the samplings. Soil concentration of P was higher under dry conditions, when plants had lower leaf concentrations of this element. This corroborates the hypothesis that the ability of plants to absorb nutrients from the soil may have been changed by environmental conditions in this period of exposure, with respect to meteorological parameters and air pollutants. Higher concentrations of Cd, Fe, Mn, and Pb in soil samples collected under dry conditions, which are related to vehicle emissions, corroborate the results derived by analyzing the composition of *T. pallida* leaves, with higher concentration of these elements as well. The decrease of trace elements during rainy periods is associated to wash-off of deposited dust, which is mobilized from plants to lower strata of the soil (Sæbø et al. 2012).

Conclusions

Plants of *T. pallida* were sensitive enough to indicate spatial and seasonal variation of metal emissions related to vehicle pollution. The study region usually owns air pollutant concentrations below the Brazilian Air Quality Standards (Cetesb 2012). However, some alterations in plants exposed in the HT area were verified, including increased frequency of micronuclei and low concentration of essential elements, especially under dry conditions and with high levels of PM_{10} and NO_2. Several epidemiologic studies have demonstrated the impact of air pollution on health, even when people are exposed to low concentrations of pollutants (Olmo et al. 2011). More restrictive acceptable air quality levels could have a positive impact on the population's health (Santos et al. 2014). This indicates the need to improve air quality assessment and management in areas that are not predominantly industrial, but with other important pollutant sources such as vehicle traffic.

Plant biomonitors are effective for mapping spatial variation of trace element contamination in the urban area, allowing the assessment of synergistic, antagonistic, or additive effects of chemicals in complex air pollutant mixtures. More specifically, *T. pallida* may be a suitable tool for understanding the oxidative stress potential of exposure to urban air pollution. Usually, trace elements in air particles are not routinely monitored in populated areas, due to technical and financial difficulties. The analysis of these elements in plants as passive biomonitors allows the inclusion of new parameters in monitoring and control systems of air quality, complementing data from fixed stations. In summary, these results contribute to the methodological improvement of the process of updating air quality standards, serving as support for the adoption of more restrictive environmental policies in Brazil, being exportable to other developing countries.

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