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Ecological implications of twentieth century reforestation programs for the urban forests of São Paulo, Brazil: a study based on litterfall and nutrient cycling

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Abstract

The focus of this study was to investigate the wide use of *Eucalyptus* spp., an exotic plant with high allelopathic ability, in the reforestation programs of urban parks in São Paulo City, Brazil, over the last century. To understand the implications of using *Eucalyptus* spp. in the city's parks, this study aimed to compare nutrient cycling and litter decomposition between a mixed composition of litter (i.e., native and exotic species) and the litter of a single species (i.e., *Eucalyptus*). To accomplish this, newly deciduous leaves were collected from two native and two exotic species that are commonly used in the afforestation of São Paulo as well as from *Eucalyptus* spp. The mixed composition of litter yielded a higher dry mass loss and return of macro- and micronutrients to the forest floor. The decomposition constant (k) values were 0.00322 and 0.00207 $\text{g g}^{-1} \text{day}^{-1}$ for the mixed composition and *Eucalyptus* spp., respectively. The time required for decomposition of 50 and 95% of deciduous material was 215 and 931 days, respectively, and for the mixed litterfall 334 and 1449 days, respectively, for *Eucalyptus* spp. Therefore, the mixed litter exhibited greater dry mass loss and nutrient cycling in an urban forest of São Paulo City, since dry mass losses as well as speed and amount of nutrients returned to the forest floor were relatively higher compared to *Eucalyptus* spp. Nutrient cycling via *Eucalyptus* spp. litter was less efficient than mixed composition of litter, demonstrating that reforestation programs carried out in the twentieth century using only one species may have had little success. The results of this work emphasize the fact that in urban reforestation programs the City of São Paulo must consider the environmental and biogeographic characteristics of the species employed and use high levels of biodiversity, since the city lies in a megadiverse biome.

Keywords: Tropical forest, Exotic species, Nutrient dynamics, Ecosystem functioning

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Introduction

The unprecedented expansion of urban centers in Brazil during the twentieth century has led to the insurgence of several environmental hazards such as soil, water, and air pollution (Ferreira et al. 2012; Pedroso et al. 2016; Nakazato et al. 2020), which are the consequence of an inadequately balanced management of urban green spaces (Chen and Hua 2015; Benchimol et al. 2017). Recently, these environmental concerns have received greater attention in terms of public policy, and topics such as biodiversity and environmental conservation have become an important focus in Brazilian (urban) society (Adams 2005; Botelho et al. 2014; Ferreira et al. 2018; Bulbovas et al. 2020).

Historically, public management in some Brazilian cities, including São Paulo, has mainly focused on industrial development resulting in restoration programs not receiving proper solicitude during the last century. As a consequence, the introduction of fast-growing exotic tree species offering shade has become the typical practice in urban centers (Jesus et al. 2014; Silva et al. 2016). However, this strategy has resulted in the expansion of exotic and alien species attracting pollinators (Hoppen et al. 2015), thus contributing to biotic homogenization in cities (Lôbo et al. 2011; Qian et al. 2016).

São Paulo's urban green spaces are mainly composed of exotic plants with high ornamental potential, such as *Ligustrum lucidum* and *Ficus benjamina*. These trees, along with many other native species, such as *Schinus terebinthifolius* and *Pleroma granulatum*, are scattered throughout the city providing important ecosystem services (Laforteza and Chen 2016; Arratia et al. 2020). Exotic trees, such as *Eucalyptus* spp., are excellent competitors in the natural system because of allelopathy and their ability to alter floristic composition and soil properties (Suominen 2013; Yitaferu et al. 2013; Gatto et al. 2014; Sampaio and Schmidt 2014; Silva et al. 2016; Shams 2016; Stromberg et al. 2016). Some studies have shown that the decomposition rate of *Eucalyptus* leaves is slower than that of native species (Louzada et al. 1997; Barlow et al. 2007; Bala et al. 2010; Demessie et al. 2012; Martins et al. 2013; Cizungu et al. 2014). However, several other cases have shown a faster decomposition rate (Pozo et al. 1998; Ferreira et al. 2006; Bachecha et al. 2016) or absence of differences (Guo and Sims 1999; Costa et al. 2005) in various parts of Brazil. In general, species-specific effects, which are considerable, are more capable of determining the variations in decomposition rates than whether or not a species is autochthonous (Kumar 2008). The *Eucalyptus* spp. most commonly planted in the urban parks of São Paulo is *Eucalyptus grandis*; it is sometimes hybridized with *E. urophylla*. The species and its hybrids are fast growing, reaching more than 50 m in height in a few decades. They have

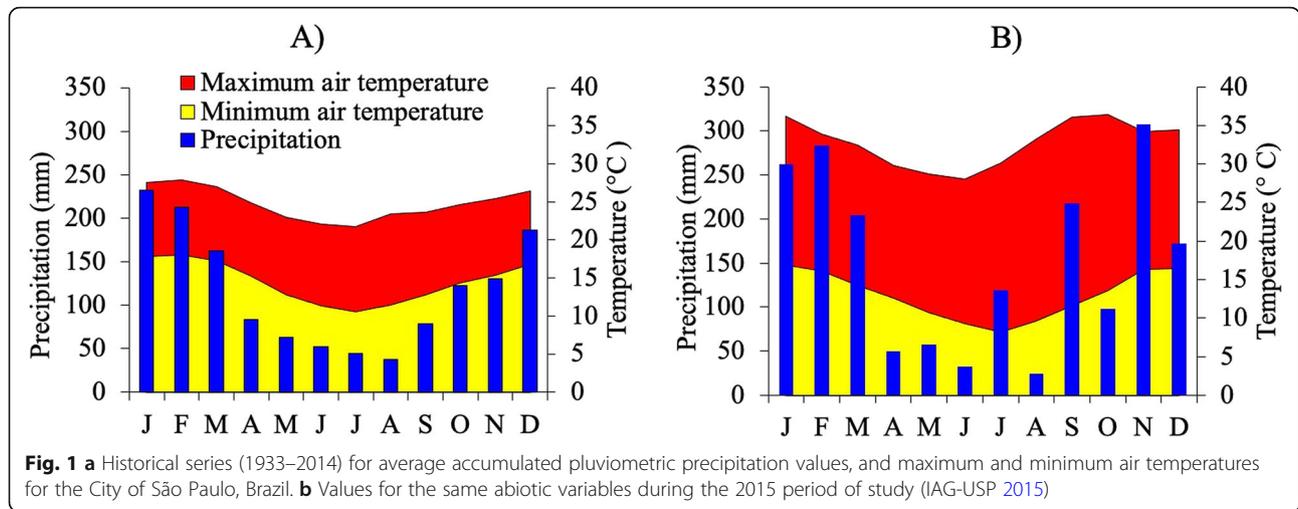
been widely used from the early to mid-twentieth century as a means of “draining” humid soil. Due to certain characteristics of the species, such as an abundance of oil in the leaves and leaf laminae, the decomposition rate is expected to be slower than that of most native species in the study region.

Although litter decomposition and nutrient cycling are important ecosystem processes (Ferreira et al., 2017; Sousa-Neto et al. 2017), little is known about them in the tropical and subtropical urban forests of the southern hemisphere (Silva-Junior et al. 2014; Enloe et al. 2015; Ferreira et al. 2019). Some authors have shown and compared litterfall production and decomposition rates in tropical urban systems and natural areas; however, research of this nature is still little explored in Brazil (Ferreira et al. 2014a; Ferreira et al. 2014b; Martinielli et al. 2017). In this context, the processes of underlying forest dynamics in public spaces must be investigated with the aim of improving biodiversity management in green urban areas. In this study, it can be inferred that the urban area influences litterfall decomposition processes, especially since it interferes with microbial activities, i.e., external factors such as microclimate and deposition of atmospheric contaminants that can vary considerably in less anthropized areas (Moraes et al. 1999). Therefore, this study is driven by the hypotheses that (i) the decomposition of *Eucalyptus* leaves will be slower than the decomposition of mixed-leaf ornamental species (i.e., two other exotic plus two native species), as is traditionally found in São Paulo's treescape, and (ii) the rates of return to the soil of nutrients from canopy leaves and litterfall of *Eucalyptus* will be slower than those from the mixed composition over time. To test these hypotheses, we evaluated the rate of litter decomposition and return of nutrients between *Eucalyptus* leaves and a mixed composition of exotic and native leaves over a period of 6 months to determine the implications of using *Eucalyptus* spp. as an alternative for treescape replacement. The results of this investigation will be of great importance in promoting public policies that have been prepared by the City of São Paulo, such as the Municipal Plan for Urban Afforestation, and the Municipal Plan for Protected Areas, Green Areas, and Free Spaces, among others.

Materials and methods

Study area

The region comprising the study area of São Paulo is characterized by a warm, temperate climate with variable rainfall throughout the year (Fig. 1). The average temperature is approximately 18.5 °C, and the yearly pluviometric precipitation is about 1340 mm. The driest month of the year is July, while the wettest is January. February is the hottest month of the year, with an



average air temperature of 21.3 °C (Climate-Data.Org 2015). According to the Brazilian Institute of Geography and Statistics, the city of São Paulo counts approximately 12.5 million inhabitants and has a population density of 7.4 inhabitants/km² (IBGE 2020). Hence, the metropolitan area of São Paulo (MASP) produces a significant urban heat island effect. The center of the MASP is significantly warmer than its surroundings (i.e., green belt zone around MASP), having reached an increase in temperature of 3.8 °C over the past 80 years. The warmer built-up area also has lower relative humidity, greater thermal variability, and more intense and concentrated rainfall (IAG/USP 2015; Lima and Rueda 2018).

The study was carried out in Jardim Conquista Park, located in eastern São Paulo, which extends over an area of 559,292 m². This site was preserved as a protected area in 2014, but till now, no studies on floristic composition and vegetation structure have been reported. Nevertheless, it is possible to identify the presence of exotic species, for example, *L. lucidum* and *Eucalyptus* spp., among several other native species such as *P. granulatum* and *S. terebinthifolius*. The physical-chemical characteristics of the soil classify the study area as dystrophic yellowish-red latosol, typical, medium texture, with minimum content between 15 and 35%, and slightly acid pH (Table 1) (MDA 2008).

Table 1 Chemical properties of the soil in Parque Jardim da Conquista, the site of litterfall material exposure. pH potential of hydrogen, P phosphorus (mg/dm³), K potassium (mg/dm³), Ca calcium (cmolc/dm³), Mg magnesium (cmolc/dm³), H+Al hydrogen + aluminum (cmolc/dm³), SB sum of bases (cmolc/dm³), SOM soil organic matter (dag/kg), V base saturation (%)

Soil depth	pH	P	K	Ca	Mg	H+Al	SB	SOM	V
0–20 cm	6.1	230	207	5.35	1.72	1.9	7.6	2.74	80

Litter decomposition

Litter decomposition was assessed in terms of dry mass loss over time. In the first step of the assessment procedure, the leaves of native and exotic trees (Table 2) were randomly collected in litter traps and dried in an oven at 65 °C for 7 days. Afterwards, 72 nylon bags with a 1-mm opening (litterbags), measuring 25 cm × 25 cm, were filled with 10 g of the dry leaves. In the second step, 36 litterbags were prepared with a mixed composition of leaves from two native and two exotic species (hereinafter termed “mixed litterfall fraction” or MLF), and other 36 litterbags were prepared solely with the leaves of *Eucalyptus* spp. (hereinafter termed *Eucalyptus* spp. fraction or “EU”) (Table 2).

All the litterbags were randomly spread out on the soil of Jardim Conquista Park. For litter dry mass loss and nutrient return assessment, 12 litterbags were removed each month from the study area over a period of 6 months (Ferreira et al. 2014b). In the laboratory, the contents of each bag were washed under running water for 5 min to remove any excess nutrients from the leaves, whether originating from the park’s fauna or from atmospheric deposition, and dried in an oven at 65 °C for 7 more days.

According to the method of Ferreira et al. (2014b) and Ferreira and Uchiyama (2015), the litter decomposition rate was estimated applying an exponential model (Thomas and Asakawa 1993). The decomposition constant *k*, half-life (*t*_{0.5}), and loss of 95% (*t*_{0.05}) of the material were estimated based on the calculations of Shanks and Olson (1961).

Macro- and micronutrient cycling

To conduct a nutritional analysis of the leaves in canopy, about 15 mature and expanded leaves were collected from the extremities of branches given the fact that nutrient distribution increases or decreases in relation to

Table 2 Taxonomic and biogeographic characteristics of the chosen species in the present study

Species	Family	Popular name	Geographic origin	Status
<i>Eucalyptus</i> spp.	Myrtaceae	Eucalyptus	Australia	Exotic
<i>Ligustrum lucidum</i>	Oleaceae	Japanese privet	Japan	Exotic
<i>Ficus benjamina</i>	Moraceae	Fig tree	Asia	Exotic
<i>Schinus terebinthifolius</i>	Anarcadiaceae	Brazilian peppertree	Brazil	Native
<i>Tibouchina granulosa</i>	Melastomataceae	Purple glory tree	Brazil	Native

the position of the leaf in the canopy (Magalhães and Blum 1999). Subsequently, all the leaves were dried in an oven at 65 °C for 7 days. The leaf material was then separated into 12 bags, 6 with MLF and 6 with EU leaves alone. All the material was chemically analyzed to determine nutrient contents. Carbon was estimated as 45% of the dry mass of the leaves (Lewis et al. 2009; Saatchi et al. 2011). The nutritional analysis of the leaves was carried out according to the method of Martins and Reissmann (2007). To analyze nitrogen translocation efficiency (NTE), the model proposed by Finzi et al. (2001) was applied as follows:

$$NTE\% = \frac{(N \text{ in green leaves}) - (N \text{ in litterfall leaves})}{(N \text{ in green leaves})} \times 100 \tag{1}$$

Data analyses

Loss of nutrients and dry mass over time was assessed using regression models. Several authors have reported high R^2 values (>70%) for litter decomposition through time in the tropics (Ferreira et al. 2014a; Ferreira et al. 2014b; Giweta 2020). To identify homogeneous groups based on litter origin (MLF or *Eucalyptus* spp.), a non-metric multidimensional scaling (NMDS) analysis was performed. The Bray-Curtis similarity metric index was employed in this analysis, considering a stress value < 0.15. Dissimilarity between the groups was tested using a multivariate analysis of similarity (one-way analysis of similarities, ANOSIM), considering a Bonferroni-correction p value of ≤ 0.05 and R value of <1 as significant. Multivariate analysis of variance (MANOVA) was used to determine if variance in the concentration of nutrients in the litter showed significant differences between the two types of material (MLF or EU). Concentration of nutrients was considered a dependent variable in the model, and the origin of the material (MLF or EU) was considered as an independent variable.

For metric standardization, all variances were standardized using z -transformation. The analyses were performed with SPSS Statistics 20 (Armonk, NY: IBM Corp).

Results

Litter decomposition

The material formed by MLF lost more mass over time than the material formed by EU. The decomposition constant (k) for MLF was estimated as $0.00322 \text{ g g}^{-1} \text{ day}^{-1}$ and for EU as $0.00207 \text{ g g}^{-1} \text{ day}^{-1}$, with $t_{0.5} = 215$ and $t_{0.05} = 931$ days for MLF, and $t_{0.5} = 334$ and $t_{0.05} = 1449$ days for EU. The rate of dry mass loss over time was faster in the bags with MLF compared to those with EU material (Fig. 2). In general, the beginning of the MLF decomposition curve was more pronounced, while in both cases a greater mass loss was observed in the first 30 days. After this time, the remaining dry mass values stabilized. R^2 values show that the model was highly reliable for the exponential decomposition presented by Shanks and Olson (1961), since it explained 84% of MLF decomposition and 90% of EU decomposition. The decomposition constant found is in the range of other studies in tropical forest (Table 3).

Macro- and micronutrient return

The average nutritional values found in canopy leaves which formed MLF differed from the values found for EU leaves. Overall, the fallen leaves of *Eucalyptus* contained a lower quantity of macronutrients. For example, the average nitrogen (N) and potassium (K) values were slightly lower in EU tree leaves than in the mixed leaves of the other trees (i.e., MLF). A similar trend was observed for other nutrients, such as calcium (Ca) and zinc (Zn), which presented

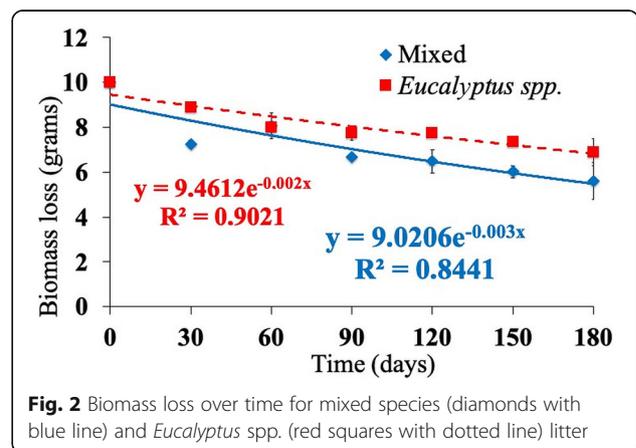


Fig. 2 Biomass loss over time for mixed species (diamonds with blue line) and *Eucalyptus* spp. (red squares with dotted line) litter

Table 3 Decomposition constant (*k*) and time required for decomposition of 50% and 95% of litter in studies conducted in the Atlantic Forest and Cerrado biomes. *t*_{0.5} and *t*_{0.05} time required to decompose 50% and 95% of the litter, respectively; *BI* biome (AF Atlantic Forest, CE Cerrado); *PR* precipitation

Location	BI	PR (mm)	<i>k</i>	<i>t</i> _{0.5}	<i>t</i> _{0.05}	Source
São Paulo, SP, Brazil	AF	1300	0.0027	248	1069	(Ferreira et al. 2014a, 2014b)
Itaguaí, RJ, Brazil	AF	2097	0.0049	124	540.2	Valente et al. (2005)
São Paulo, SP (mixed litter)	AF	1300	0.0032	215	931	This work
São Paulo, SP (<i>Eucalyptus</i> spp.)	AF	1300	0.0020	334	1449	This work
Guaraqueçaba, PR, Brazil	AF	2000	0.0068	365	1606	Scheer (2008)
Luis Antônio, SP, Brazil	CE	1684	0.0056	657	839.5	Cianciaruso et al. (2006)

concentrations three and two times lower in the EU group compared to the MLF group, respectively. However, it is worth noting that the manganese (Mn) concentration was much higher in the canopy leaves of *Eucalyptus*. When comparing the nutritional state of leaves in canopy with those recently fallen, we observed a loss of about 24% of N, 51% of phosphorus (P), 3.7% of K, and 14% of boron (B) for the MLF composition after leaf fall. EU leaves showed a loss of approximately 22% N, 52% P, 33% K, and 20% B. In this species, the concentration of Mn in canopy leaves was 31% higher than in that of fallen leaves (Table 4).

NTE was very similar in both leaf materials, with values of 22.93% for MLF and 24.03% for EU. In general, the macro- and micronutrient values found in MLF were higher than those found in EU, demonstrating that *Eucalyptus* leaves are nutritionally poorer. Each macronutrient returned to the soil at different rates over time. Nitrogen, for example, showed a similar curve between MLF and EU, with values and inclinations almost overlapping (Fig. 3a). In contrast with N, the values and

Table 4 Nutritional values of leaves in the canopy and litter. *N* nitrogen (g kg⁻¹), *P* phosphorus (g kg⁻¹), *K* potassium (g kg⁻¹), *Ca* calcium (g kg⁻¹), *Mg* magnesium (g kg⁻¹), *S* sulfur (g kg⁻¹), *B* boron (mg kg⁻¹), *Zn* zinc (mg kg⁻¹), *Mn* manganese (mg kg⁻¹), *Fe* iron (mg kg⁻¹), *Cu* copper (mg kg⁻¹)

Nutrients	Canopy		Litter	
	Mixed	<i>Eucalyptus</i> spp.	Mixed	<i>Eucalyptus</i> spp.
N	12.9 ± 0.11	11.6 ± 0.65	9.80 ± 0.70	8.94 ± 0.70
P	1.36 ± 0.13	0.72 ± 0.04	0.66 ± 0.09	0.34 ± 0.11
K	10.6 ± 0.95	7.82 ± 0.16	10.2 ± 0.88	5.26 ± 0.67
Ca	28.1 ± 2.21	15.1 ± 1.26	41.4 ± 3.24	13.2 ± 1.82
Mg	3.66 ± 0.42	2.16 ± 0.11	3.22 ± 0.31	1.60 ± 0.23
S	2.92 ± 0.18	0.98 ± 0.04	3.06 ± 0.15	0.64 ± 0.05
B	24.1 ± 1.43	23.5 ± 1.33	20.7 ± 0.95	18.7 ± 1.68
Zn	86.8 ± 24.6	22.5 ± 2.04	70.4 ± 18.8	22.4 ± 1.39
Mn	98.4 ± 21.1	1022.0 ± 69.1	77.7 ± 19.8	700.8 ± 81.3
Fe	115.1 ± 14.0	145.4 ± 41.5	113.6 ± 10.1	102.3 ± 11.8
Cu	5.84 ± 0.56	7.62 ± 0.70	4.10 ± 0.49	4.46 ± 0.33

inclinations of phosphorus, calcium, and magnesium were originally greater in MLF compared to EU, but over time, nutrient loss basically occurred at the same speed in both MLF and EU given that the slopes of the curves were similar (Fig. 3 b, d, and e). The litter composition of MLF and EU released elevated amounts of K into the soil in the first month of exposure and then stabilized over time (Fig. 3c). The sulfur contained in MLF litterfall declined in the first months of exposure, while EU litter maintained its low level of release from start to finish of exposure (Fig. 3f).

For micronutrients, B presented similar curves for both MLF and EU litterfall, with a greater reduction in soil nutrient return after the third month of exposure (Fig. 4a). The initial concentration of Zn in MLF was about 3-fold higher than that of EU and remained higher throughout the observation period (Fig. 4b). Manganese was the only nutrient that showed a slightly steep curve for both types of litterfall. The initial amount of Mn in the *Eucalyptus* litterfall was nearly three-fold higher than the amount found in the mixed litterfall (Fig. 4c). Iron (Fe) concentration in MLF showed strong variability of data around the average for most observed values. This element showed a decomposition curve oscillating over time with absolute values at the beginning of exposure twice those for MLF at the end of the study (Fig. 4d). Both types of litterfall presented very similar curves for copper (Cu) loss, and a gradual loss could be observed by the end of leaf exposure (Fig. 4e).

In relative terms, dry mass loss in the MLF material was observed to be higher than that in the EU material, with values of about 44% and 31%, respectively (Table 5). Overall, MLF macronutrients demonstrated relative losses which were more dramatic when compared to the EU material, except for P and Ca. The micronutrients also presented the same trend, except for Zn.

The MLF material, in general, had lower carbon C/N, C/P, and N/P ratios than the EU material, and from the fourth month of exposure, the C/N ratio, as well as the C/P ratio, registered a greater increase. The N/P ratio showed a decreasing curve over time (Fig. 5).

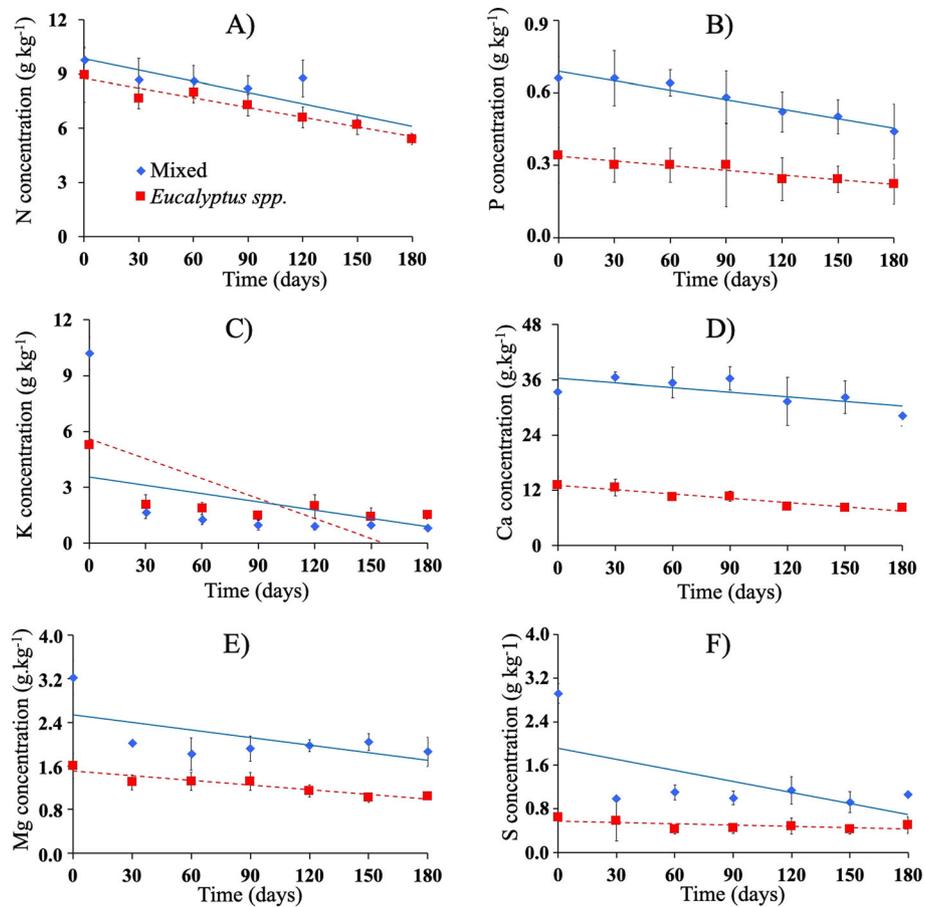


Fig. 3 Loss of macronutrients over time in mixed species (diamonds with blue lines) and *Eucalyptus* spp. (red squares with dotted lines). **a** Nitrogen loss, **b** phosphorus loss, **c** potassium loss, **d** calcium loss, **e** magnesium loss, **f** sulfur loss

Comparing mixed and *Eucalyptus* compositions

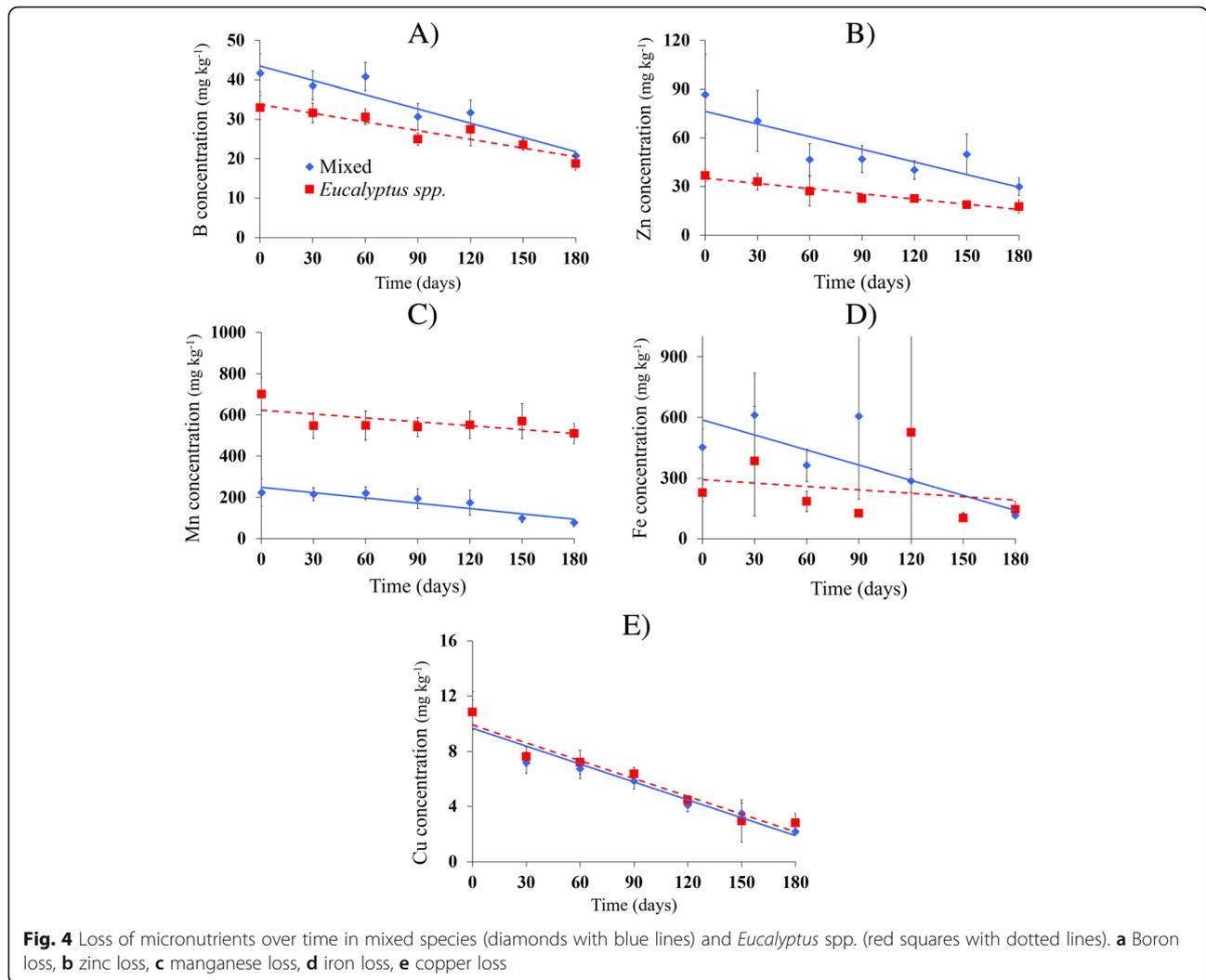
After performing multivariate analyses, the loss of macro- and micronutrients showed two homogeneous groups promoting a distinct separation of the material composed by MLF and *Eucalyptus* spp. alone (Fig. 6). Thus, the lack of clustering between the groups shows the high dissimilarity between the MLF and EU compositions. Moreover, the EU sample group presented a greater internal similarity, which was to be expected since the group formed by the mixed composition presented higher diversity due to the combination of exotic and native species. The separation into homogeneous groups, as shown by NMDS, was significant with statistical inference values of $p < 0.0001$ and $R = 0.75$, as determined by ANOSIM. This means that for the analyzed variables (macro- and micronutrients), the set of EU leaves presented different characteristics of nutrient cycling when compared to MLF.

MANOVA showed a multivariate difference in the effect of litter origin, unlikely to have occurred by sample mistake or by accident, presenting a p value of

> 0.001 (Table 6). It is also possible to observe that this effect in litter origin is responsible for about 98% of multivariate variability in the dataset (η^2 partial = 0.979), corroborating the NMDS graphics.

Discussion

This study revealed that the decomposition constant (k) and time to decompose 50 and 95% of litter was close to the expected for non-urban rainforests. The values reported by Ferreira et al. (2014b), who also conducted a similar study in the urban area of São Paulo, were close to those found for the mixed litter in this study. On the other hand, the k values presented by Valente et al. (2005), who studied a location with similar vegetation type, were almost half those observed in our study. In this case, it can be inferred that urban areas influence litter decomposition processes, especially because they interfere with microbial activities, i.e., external factors such as microclimate and the deposition of atmospheric contaminants that can vary considerably in less anthropized areas (Moraes et al. 1999). Several other factors

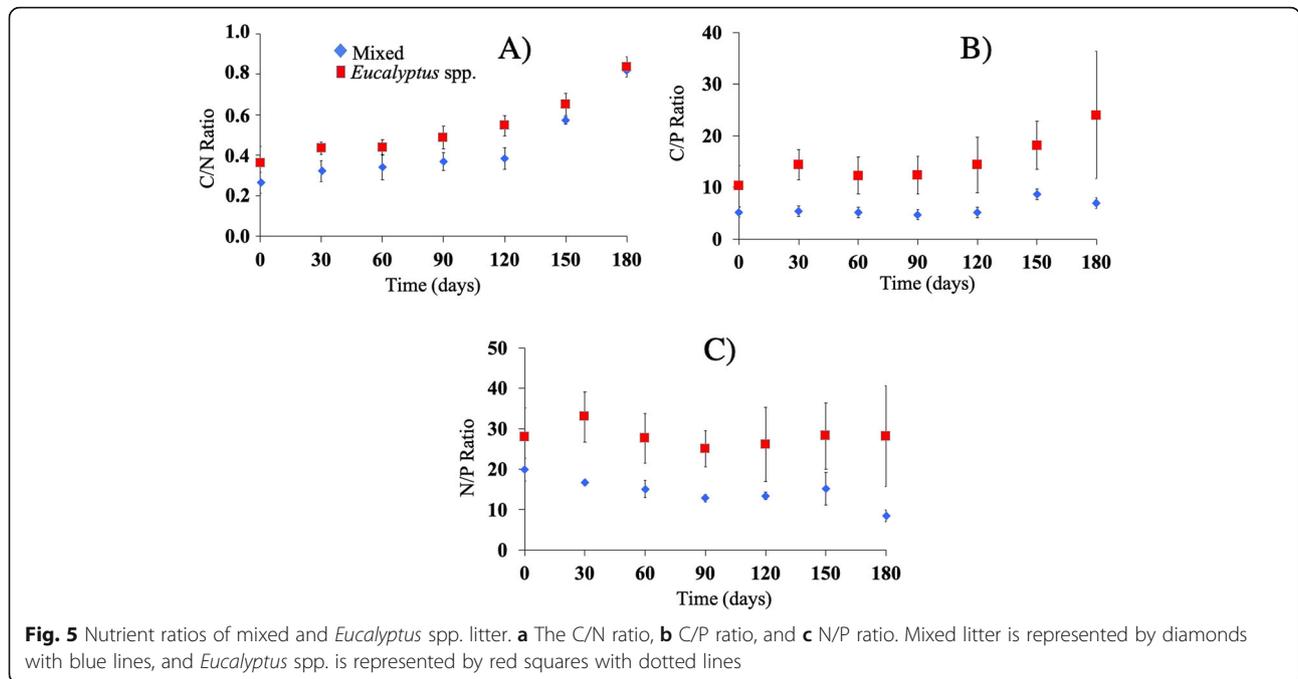


might interfere with decomposition processes. Scheer (2008) reported that abiotic factors have a strong influence on litter decomposition rates, especially in the first months of exposure when high values of available macronutrients are found in deciduous material (Fig. 3). This finding lends support to the evidence that divergent particularities can affect nutrient return to urban forest soil.

Of relevance is the fact that the edaphic flora and soil macro-invertebrates responsible for litter degradation and decomposition might differ in urban areas as a result of insufficient space to maintain stable populations, which, in turn, may be reflected in the time required to decompose organic material. However, considering that the MLF and EU material were under the same climatic regime and environmental interferences, *Eucalyptus* litter was less efficient in losing mass to the forest floor than that formed by MLF. Thus, the results confirm the hypothesis that the leaves of MLF material are, in fact,

Table 5 Relative values of nutrients and mass loss in mixed and *Eucalyptus* spp. litter between the first and last month of observation. *N* nitrogen, *P* phosphorus, *K* potassium, *Ca* calcium, *Mg* magnesium, *S* sulfur, *B* boron, *Zn* zinc, *Mn* manganese, *Fe* iron, *Cu* copper

Nutrient/mass	Mixed (%)	<i>Eucalyptus</i> spp. (%)
Mass	44.0	31.1
N	43.9	39.6
P	24.2	35.3
K	92.4	71.5
Ca	19.5	24.6
Mg	42.2	35.0
S	65.4	21.9
B	46.2	45.7
Zn	28.2	39.0
Mn	60.2	27.3
Fe	78.7	66.5
Cu	64.2	59.3



more efficient at decomposing and cycling nutrients than the material composed only of *Eucalyptus* leaves, which might drive the restoration process in some urban areas.

The mixed composition of litter was also more efficient in nitrogen retranslocation than were the *Eucalyptus* leaves, demonstrating a greater efficiency of these species in translocating nitrogen prior to leaf abscission, which generates less dependence on the nitrogen absorbed by plant roots. Finzi et al. (2001) showed similar nitrogen retranslocation values for *Betula ermanii* (34%), but higher values for *Sasa kurilensis* (51%). This value was not higher in *Eucalyptus* leaves, given that the

strategy is expected to be more efficient in faster-growing exotic species.

The abundant presence of macro- and micronutrients in tree leaves forming MLF shows a particularity which is very favorable for the establishment of tree species in the soils of tropical areas (Gama-Rodrigues et al. 2003). Even though MLF composition is not formed exclusively by the leaves of native species, the strategy of mixing native and exotic species has been widely used in reforestation programs, since some non-native trees have a high potential for decorating public spaces. An example of this use of exotic species can be found in the

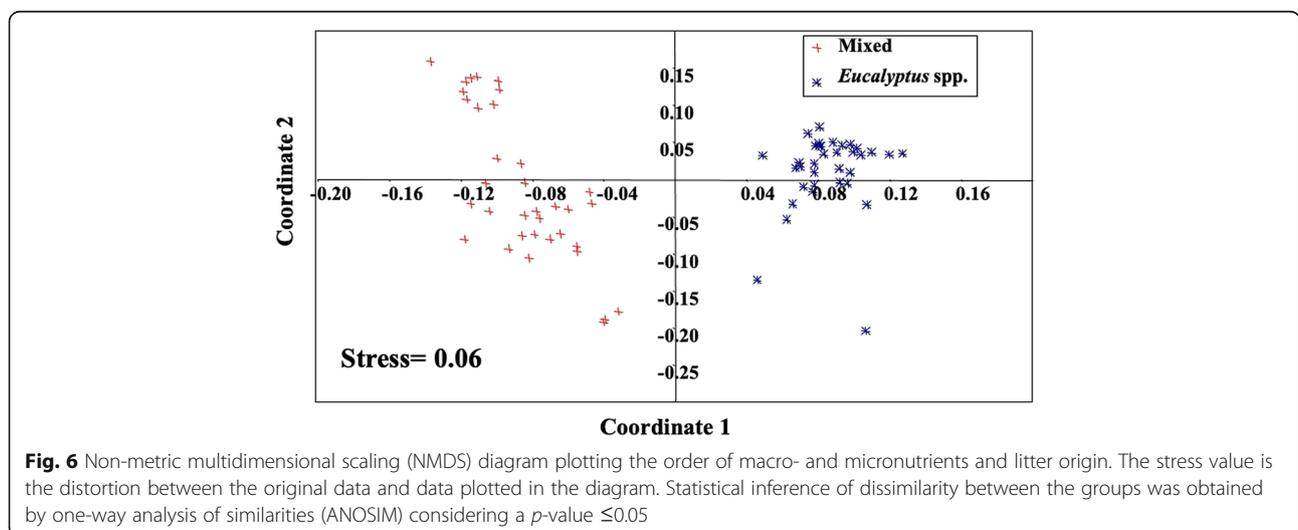


Table 6 Main effects of origin, time, and the interaction between both (origin \times time) on macro- and micronutrients obtained by multivariate analysis of variance (MANOVA)

Effect	Wilks λ value	Degree of freedom (DF)	DF error	p value	η^2 partial
Interception	1.000	11	50.000	1.000	>0.001
Origin	0.021	11	50.000	>0.001	0.979
Time	0.679	44	193.242	0.998	0.092
Origin \times time	0.675	44	193.242	0.998	0.094

Significance occurs at the 0.05 level

recently updated Reforestation Manual of São Paulo City (São Paulo 2016).

The discrepancy in nutritional content reported between the canopy leaves of EU and those forming MLF can be attributed to an intrinsic characteristic of each species, even though the initial Mn content in *Eucalyptus* spp. litter was almost twice that of MLF (Magalhães and Blum 1999; Gama-Rodrigues et al. 2003). Aside from the amount of nutrients in the leaves, some elements are scarce in nature but still very important for vegetal metabolism. Thus, plants translocate some elements through the phloem, optimizing their reutilization for metabolic activities (Xu et al. 2012). Some authors have shown that the nutritional scarcity in soil makes plants more efficient in nutrient translocation, thus interfering with soil fertility maintenance in tropical forests (Silva et al. 1998; Nunes et al. 2014). This was the case for some nutrients that exhibited values in recently fallen leaf material that were much smaller than the values observed in canopy leaves.

Macronutrients, including N, P, and K, are important for building biological tissue and maintaining metabolic processes. As such, they are fundamental elements for biodiversity maintenance (Vitousek 1984). The loss of these elements during the first 30 days of the study demonstrates the efficiency of decomposing organisms before the elements are eventually leached from the system (Boeger and Wisniewski 2003). MLF potassium revealed a more evident decomposition in time than did EU potassium. These results reinforce the concept that initial concentrations of N, P, and K have major influences on mass loss (Yang et al. 2004; Tatenó et al. 2007).

The loss of N, P, and K reported in this study is in agreement with the results of Parrota (1999) and Wang et al. (2008), who found a greater loss of these elements in MLF compositions than in the litter composition of only one species, even though these studies were not specifically focused on the use of exotic or alien species. In studying MLF compositions, Wang et al. (2008) found that the rapid decomposition of deciduous material accelerates nutrient return to the soil, thus facilitating tree growth and the increase of litterfall production.

The Ca decomposition curve over time was higher for MLF than for EU litter. This could be attributed

to the high Ca content contained in litter composition as well as the multiple benefits that elements provide to the microbial community in the soil. Specifically, Ca promotes the reduction of acidity in the edaphic system, increases microbial activity, decreases aluminum toxicity, and indirectly benefits root development. Asner and Martin (2015) reported a relationship between soil fertility and the presence of both P and Ca in the tree leaves of a tropical region. Although a phylogenetic signal in nutritional content is found in the tree leaves of tropical regions, this finding suggests that the amount of P and Ca in leaves can be strongly influenced by the conditions of the study site.

Sulfur (S) in MLF decreased more than in EU litter over time. This element is known to play an important role in maintaining bacterial populations, since the oxidation of sulfates present in the soil is strongly associated with the presence of autotrophic aerobic bacteria (Kennedy 1999), thereby strengthening the food chain in the edaphic system.

It was observed that zinc, a micronutrient, declined constantly throughout the experimental period in the material formed by *Eucalyptus* leaves. A different behavior was observed in MLF over time. According to Martins (2009), soil pH can interfere with the availability of Zn for plants and other decomposing organisms.

The micronutrients boron and manganese showed stability over time in *Eucalyptus* spp. litter, unlike the mixed species that showed significant decomposition. Manganese plays a crucial role in photosynthesis, and its release and consequent reabsorption are very important to protect new leaves against fungi and to participate in energy metabolism (Malavolta et al. 1997). In the present study, the mixed composition of litter presented a higher contribution of Mn return, demonstrating the potential for quickly aiding forest productivity. The iron decomposition curve in this study showed strong data variability around the average, making it difficult to visualize any trend over time. The return of copper to the soil presented a similar curve between MLF and EU composition; however, mixed species presented a greater amount of this content during all analyzed periods. Mateus et al. (2008) reported an association between Cu

and soil organic matter, which contributes to its rapid absorption by the edaphic system.

The study showed that MLF was more efficient in losing mass and returning nutrients to soil than EU. This finding reinforces the use of a mixed species approach in restoration programs of urban areas instead of a single species approach, as was done in some São Paulo reforestation programs.

The efficiency of nitrogen use is often characterized by high values of the C:N ratio (Vitousek 1984; Luca et al. 2018). The present study identified an increase in this ratio over time noting that, proportionally, N was preferably consumed by decomposers in relation to C (Fernandes et al. 2006; Tripathi et al. 2006). One important factor that could interfere with this relationship is the abundance of Leguminosae, which might alter the availability of N in the soil (Siddique et al. 2008). Pinto et al. (2016) also found higher values of C and N in *Eucalyptus* litter in relation to native forest leaves in Bahia, Northeastern Brazil. The authors related the lower C:N ratio in native leaves to the quality of the material and thus the preference for decomposition by microbial diversity. The C:P ratio followed a trend similar to that of nitrogen; however, the same increase was not noticed after 150 days of material exposure, as shown in the C:N ratio. In EU litter, the N:P ratio revealed that nitrogen loss was higher than phosphorus loss over time, highlighting the decomposition rate in time and increased nitrogen consumption in relation to phosphorus.

Multivariate analyses (NMDS and MANOVA) clearly pointed out that litter nutrient loss to the soil is distinct between MLF and EU. Such evidence further reinforces the efficiency of mixed composition in nutrient cycling in the urban forest of São Paulo. It also emphasizes that having used *Eucalyptus* spp. in the green area reforestation programs of São Paulo over the last century can impact ecosystems in city forests.

The results presented herein clearly shed light on the ecological implications of São Paulo's reforestation programs in the last century, which have basically appropriated *Eucalyptus* as a species to recompose urban green areas. However, a larger number of species must be tested to obtain greater clarity on nutrient cycling in urban forest fragments (Sanesi et al. 2017; Tomao et al. 2017).

Conclusions

Litter formed by mixed species shows a higher decomposition rate in relation to that formed only by the leaves of *Eucalyptus* spp. This was demonstrated by major mass losses and nutrient return to the soil. In general, nutrients were found in higher amounts in MLF and yielded higher soil return values compared to EU material; the same trend was observed for micronutrients. The C:N and C:P

ratios exhibited an efficient devolution of these elements to the edaphic system, highlighting their importance in the decomposing community.

The significant difference in nutrient return, as shown by NMDS and MANOVA, reinforces the concept that in urban reforestation programs the City of São Paulo must consider the environmental and biogeographic characteristics of the species employed. Relevant attributes of city treescapes such as high-shade capacity and relatively fast growth are important, but soil nutrient return must also be accounted for so that vegetation can contribute to higher soil fertility and better conditions for urban forest productivity (Mattijssen et al. 2017; Chen et al. 2016).

Abbreviations

MASP: Metropolitan area of São Paulo; EU: Leaves of *Eucalyptus* spp.; MLF: Leaves from two native and two exotic species; NMDS: Non-metric multidimensional scaling; ANOSIM: One-way analysis of similarities; MANOVA: Multivariate analysis of variance; N: Nitrogen; P: Phosphorus; C: Carbon; K: Potassium; Ca: Calcium; Mg: Magnesium; S: Sulfur; B: Boron; Zn: Zinc; Mn: Manganese; Fe: Iron; Cu: Copper; pH: Hydrogen potential; H + Al: Hydrogen + aluminum; SB: Sum of bases; SOM: Soil organic matter; V: Base saturation

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Authors' contributions

All authors have collaborated in an equal manner in designing the work, collecting and analyzing data, or writing the manuscript. All authors have read and approved the final manuscript.

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Availability of data and materials

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Declarations

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Consent for publication

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Competing interests

The authors declare they have no competing interests.

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