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Atmospheric pollution assessed by in situ measurement of magnetic susceptibility on lichens

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ABSTRACT

The use of environmental magnetism methods and biomonitors allows us the development of a low-cost tool for assessing atmospheric pollution through trapped magnetic particulate matter. Such particles concentration was monitored in situ, on the lichen's thallus, using magnetic susceptibility as a pollution proxy. We studied the magnetic particle distribution on the thallus surface from weekly measurements of in situ magnetic susceptibility κ_{is} during 16 months for seven sites. A total of ~8300 measurements was carried out; and mean overall κ_{is} values for each lichen varied between 4.1 and 23.9×10^{-5}SI revealing the influence of different atmospheric pollution sources on *Parmotrema pilosum*, such as metallurgical factories and vehicular emissions. Weekly measurements of κ_{is} show areas of magnetic accumulation on the thallus over a period of 60 measurement campaigns. Iron rich spherules and irregular particulate matter between $PM_{2.5}$ and $PM_{1.0}$ were observed by SEM-EDS. A joint analysis of meteorological variables and magnetic susceptibility shows an inverse relation between this magnetic parameter and temperature, i.e., a trend of decreasing κ_{is} values during seasons of higher temperatures which tend toward higher values of atmospheric mixing height. Precipitation also affects the magnetic signal over time, producing decreases in mean values of κ_{is} after rainy periods.

1. Introduction

The terms bioindicator and biomonitor have different meanings, the first one refers to the use of organisms through which any current (or past) phenomenon or event related to the study of the environment can be decoded. The second term is the quantitative measurement of particulate matter, elements and compounds (e.g., polycyclic aromatic hydrocarbons PAHs, polychlorinated biphenyls PCBs, etc.) deposited and/or accumulated in organisms or their parts. Among epiphytic species, lichens, *Tillandsia* spp. and mosses in their natural state have been used as bioindicators and/or biomonitors (Shacklette, 1973; Grodzinska, 1978; Schrimpff, 1984; Rhoades, 1999; Ares et al., 2012; Chaparro et al., 2013; Kováčik et al., 2014). Lichens are recognized as air pollution bioindicators and biomonitors, as due to the absence of a root system, a protective cuticle, and of stomata, their exchange of nutrients with the atmosphere occurs over the entire surface of their thalli; moreover, they grow slowly and are long-lived (Zschau et al., 2003; Lodenius, 2013). Lichens accumulate metals and others pollutants (NO_2, SO_2, HF, ozone compounds and particulate matter) from the atmosphere by dry and wet deposition (Sett and Kundu, 2016, Boamponsem and de Freitas, 2017). Particulate matter (PM) and potentially toxic elements (PTE) can be incorporated by these natural collectors in different ways and times.

According to Chaparro de Valencia and Aguirre Ceballos (2002), the accumulation of contaminants in the lichen's thallus over time may be determined because of their longevity. The growth of lichens depends on the presence of PM and/or PTE and may even stop in highly contaminated environments (Bardelás, 2012); since the lichen's sensitivity is greater (and resistance is lesser) when the stems are young. In particular, the growth can be interrupted by high values of SO_2; although some species such as *Lecanora conizaeoides* have shown in experiments to be resistant to this compound. Kováčik et al. (2011) studied the physiological responses of lichens *Hypogymnia physodes and Xanthoria parietina*, as well as the Bromeliaceae *Tillandsia albida,* exposed to

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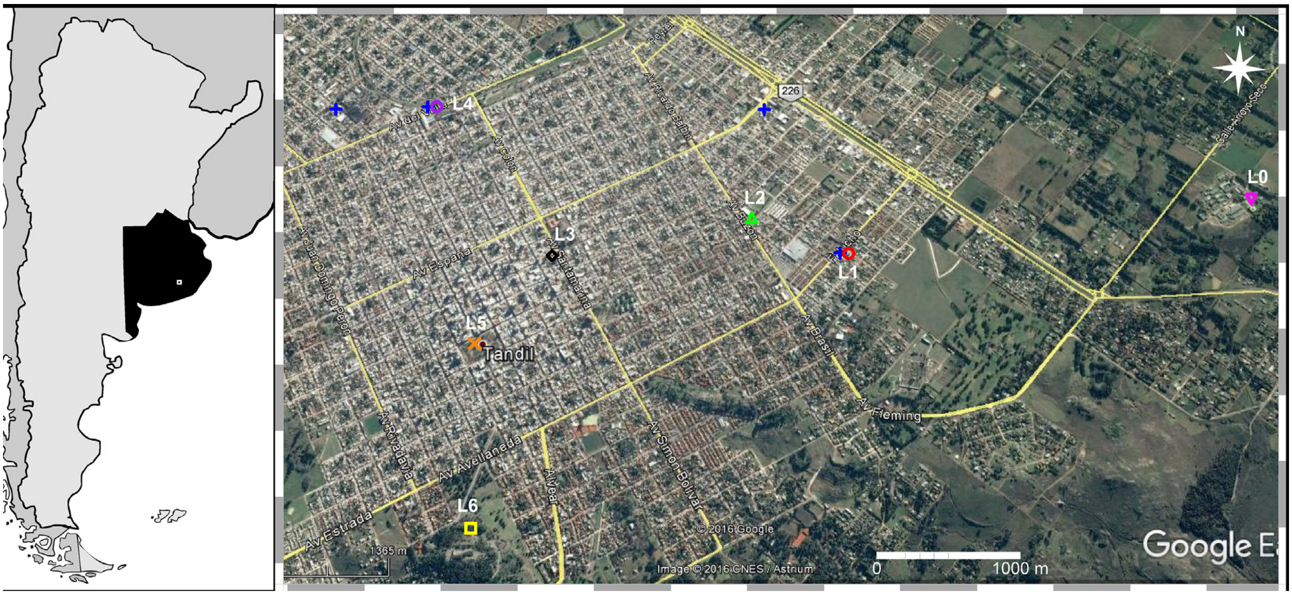

Fig. 1. Study area in Tandil city (Buenos Aires Province, Argentina). Measurement sites (and lichen individuals L0–L6) and metallurgical factories location (plus signed).

simulated acid rain. Pigments were depressed in all species, with *Tillandsia* sp. being the most affected. Macronutrients (K, Ca, and Mg) decreased more pronouncedly in comparison with micronutrients in all species. The comparison between lichen species showed that *X. parietina* has the highest tolerance, suggesting its use as a long-term biomonitor. Recently, studies carried out by Kováčik et al. (2018a,b) showed changes in metabolism and oxidative stress symptoms for two lichen species *Cladonia arbuscula* subsp. *mitis* and *Cladonia furcata* exposed to Ni, Cu, and Cr excess.

Sett and Kundu (2016) found that the lichen's size is a good indicator of air quality. However, the lichen growth rate is species dependent and is influenced by their habitat, that is, specific geographical conditions for each zone, such as height above the sea level, length of sun exposure, etc. Dumont et al. (2013) obtained a growth rate for lichen *Caloplaca cinericola* of 0.2 mm/year that is comparable to those obtained by Lindsay et al. (1973) for the species *Rhizocarpon geographicum* (0.13 mm/year), where their studies were carried out in the Antarctic Peninsula.

The use of biological material for atmospheric pollution monitoring is an alternative method to assess the air quality in urban areas and other sites of interest such as industrial settings (e.g., Salo et al., 2014; Abril et al., 2014; Castañeda Miranda et al., 2016; Gargiulo, 2018). Magnetic biomonitoring combines environmental magnetism techniques and the use of biological collectors (e.g., epiphytic species) for assessing industrial and urban pollution. This kind of magnetic biomonitoring studies has become a methodology of growing interest since last decades. Jordanova et al. (2010), Chaparro et al. (2013), Marié et al. (2016), and Kodnik et al. (2017) have conducted magnetic monitoring studies using different lichen species as biomonitors of atmospheric pollution. Chaparro et al. (2014), Castañeda Miranda et al. (2016) and Mejia-Echeverry et al. (2018) proved the inexpensive use of *Tillandsia* spp. as efficient collectors and sensors of airborne pollutants, which allowed identifying adversely impacted areas in Argentina, México and Colombia. Fabian et al. (2011), Salo et al. (2012), and Vuković et al. (2015) used in situ and transplanted mosses for monitoring air pollution in Norway, Finland and Republic of Serbia.

Marié et al. (2016) determined that among 20 species of corticolous foliose and microfoliose lichens, *Parmotrema pilosum* was the most abundant species living in tree bark and having a good distribution over the urban area of Tandil city (Argentina). The aims of the present work are: a) to study the *P. pilosum* morphological change and its growth rate during 60 measurement campaigns; b) to determine the distribution of magnetic particulate matter on thalli surface for lichens exposed to different pollution sources; c) to evaluate temporal changes of such PM distribution and the influence of meteorological conditions during about one year; d) last but most important, to validate the use of in situ measurements of magnetic susceptibility (κ_{is}) on lichen's thallus as a novel methodology for magnetic assessment of the atmospheric pollution over periods from days to years, which is non-destructive and thus preserves the species.

2. Methods

2.1. Study area, measurement sites and lichens

This study was carried out in Tandil city (37° 19.5′ S; 59° 08.3′ W), which is located in the SE part of Buenos Aires Province, Argentina. The city has a population of 125,000 inhabitants (Censo, 2010) and a number of 60,000 vehicles (Sosa, 2015), including cars, trucks and heavy transport. The study area has a sub-humid to humid climate and is characterized by strongly differing summer and winter seasons that is a distinctive characteristic at this Pampean region. As general characteristics, summer seasons are hot and rainy, and the winters are cold and dry. Meteorological analysis realized in 2001–2010 (Picone et al., 2012) indicates an annual mean temperature of 13.4 °C and annual precipitation of 845.2 mm (Picone, 2014; Sosa, 2015). Meteorological variables for the study period (March 2016–July 2017) indicate an annual precipitation of 1237.6 mm, and maximum and minimum mean temperatures of 19.6 °C and 6.7 °C, respectively (CIM, 2017).

Seven lichen individuals labelled as L0 to L6 were selected in locations with variable pollution sources and intensities within this urban area (Fig. 1- Table 1). The species *Parmotrema pilosum* living on tree bark was studied for these seven sites.

The longest measurement period was carried out on a lichen located close to a car parking at the University Campus (L0, Fig. 1) where the only pollution source is vehicular emission of busses and cars. An individual thallus of about 70 mm of diameter located at 98 cm above the ground was selected. In addition, other six lichens of the same species exposed to other pollution sources were selected (L1–L6, Fig. 1). Lichen L1 is located in the vicinity of two metallurgical factories and on an avenue with high vehicular traffic, being one of the main accesses to the city. L4 is pinpointed in front of an important metallurgical factory and

Table 1
Lichen samples inside of urban area with influence from different pollution sources. The distance from base (h) and the tree diameter at 150 cm from the tree base (DBH) are detailed, as well as, measurements of lichen thallus surface between March 2016 and June 2017 and its corresponding growth rate.

Lichen	Site observation	Latitude [UTM m E]	Longitude [UTM m N]	h [cm]	DBH [cm]	Lichen thallus area [mm^2]							Growth rate [mm^2/week]						Annual growth rate [mm^2/yr.]
						Mar. 2016 fall	Aug.2016 winter	Oct. 2016 spring	Nov. 2016 spring	Jan. 2017 summer	Feb. 2017 summer	Jun. 2017 winter	Aug–Jan/Feb spring-summer	Mar–Aug fall-winter	Aug–Oct spring	Oct–Nov spring	Nov–Jan Summer	Jan/Feb–Jun Summer-Fall	
L0	Parking at University Campus	315656.0	5867486.0	98	75	4338	4583	4806	4982	5175	–	5581	26.9	14.4	22.3	58.7	21.4	21.4	953.2
L1	Metallugical factory	313048.5	5867186.3	186	97	–	7585	7697	–	–	–	–	–	–	11.2	–	–	–	583.9
L2	Bus terminal	312405.4	5867480.3	193	133	–	2584	–	–	–	2718	–	5.0	–	–	–	–	–	258.8
L3	Square	311117.6	5867248.5	117	139	–	2562	–	–	–	2918	3344	13.2	–	–	–	–	30.4	687.5
L4	Metallugical factory	310312.7	5868405.5	147	159	–	2360	–	–	–	2675	–	11.7	–	–	–	–	–	608.3
L5	City centre	310639.3	5866606.2	182	63	–	3333	–	–	–	3446	–	4.2	–	–	–	–	–	218.2
L6	Green area – Control	310679.6	5865210.8	153	210	–	2243	–	–	–	2429	–	6.9	–	–	–	–	–	359.2

on an avenue. The remaining lichens are influenced by vehicular emissions as the main source of pollution. Lichen L2 is located behind the bus terminal; L3 in a square on an avenue and L5 at downtown. A control site (L6) located in a green area (park) at high elevation and with minimal pollution influence was also studied. The lichen locations, height above the ground, and the trunk diameter at 150 cm height from the ground are detailed in Table 1. Lichen contours were recorded on tracing paper with a grid and scanned in the laboratory.

2.2. Magnetic measurements

Measurements were done in situ using the susceptibility meter MS3 (Bartington Instruments Ltd.) connected to an MS2E sensor, which is designed for doing high resolution measurements of magnetic susceptibility (κ) along surfaces. Measurements were done using the resolution range (0.1×10^{-5}SI), and κ values were corrected for drift through a 3 measurement protocol (two air and one sample readings). Accuracy value for this measurement is 2% of the measured value; the sensor has a response area of 4 mm × 10 mm, and 50% of the magnetic signal is integrated from 1 mm depth. A measurement grid of 10 mm spacing was used for mapping the thallus surface. Measurements were made over a period of 60 measurement campaigns for L0, and 44 measurement campaigns for Lichens L1–L6.

A tracing paper with a grid of 10 mm × 10 mm was used for each lichen, with the center matched to the lichen's growing center. The lichen's contour was recorded and measurement points inside the thallus surface were marked for centering the susceptibility sensor. This was oriented with the long response axis horizontally. Susceptibility contour maps were constructed using each weekly dataset of κ_{is} (about 50 values for each lichen) in order to study the concentration and distribution of magnetic PM accumulated on the thallus of each *P. pilosum*.

The magnetic PM density and distribution on the thallus surface was determined from weekly measurements of κ_{is} during 60 measurement campaigns for L0, accounting for a total of ~3200 measurements. The other lichens (L1–L6) were measured during a shorter period of about 44 campaigns and involved ~1000 measurements for each lichen. A total of ~8300 measurements of κ_{is} was carried out during this study.

2.3. Scanning electron microscopy

In order to characterize the PM morphology and quantify its elemental composition, two small thallus portions (about 3 mm × 3 mm) from L0 were cut after 27 weeks, identified as C1 and C2 (Fig. 2), and stored in the laboratory for additional microscopy studies. Such small samples that include the deposited particles on its surface were mounted on an Aluminum plate and carbon coated, which was designed to avoid altering particle morphology. Particles were identified by a Phillips model XL30 scanning electron microscopy (SEM). This microscope also allowed to analyze the elemental composition of each specimen by X-ray energy dispersive spectroscopy (EDS) with an EDAX model DX4 (detection limit 0.5%).

3. Results and discussion

3.1. Growth rate of Parmotrema pilosum

The thallus area of L0 was determined by scanning its surface six times during 60 measurement campaigns, from March 2016 (4338 mm^2) to June 2017 (5581 mm^2) (Table 1, Fig. 2). The polygonal maps were created from each lichen scan and its corresponding thallus area was calculated by using open source software (QGIS software). Surface growth rate between measurement periods is expressed as area increase per week (mm^2/week). Growth rates varied between 14.4 and 58.7 mm^2/week and was in average 18.3 mm^2/week (0.4% of its surface per week) over the period of 16 months (68 weeks). The lowest growth rate was recorded during autumn/winter, and the highest

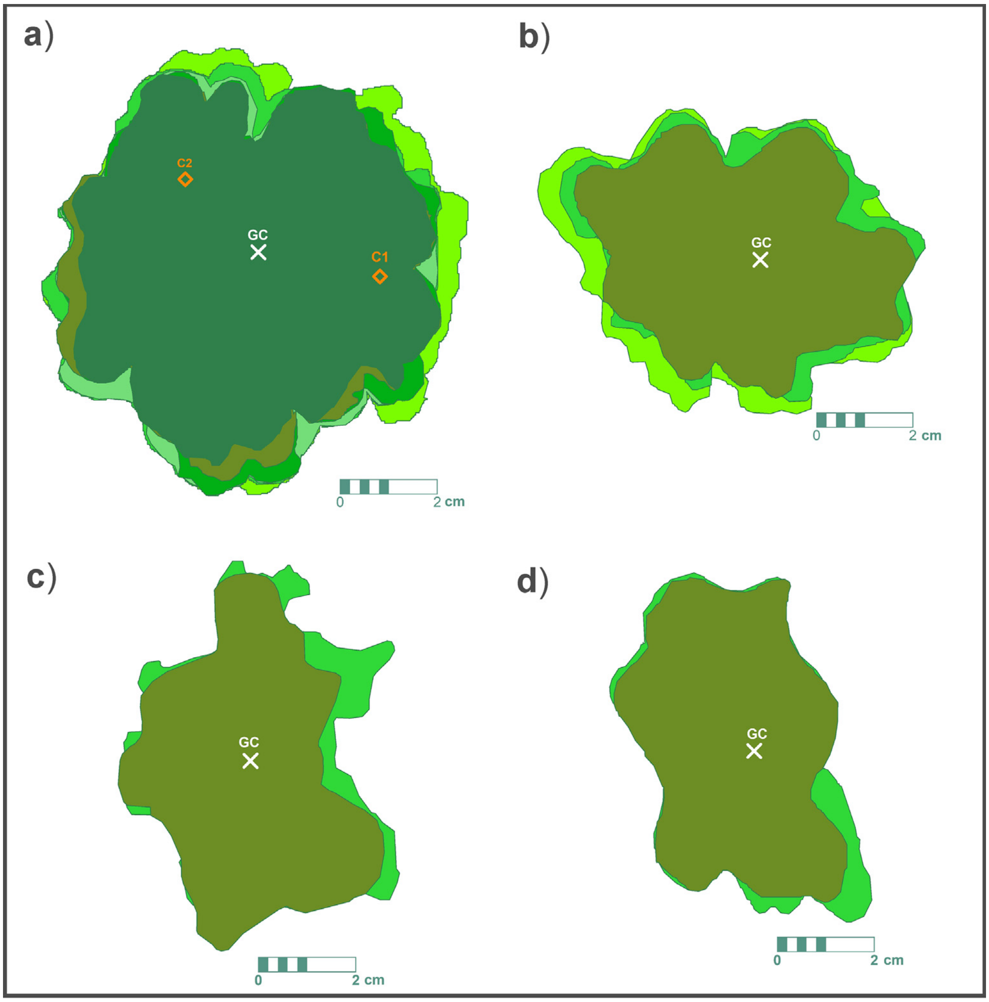

Fig. 2. Size measurements of lichen's thallus surface for L0 (a); L3 (b); L4 (c); and L6 (d). Measurement periods are: March 2016 (forest green), August 2016 (olive green), October 2016 (pale green), November 2016 (lime green), January 2017 (yellow green) and June 2017 (lawn green). The growing center (white cross) and extracted thallus portions (3 mm × 3 mm) C1 and C2 for SEM-EDS analysis (orange diamond) are indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

during winter/spring when this lichen seems to be more active as evidenced by its growth rate (Table 1). Nash et al. (1995) and Bačkor and Loppi (2009), also reported a greater metabolic activity during wet periods, which favors mineral absorption and growth.

The thallus areas of lichens L1, L2, L3, L4, L5, and L6 were only determined twice during measurement campaigns 10 and 27, from August to October 2016 and to February 2017 (Table 1). The growth rates for these lichens varied between 4.2 and 13.2 mm^2/week, being lower than the growth rate of 26.9 mm^2/week of L0 for a comparable period of 22 weeks.

Growth rates were variable between individuals (percent annual growth = 6.5–26.8%) and therefore growing conditions seem to be a site-specific characteristic. Because lichens usually live in habitats where nutrients are scarce (Johanson et al., 2012), their exposition to atmospheric deposition can show different responses, ranging from increased growth (McCune and Caldwell 2009) to becoming unhealthy or even die (Bando and Sugino, 1995). Sometimes the same lichen species can show a first phase in which its growth rate is accelerated followed by a deceleration before dying (Johanson et al., 2012). This could explain why *P. pilosum* reacted in some contaminated sites with a high growth rate (L3 and L4), while in others the growth rate decreased (L1 and L2) as the species were in the final phase of accumulation. In addition, since there are no native trees in the study area, *P. pilosum* is an exotic species. This species characteristic and its wide distribution in the area (Marié et al. 2016) indicates that it is a wide-ranging species, another common characteristic in pollution-tolerant species.

3.2. Fe-rich particles on thallus and in situ magnetic assessment

Magnetic properties of trapped PM were determined from the magnetic susceptibility, which is a concentration dependent parameter used as a proxy for atmospheric pollution (Petrovský and Elwood, 1999). This parameter allows assessing the magnetic concentration of iron rich particles trapped in biomonitors like corticolous foliose and microfoliose lichens as reported by Chaparro et al. (2013). Magnetic enhancement on lichen's thallus is based on two contrasting magnetic minerals: ferrimagnetic (magnetite) and ferromagnetic (iron) materials (with specific magnetic susceptibility $\chi = 0.4\text{–}1.1 \times 10^{-3}\,m^3\,kg^{-1}$, and $\chi = 2.8 \times 10^{-1}\,m^3\,kg^{-1}$, respectively), which are much different from the diamagnetic matrix of the organic thallus ($\chi = -0.9 \times 10^{-8}\,m^3\,kg^{-1}$; Dearing, 1999). Natural particles may be differentiated from the anthropogenic ones because they are generally irregular in shape and their composition contains lithic material, with the exception of those containing iron and titanium oxides, which can be both of anthropogenic or natural origin.

SEM observations on the thallus portions with slightly different magnetic susceptibility values ($\kappa_{is} = 18.0 \times 10^{-5}$SI for C1; and $\kappa_{is} = 14.5 \times 10^{-5}$SI for C2) that were extracted at the 27th campaign,

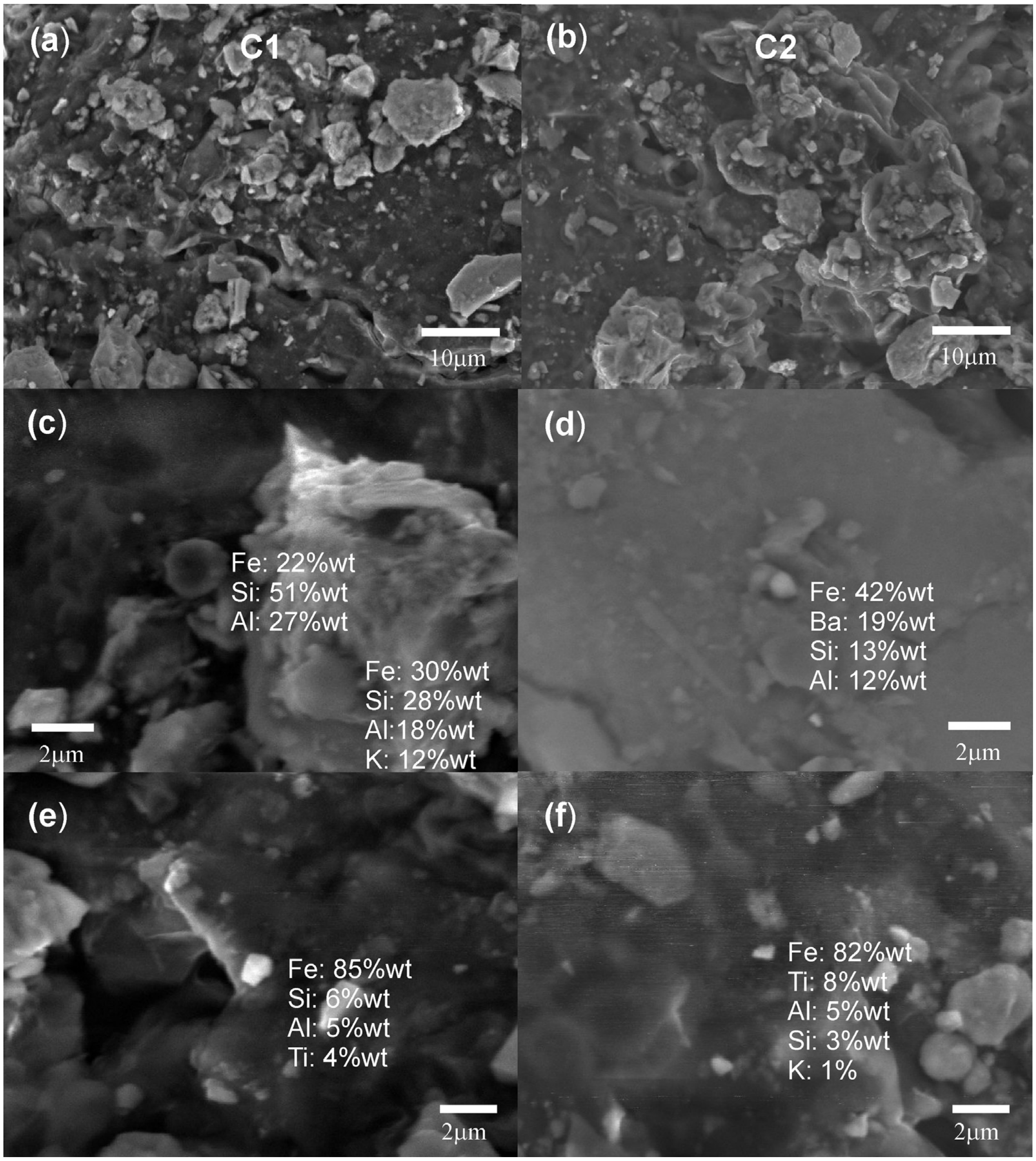

Fig. 3. SEM observations on two small thallus portions from L0 extracted after 27 measurement campaigns; C1 (high values of κ_{is}) and C2 (average/low values of κ_{is}). Irregular particles rich in Fe (≤1 µm), spherules (1–2 µm) and aggregates with different shapes and grain sizes are observed. Compositional analysis by EDS indicates the presence of Fe, Al, Si, K, Ca, Ti and Ba.

revealed the presence of iron rich particles with different morphologies and grain sizes (L0; Fig. 3a and b). The elemental analysis by EDS indicates also the presence of trace elements such as Al, Si, K, Ca, Ti, and Ba. Particles are of irregular shape, spherules or form aggregates with different sizes, and 13 out of 22 are Fe-rich (Fe content = 13–88%wt) spherules of 1–2 µm in size, that is $PM_{2.5}$ (Fig. 3c and d). In addition, irregular shaped particles seem to be common components of trapped PM as well, being smaller $PM_{1.0}$ (≤1 µm) with Fe content between 35 and 92%wt (Fig. 3e and f). Such particles are thought to come from emissions produced by cars and buses circulating at the University Campus. Similar Fe-rich particles (irregular shape, spherules and aggregates with different sizes) have been observed from vehicle-derived emissions, produced by wear particles of the brake system, engine, tires and pavement, and diesel/gas soot as reported by Lu et al. (2005) and Chaparro et al. (2010).

Descriptive statistics of magnetic data (measurements of κ_{is}) for each lichen are shown in Fig. 4. Overall mean values of κ_{is} (i.e.: values calculated for each dataset and recorded over all measurement campaigns) show differences in concentration of magnetic PM and revealed the impact of atmospheric pollution on lichens in this order: L1 (Factory) > L3 (Square) > L2 (Bus terminal) > L4 (Factory) > L5 (Downtown) > L0 (Campus) > L6 (Green area).

3.3. Spatio-temporal magnetic biomonitoring

Sixty magnetic susceptibility contour maps for L0 are represented in Fig. 5 for the whole period of 60 campaigns, showing in general a wide variability of κ_{is} reflecting the evolution of magnetic PM concentration (deposition and partial loss) on this lichen's thallus. These graphics show how Fe-rich PM accumulation changed over time in different areas of the thallus, which seems to be related to the capability of this species to adsorb and store natural/anthropogenic airborne PM. Preferential accumulation areas could be related with morphological characteristics of this lichen, such as topography, micro-scale roughness of the thallus surface, deformation and its retention capacity. The variation of magnetic susceptibility within this lichen shows magnetic

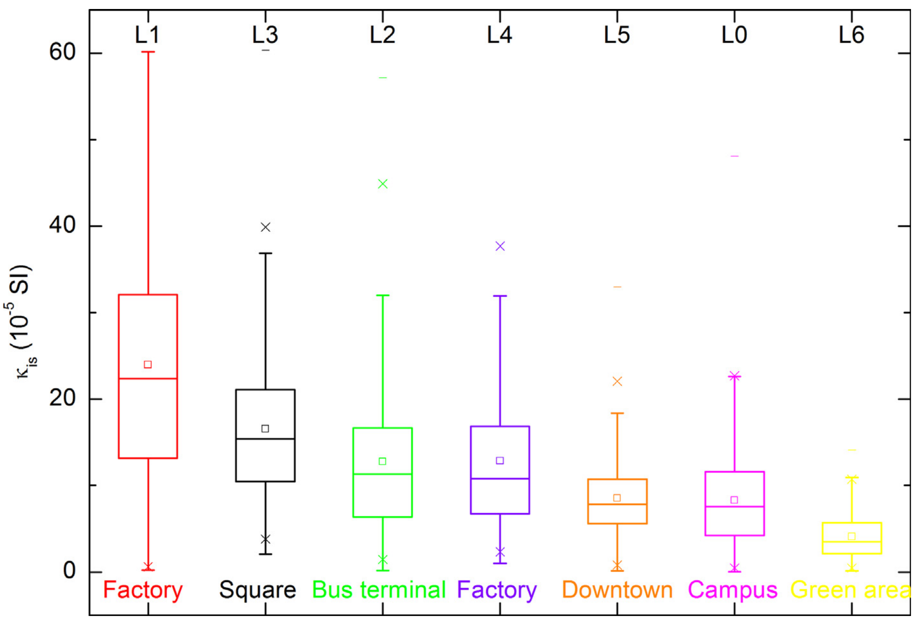

Fig. 4. Descriptive statistics of in situ magnetic susceptibility (κ_{is}) data for each lichen. Each dataset has a number of data of 3194 (L0); 638 (L1); 956 (L2); 1033 (L3); 738 (L4); 1,202 (L5); and 508 (L6). The box delineates interquartile range 25–75%, and the horizontal line in box indicates the median. Minimum and maximum values are shown using whiskers, as well as the mean value is shown with an open square.

enhancement around the growth center (Fig. 5) which was stronger in the upper and right part (39 out of 60 measurement campaigns) and less in the lower and left-lower part (9–17 out of 60 measurement campaigns). Moreover, magnetic PM was preferentially absorbed in the rougher areas of the thallus surface (Fig. 3a and b). Over time, no repetitive patterns were observed, suggesting that PM mobility, accumulation, and partial loss occurred within the thallus.

Using the κ_{is} data obtained from the weekly measurements ($n \approx 50$), an average was calculated for each lichen and defined as the representative value of PM pollution load. Fig. 6 shows the weekly mean values of κ_{is}, temperature, and rainfall during 16 months. In situ mean magnetic susceptibility shows increments during winter and spring seasons, reaching high susceptibility values between 16.0 and 23.4×10^{-5}SI for the spring season. On the other hand, the highest initial values (19.5×10^{-5}SI for L1, and 10.2×10^{-5}SI for L4) are observed for locations affected by industrial and vehicular emissions. L1 reaches the highest mean value of $\kappa_{is} = 43.2 \times 10^{-5}$SI in September 2016. In a supposedly clean site, i.e. L6, with an initial mean value of 2.6×10^{-5}SI recorded in August 2016, the highest mean value of 7.2×10^{-5}SI was obtained during the summer season (January 2017) which coincides with an increase of vehicular traffic in this area due to the holiday period.

There is a general trend of magnetic susceptibility increase with reducing mean temperatures and vice versa. On the other hand, rapid changes in mean values of κ_{is} are often observed after moderate to intense rainy periods (i.e. measurement campaign 9, 12, 16, 23, 26, 28, 30, 37, 38, 42, 43, 46, 47, 48, 52, 56, 59, and 60, see Fig. 6b), which is indicative of two possibly inter-related pollutant dependent processes taking place in 1) the lichen's thallus, and 2) the atmosphere. The first one is related to a superficial "washing" of trapped particles on the thallus and hence the storage capacity of *P. pilosum* and the second to a reduction of dispersed airborne PM by wet deposition or "pollution cleaning" by rain (Fig. 6). Contaminants previously accumulated on the thallus may be eliminated by the rainwater, reducing the magnetic PM content as was observed during the raining periods, while this increased during dry periods. Matzka and Maher (1999) have shown that rainfall reduces the concentration of magnetic particles on tree leaf surfaces. Similar results were reported by Aničić et al. (2009) using non-magnetic techniques for wet and dry bags mosses, with a linear increment of trace element concentration with time. Lichens are most active during the wet seasons, which provoke growth and consumption of minerals (Bačkor and Loppi, 2009; Hofman et al., 2017).

Mean values of κ_{is} present increasing trends during autumn (March–July 2016) and winter (July–September 2016) reaching maxima during early spring (September 2016, Fig. 6). Afterwards, κ_{is} decreased during spring (September–December 2016) and summer (December 2016–March 2017), followed by minor increments for autumn and winter (March–July 2017). Similar seasonal trends of $PM_{2.5}$ concentration (averaged hourly data of concentrations measured using a micro oscillating balance method) were reported in five cities from China (Wang et al., 2018), reaching the highest concentrations in winter (126–203 $\mu g\, m^{-3}$), followed by autumn (79–118 $\mu g\, m^{-3}$), spring (82–98 $\mu g\, m^{-3}$), and summer (67–82 $\mu g\, m^{-3}$), successively. Higher temperatures and consequently, higher mean values of atmospheric mixing height (Singh and Pandya, 2013; Myrick et al., 1994; Wark and Warner, 1998) during the summer season allow for a greater dispersion of pollutants in these cities. According to Wang et al. (2018), stagnant meteorological conditions in Southern North China often occurred in winter and autumn with less precipitation, moderate humidity, and lower planetary boundary layer heights, which together suppressed pollution diffusion and facilitated particle production and hygroscopic growth. Although the warm temperature and high humidity during summer promoted the photochemical formation of particles, the lower emissions and higher precipitation resulted in the lowest $PM_{2.5}$ concentrations. In the present study, such meteorological factors seem to be responsible for variations of mean values of parameter κ_{is} (Fig. 6a), that is, precipitation periods correspond to relative lows of κ_{is}, and lower mean temperatures (Fig. 6b) correspond to higher mean values of κ_{is}, and vice versa.

4. Conclusion

A new methodology of magnetic biomonitoring of the pollution tolerant species lichen *Parmotrema pilosum*, living on urban trees of Tandil city in Argentina is proposed. In situ measurements of magnetic susceptibility distribution of the thallus suggests a highly variable particle accumulation over time, comprising up to 16 months. Growth rates of seven lichen individuals selected from areas with different pollution degree were variables (from 218.2 to 953.2 mm^2/yr.) and growing conditions seemed to be site-specific for this exotic lichen.

Preferential accumulation areas (of the thallus) of magnetic PM were determined through spatio-temporal distribution of in situ magnetic susceptibility κ_{is} measured on the surface of seven lichen individuals. Scanning electron microscope observations indicate the presence of 1–2 µm Fe-rich spherules and irregular particles of ≤ 1 µm, corresponding to particles of the $PM_{2.5}$ and $PM_{1.0}$ categories.

Thus, magnetic biomonitoring is a suitable methodology to assess air pollution because it measures trapped magnetic particles on the thallus and it is independent of species' growth rates.

Low temperatures reduce the mobility of contaminant particles in the atmosphere, which is evidenced by the increase of mean values of κ_{is} during autumn and winter. The highest mean values of κ_{is} were reached during late winter and early spring, followed by a decrease of κ_{is} values indicative of dispersion and pollution reduction. Precipitation records

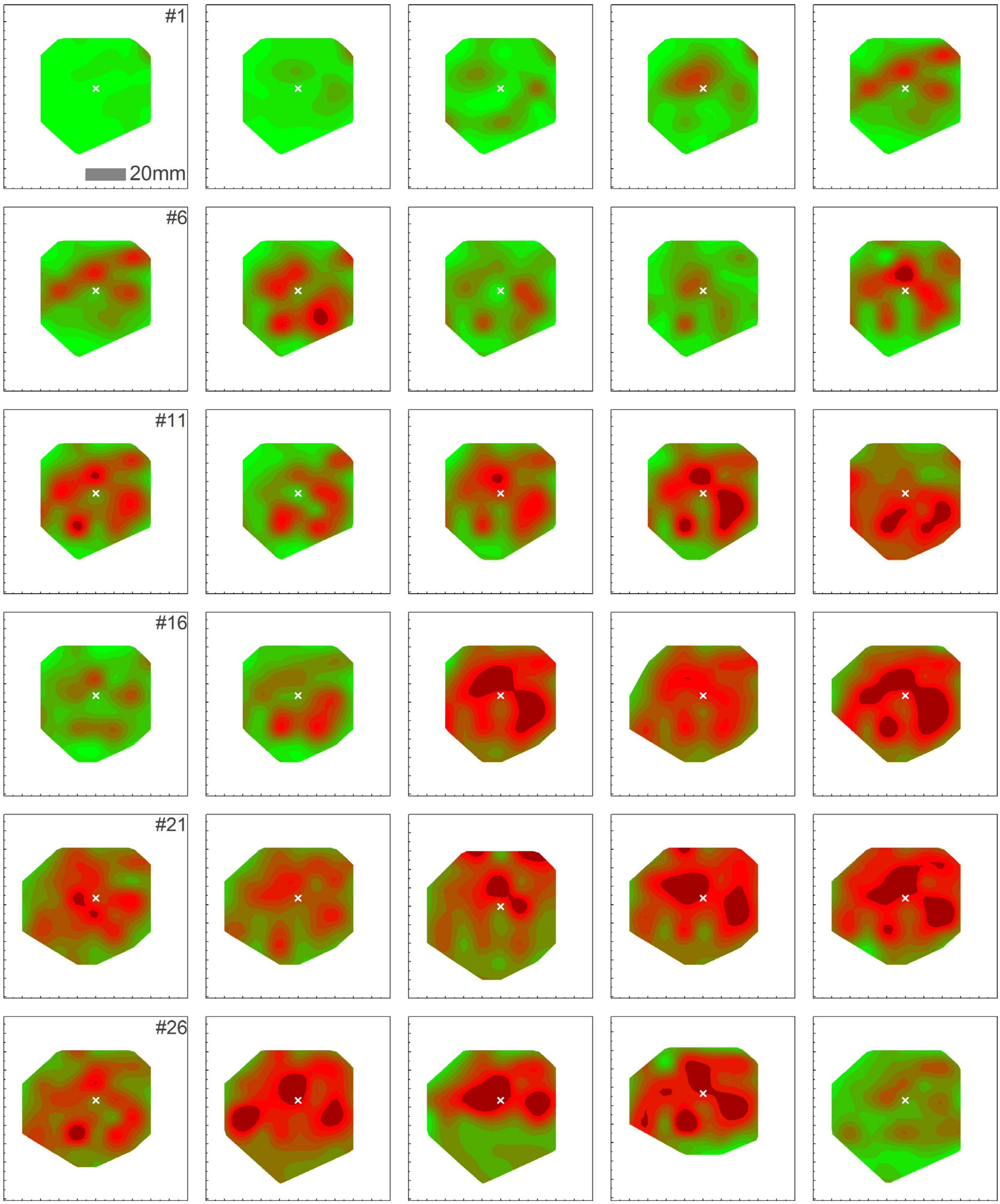

Fig. 5. Weekly contour maps of κ_{is} for the species *P. pilosum* from L0, based on 45–54 measurements of κ_{is}. Lower values of κ_{is} ($< 0.3 \times 10^{-5}$SI) are represented with light green, higher values of κ_{is} ($> 18.0 \times 10^{-5}$SI) with dark red. The growth center is marked (cross). Map #1 corresponds to measurements done in March 2016, and map #60 to measurements in July 2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

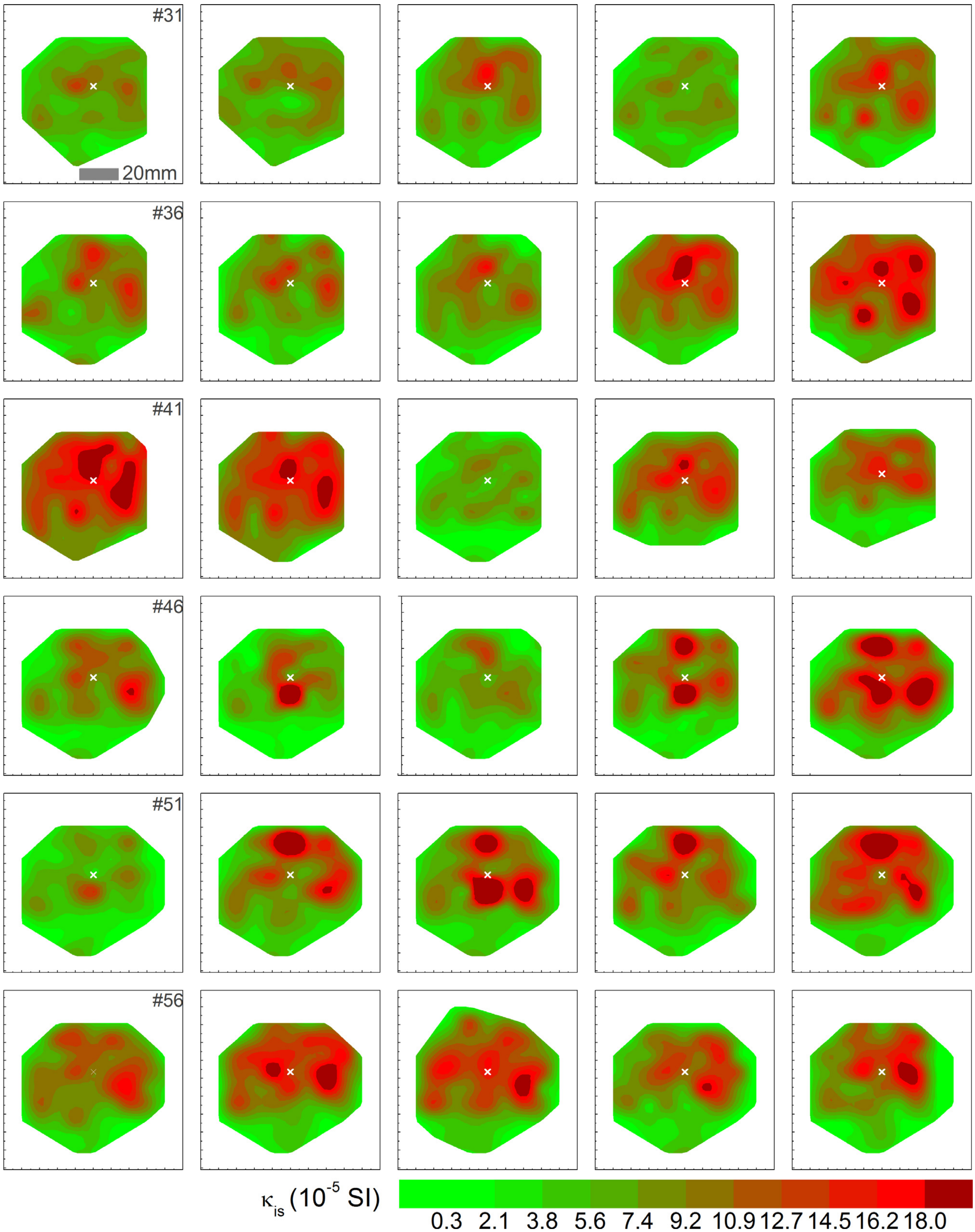

Fig. 5. (*continued*)

show that rain influenced the magnetic signal measured on thalli, as rapid changes of mean values of κ_{is} were observed after moderate to intense rainy periods. Such changes are related to a partial washing of trapped particles from the thallus, and a reduction of PM in air by wet deposition.

The main advantage of the new methodology used in this work is the collection of measurement data in any chosen time period, from days to years. Performing in situ magnetic measurements not only contributes to preserve biomonitors such as *Parmotrema pilosum*, but also provides a useful low-cost tool that allows assessing atmospheric pollution over short to long periods.

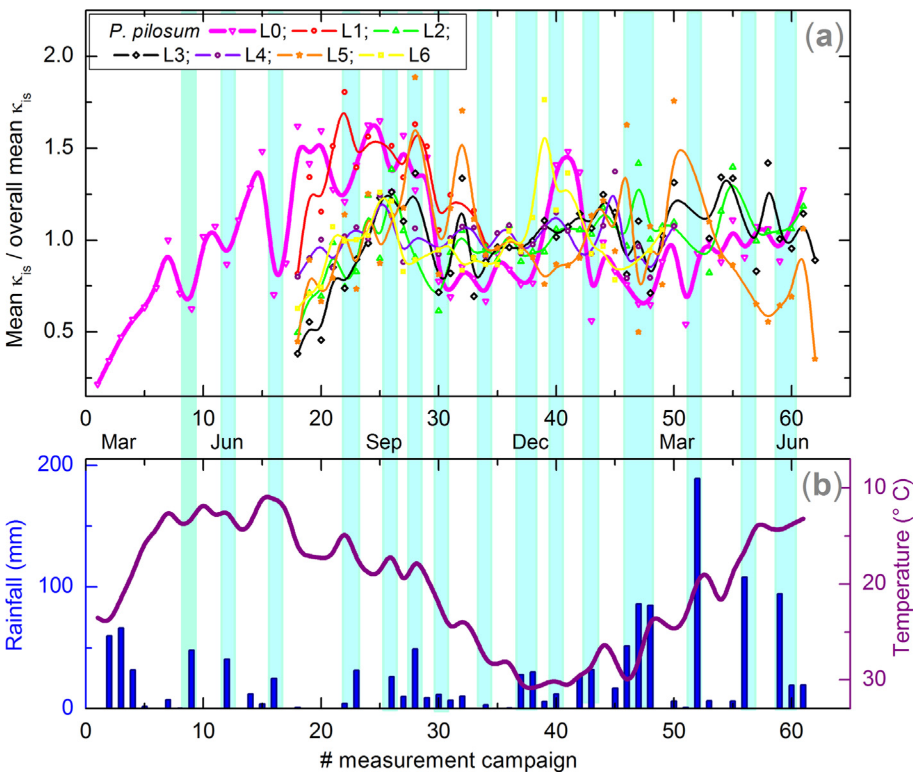

Fig. 6. Weekly average measurements for all studied lichens of (a) mean κ_{is} values were normalized using the corresponding overall mean κ_{is} for each lichen, that is, 8.3×10^{-5}SI (L0); 23.9×10^{-5}SI (L1); 12.8×10^{-5}SI (L2); 16.5×10^{-5}SI (L3); 12.8×10^{-5}SI (L4); 8.5×10^{-5}SI (L5); 4.1×10^{-5}SI (L6); and (b) rainfall and temperature per week in Tandil city.

Conflict of interest

There is no conflict of interest.

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