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Epiphytic lichens as biomonitors of airborne heavy metal pollution

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ABSTRACT

The research aims to assess the performance of the lichen *Parmotrema reticulatum* as an air pollution biomonitor of four heavy metals, namely, chromium (Cr), copper (Cu), lead (Pb) and zinc (Zn). Four contrasting land use sites within the greater Auckland region of New Zealand are used. One site is located within the relatively clean air shed of conservation land, the others within residential, commercial, and industrial areas, characterised by increasingly polluted air sheds, respectively. Three groups of lichens are monitored over a two-year period using active and passive biomonitoring methods to assess 'on-thallus' and 'in-thallus' concentrations of heavy metals. Seasonal transplants are used to quantify heavy metals accumulated by the lichen during each season. Long-term transplants are used to measure how fast lichens accumulate heavy metals and to better understand how and when heavy metals within the lichen thallus achieve equilibrium with air pollutant concentrations over time. The results show that the lichens continuously accumulates pollutants from the air until equilibrium is reached, thus transplanted lichens are useful for monitoring air pollution concentrations over time. Since pollutant concentration in the transplanted lichen at equilibrium stabilises, at this point the lichen ceases to be useful for monitoring temporal trends in air pollution, but may useful for spatial air pollution monitoring. The industrial location has the highest total accumulation for all four heavy metals, followed by the commercial and residential locations, respectively. Overall, the results show that the lichen *P. reticulatum* may be successfully used to monitor spatial and temporal pollution patterns caused by even very low concentrations of Cr, Cu, Pb and Zn.

1. Introduction

As scientific understanding of the environmental and health impacts of air pollution improves, there is an increasing demand for air quality monitoring techniques that can be easily applied in different situations. Lichens can be used as biomonitors of air pollution because they readily accumulate pollutants in their thallus in line with atmospheric concentrations. Lichens intercept allogeneic atmospheric materials dissolved in wet precipitation, dry depositions, and gaseous emissions (Nash, 2008). Their physiology is such that they are able to indiscriminately absorb a large range from the ambient air through their entire surface (Aznar et al., 2008; Conti et al., 2011). Accumulated pollutants show a close correlation with their atmospheric levels and have proved the lichen's capability as an effective biomonitor (Adamo et al., 2008; Godinho et al., 2009; Wolterbeek et al., 2003). Because of this, various lichen species have been used as biomonitors in air quality assessment studies (Conti and Cecchetti, 2001; Conti et al., 2004; Garty, 2001). Lichens produce results that are complementary to chemico-physical monitoring methods.

With time, concentrations of pollutants in the lichen thallus achieve equilibrium with the mean level of pollution in the ambient air. The equilibrium state is one in which the rate of pollutant accumulation in the thallus is equal to the rate of pollutant release from the thallus, so that the chemical concentrations of the reactants and products have no significant net change over time. In this situation, the rate of the forward chemical process is equal to the rate of the reverse chemical process.

Three mechanisms can explain the accumulation mechanism of pollutants in the lichen thallus: (1) particulate materials absorbed onto the thallus surface or within intercellular spaces; (2) extracellular binding of cations; and (3) intracellular uptake (Bargagli and Mikhailova, 2002; Garty, 2001; Nieboer et al., 1978). In many pollutant uptake, retention and release studies, the lichen thallus is considered as a homogenous organism for metal uptake and release (Puckett et al., 1973; Reis et al., 2002, 1999; Sloof, 1995). However, the surface layer of the thallus plays an important role in this process, as it is the interface between the atmosphere and the interior tissues of the lichen thallus. Wolterbeek et al. (2003) proposed a surface-layer model to explain pollutant accumulation and release process. In the current research, pollutants accumulated on the lichen surface layer are defined as 'on-thallus' pollutants and those translocated from the surface layer to the interior tissue are defined as 'in-thallus' pollutants. A lichen–air model is used to illustrate

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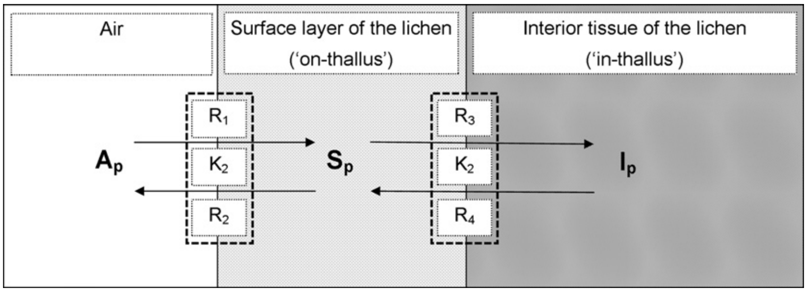

Fig. 1. A conceptual lichen–air model of how the lichen thallus achieves equilibrium with mean pollution level of ambient air. Pollutant concentrations in the atmosphere, surface layer of the thallus and the interior tissue of the thallus are A_p, S_p, and I_p, respectively. K_1 and K_2 are equilibrium constants. R is pollution accumulation rate, from air to surface layer (R_1), surface layer to air (R_2), surface layer to interior tissue (R_3), and interior to surface layer (R_4).

schematically the behaviour of the surface layer in the processes of pollution accumulation, release and equilibrium (Fig. 1).

When a lichen's thallus is in equilibrium, the rate of pollutant uptake into the interface or on-thallus (R_1) is equal to the rate of the pollutant release (R_2) to the environment. Similarly, the rate of the pollutant uptake into the interior (in-thallus) of the thallus from the interface (R_3) is equal to the rate of the pollutant release into the interface (R_4). At this stage, the thallus is in equilibrium, and the rate constant from the atmosphere to the interface is K_1 and the rate constant from the interface to the interior is K_2. The total content of a target pollutant in the lichen thallus is the combination of pollutants available in interface (on-thallus) and interior (in-thallus).

When the same thallus is transplanted to a site with higher pollution level, the rate of pollutant uptake by the interface (R_1) will increase due to the higher concentration of pollutants available in the air. Because (R_1) is higher than the rate of pollutant release to the environment (R_2), pollutants accumulate in the interface. Similarly, the rate of pollutant uptake into the interior (R_3) will be increased compared to the pollutant release to the interface (R_4) because the pollutant concentration at the surface is higher than the interior, thus pollutants accumulate in the interior tissues. The equilibrium changes due to the alteration of rates of uptake and release (R_1, R_2, R_3 and R_4); consequently, K_1 and K_2 will be altered accordingly. The system moves towards a new tends to equilibrium (K_1 and K_2) over time, and at that point all uptake and release rates will be equal ($R_1 = R_2 = R_3 = R_4$).

All biomonitoring methods using lichens are based on the pollutant equilibrium process; however, details of the process for different pollutants and for different lichen species are not yet well explored. Lichen transplant studies to date have been designed to assess either the spatial or temporal patterns of heavy metals perspectives (Conti and Cecchetti, 2001; Conti et al., 2004; Garty, 2001). Both are examined together in current research. The aim here is to assess the performance of the epiphytic foliose lichen *Parmotrema reticulatum* as a biomonitor of four heavy metals, chromium (Cr), copper (Cu), lead (Pb) and zinc (Zn). The research also investigates how lichens achieve equilibrium with the heavy metal concentration of the new environment when they transplanted from a clean site to a polluted site. The study is conducted in New Zealand, where no such biomonitoring has so far been undertaken (Johnson and Galloway, 1999).

2. Materials and methods

2.1. Study area

The study site is the greater Auckland region of New Zealand, which contains the country's largest urban area with a population of over 1.4 million people covering an area of 4518 km^2 (Auckland Council, 2010). This region is located between the Hauraki Gulf, bordering the Pacific Ocean, with the Hunua Ranges to the south-east, the Manukau Harbour to the south-west, and the Waitakere Ranges to the west. Auckland's central business district (CBD) is positioned on an isthmus between Manukau and Waitamata harbours.

The climate of the region is temperate with wet winters and warm, humid summers. Mean maximum and minimum air temperatures are 15–23 °C for summer (December to February), 12–20 °C for autumn (March to May), 8–15 °C for winter (June to August) and 11–18 °C for spring (September to November) (Auckland Regional Council, 2006). The average rainfall for each these seasons are 77 mm, 101 mm, 135 mm, and 100 mm respectively. The average number of 'wet days' (>1 mm) is 8 for summer, 11 for autumn, 15 for winter and 12 for spring (NIWA, 2010). Total rainfall, number of wet days and mean air temperature in the study area during the year 2010 are 958.7 mm, 116 days, 16 °C, respectively (NIWA, 2011). The prevailing wind is from the southwest or west southwest.

2.2. Sampling sites

Four categories of land use sites within the greater Auckland region of New Zealand are used. One site is located within the relatively clean air shed of conservation land, the others within residential, commercial, and industrial areas, characterised by increasingly polluted air sheds, respectively. The industrial site is located in Penrose, a formally designated industrial area. Several industries with potential air pollution sources are located in the Penrose industrial park: hot-dip galvanising operations; concrete batching; glass bottle manufacturing; the manufacture of polystyrene products using natural gas fired boilers; manufacturing lead-based products; generating power, using gas fired combined cycle generators; manufacturing automotive radiators; the chemical refining of precious metals; and zinc electroplating (Davy et al., 2007; Metcalfe et al., 2006). The Southern Motorway runs through Penrose, which has an annual average daily traffic flow of about 140,000 vehicles (Auckland Regional Council, 2006).

The commercial site is adjacent to the CBD located on Symonds Street, one of the busiest roads in the central city. On an average day, nearly 75,000 vehicles use Symonds Street (NZTA, 2010). A large number of traffic lights are scattered through this area. Exhaust emissions are likely to be elevated due to stop-and-start traffic. The residential site is located in the suburb of Mount Eden, well away from motorways and large commercial or industrial centres. The land here is formerly zoned 'residential only'. The main sources of air pollution are from vehicular emission and possibly wood burning for domestic heating during the winter season (Auckland Council, 2010).

The main criterion for the selection the 'clean' (or control) site is that it should be within an air shed free from local anthropogenic influences, well away from, as well as upwind of, sources of air pollution. Clearly, it is not possible to guarantee