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BIOMONITORING OF URBAN AND REGIONAL AIR QUALITY IN INDUSTRIALISED AND DEVELOPING COUNTRIES – EXPERIENCES AND PERSPECTIVES

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ABSTRACT

Unrestrained industrialisation and urbanisation have caused serious environmental problems in many developing countries, and despite emission reductions during the last decades, air pollution still represents one of the urgent environmental problems also in highly industrialised countries. In this paper, environmental monitoring using bioindicator plants is presented as an appropriate tool to detect and monitor air pollution effects thus supplementing information gained from conventional pollution monitoring and modelling. The use of bioindicator plants in urban and regional air quality control is illustrated by examples from two major projects dealing with industrial pollution in South America and urban pollution in several European countries. Recommendations for the successful use of bioindicator plants are given and perspectives for future application are discussed.

Key Words: Air Quality, Biomonitoring, Pollution Impact, Industrial Pollution, Urban Pollution

1. INTRODUCTION

Progressive and unrestrained industrialisation and urbanisation, together with insufficient emission control and shortcomings in environmental legislation and implementation of pollution abatement measures have caused serious environmental problems in many emerging nations in Asia, Latin America and Africa. Asian megacities figure among the most polluted cities in the world resulting in high rates of air pollution induced morbidity and mortality (Srivastava and Kumar, 2002; Molina and Molina, 2004; Fang et al., 2005; Gurjar and Lelieveld, 2005). The economic, social and ecological consequences associated with the elevated pollution levels cannot be overseen yet. Various global scenarios indicate that air quality in this region as well as in many other developing countries may further deteriorate rather than improve in the 21st century (Prather et al. 2003). Air pollution and climate change are interrelated and these linkages are considered in integrated policy approaches (EEA, 2004). In order to address the issue of air pollution in developing countries, several initiatives have been taken recently, e.g. the APMA project (www.asiairnet.org) and the Clean Air Initiative for Asian Cities (www.cleanairnet.org/caiasia), among others. But also in highly industrialised countries, air pollution still represents one of the most urgent environmental problems although in those regions air quality has improved considerably over the last decades. Thus, during the last years, the European Union has been devoting several programmes and directives with an integrated view to improve air quality particularly as to pollutants responsible for acidification, eutrophication and ground-level ozone pollution as well as particulate matter (EU, 1996).

Air quality in urban agglomerations, industrial sites and rural areas may routinely be assessed by emission inventories, modelling and physico-chemical measurements of ambient pollutant concentrations. In many developing countries, however, such monitoring systems are still completely absent or are just in the phase of being set-up. Yet, it should be stressed that such measuring techniques permit to control whether air quality standards set in accordance with national and international legislation are adhered to, but that they do not provide any direct information regarding the possible impact of air pollution on man and environment. That is because the response of organisms to a given pollutant does not only depend on its concentration or dose, but also on a range of predisposing and accompanying factors. Hence, environmental monitoring using bioindicator plants is considered an appropriate tool to detect and monitor air pollution effects supplementing information gained from conventional pollution measurements and modelling. In regions with limited financial and technical resources, biomonitoring using indicator plants also offers the possibility to detect the presence of elevated pollutant levels and to determine the large-scale pattern and temporal changes of pollutant distribution (De Temmerman et al., 2004).

In the present paper, examples from two major projects will be given illustrating the use of bioindicator plants for the assessment and monitoring of air quality in urban agglomerations and industrial areas of developed and developing countries. In the first example, the implementation of a biomonitoring programme in a strongly polluted industrial area in Brazil and the main results obtained from the exposure of various bioindicator species over several years are depicted. The second example describes the use of highly standardised biomonitoring methods at more than 100 sites throughout Europe aiming at assessing and demonstrating the effects of air pollutants in urban agglomerations of eight countries. Finally, recommendations towards the successful application of bioindicators will be given and perspectives for future developments will be discussed.

2. SOME DEFINITIONS AND CONCEPTS

Bioindicators may be defined as "organisms or communities of organisms reacting to environmental factors with changes in their life functions and/or their chemical structure thus permitting to conclude on the state of the environment" (Arndt, 2001). Based on this definition, bioindicators may principally be differentiated into sensitive (or *response*) and accumulative indicators (Figure 1). While the **sensitive indicator** shows distinct biological effects, for example foliar injury, upon the exposure to a pollutant, **accumulative indicators** may show enhanced concentrations of a chemical compound without exhibiting a decreased vitality or visible injury symptoms. The two basic types of bioindicators can be found among **test organisms** which are used in highly standardised laboratory procedures, **ecological indicators** which provide information on the conditions of whole ecosystems and finally **monitoring organisms** which are generally used for qualitative and quantitative monitoring of environmental conditions, e.g., in air quality control. Procedures which study or sample organisms already present in the ecosystem under investigation are called **passive biomonitoring**, whereas **active biomonitoring** means to introduce the monitoring organisms into the ecosystem under more or less standardised conditions (Arndt et al., 1987; VDI, 1999; Mulgrew and Williams, 2000). Studies applying active monitoring procedures like those presented in this paper generally follow a common methodological approach as displayed in Figure 2.

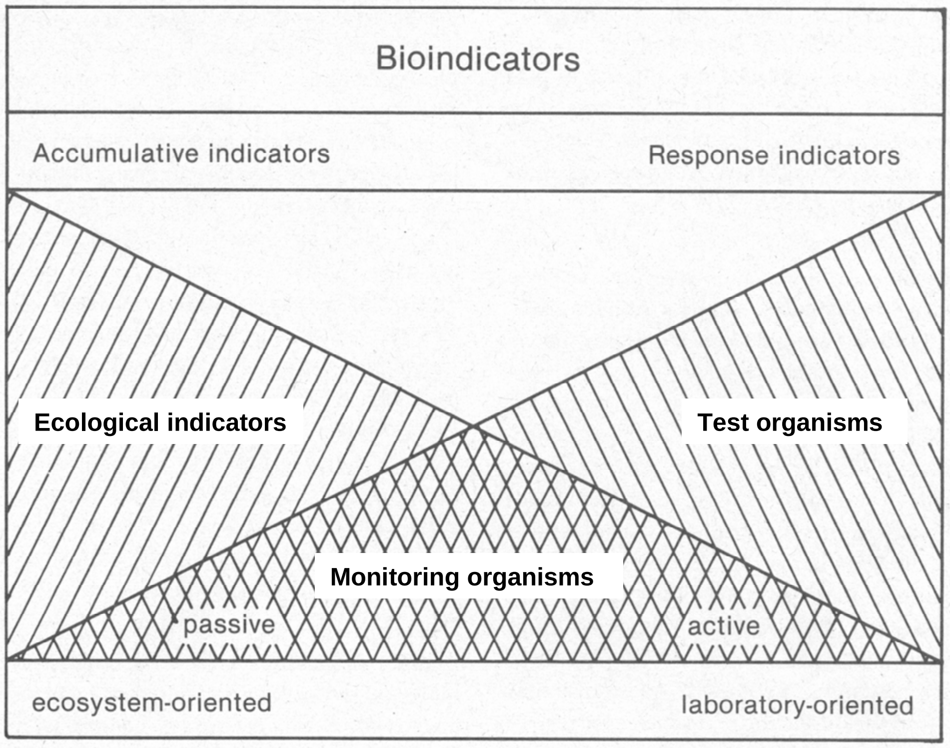

Figure 1. Overview of different biomonitoring procedures (modified after Arndt, 2001)

3. IMPACT OF INDUSTRIAL EMISSIONS ON THE BRAZILIAN ATLANTIC RAIN FOREST

The industrial complex of Cubatão in SE-Brazil is a worldwide known example for the disastrous consequences of unrestrained industrialisation for man and environment representing a typical situation in many developing countries. Since the early 1950s, this complex, one of the largest industrial centres in South America, including steel and fertiliser plants as well as chemical and petrochemical facilities, had been built on the narrow plain between the Atlantic shore and the steep slopes of the coastal mountains. Due to insufficient emission control and the topographic and meteorological characteristics of the region, air pollutants have been transported into the narrow valleys by the prevailing sea-land-breeze for decades causing serious health problems to the local population and strong damage to the Atlantic Forest ecosystem.

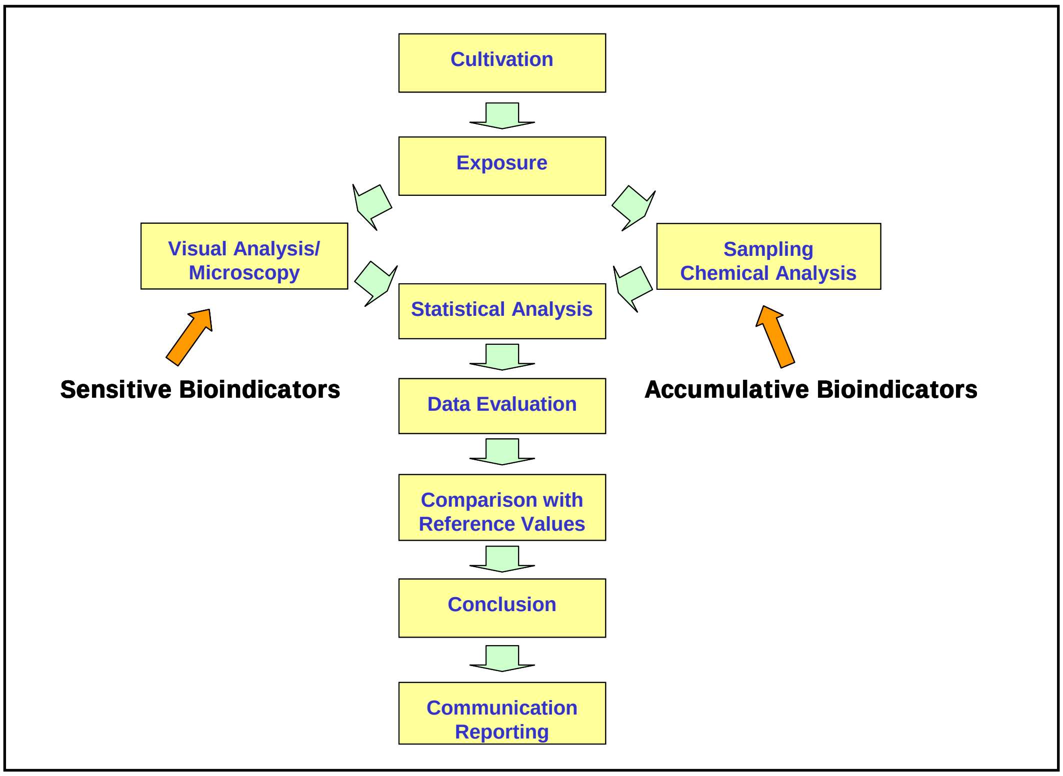

Figure 2. Flow chart on the work steps essential within active biomonitoring studies.

Within the scope of an interdisciplinary research project, bioindication methods were applied to detect the phytotoxic compounds responsible for the forest dieback and to obtain information on the spatial and temporal distribution of the most relevant air pollutants. Data from the exposure of various sensitive and accumulative bioindicator species over several years permitted to delimit distinct sub-areas which were affected by various air pollutants originating from different emission sources. Typical tip necroses on leaves of sensitive plant species like *Gladiolus sp.* and *Hemerocallis sp.* and strongly elevated foliar fluoride concentrations in rye grass (*Lolium multiflorum*), an accumulative indicator plant, were detected in an area downwind from several superphosphate-producing fertiliser plants (Figure 3). The fluoride contents in rye grass reached mean values of more than 100 µg g^{-1} DW which upon ingestion may cause harmful effects on animals. In greater distance to the emission sources and at higher altitudes, by contrast, there was no fluoride impact observed (Klumpp et al., 1996).

Areas close to a petrol refinery, by contrast, were characterised by clearly increased sulphur and nitrogen levels in plants. Particularly strong sulphur accumulation was found in rye grass exposed at intermediate altitudes of the mountain range where high atmospheric concentrations of sulphurous and nitrogenous compounds and high sulphur and nitrogen deposition to soil and vegetation were regularly registered. The latter fact can be explained by the complex atmospheric circulation processes in the area driven by distinct land/sea breeze systems which contribute to prolonged periods of polluted airmasses stagnating in front of the slopes (Vautz et al., 2003).

Ozone-induced injuries on leaves of the sensitive tobacco cultivar Bel-W3 were observed at all exposure sites. Particularly strong ozone damage was recorded at greater distances to the emission sources of primary pollutants and at higher altitudes, whereas only slight foliar injuries occurred at sites close to the factories and in the lowlands. The spatial distribution of phytotoxic ozone levels was found to be triggered by high NOx and VOC emissions originating from the industrial centre itself as well as from the urban agglomeration of São Paulo. By exposure of the sensitive indicators *Urtica urens* and *Petunia sp.*, occurrence of phytotoxic levels of peroxyacetyl nitrate (PAN) in Brazil was proven for the first time (Klumpp et al., 1994; Domingos et al., 1998). This type of pollution was attributed to emissions of volatile organic pollutants from petrochemical plants and from alcohol-fuelled passenger cars. Such detailed information on the intensity and geographical distribution of different gaseous and particulate air pollutants was only possible to be obtained by means of biomonitoring procedures as extensive physico-chemical air monitoring was not feasible in that region due to technical and financial limitations and the very complex terrain and climatic conditions making the installation of dense networks of technical monitoring equipment impossible.

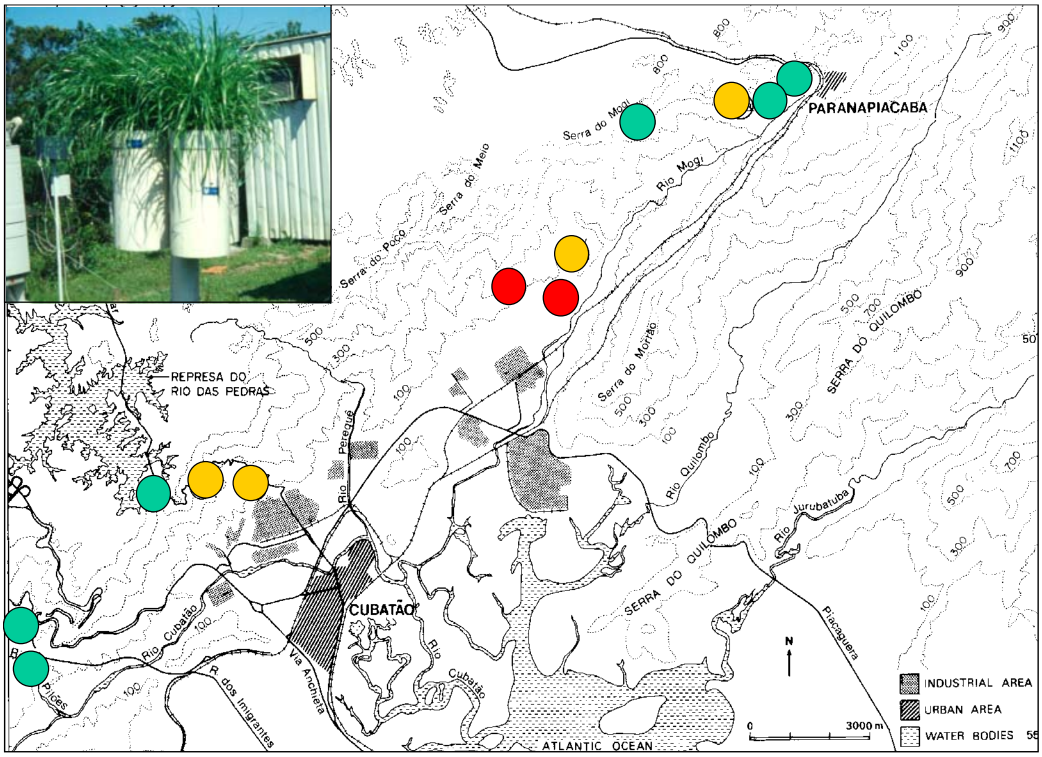

Figure 3. Spatial pattern of fluoride accumulation in exposed rye grass cultures (mean values of 26 exposure periods of 28 days each). Red dots characterise sites with high foliar fluoride concentrations (>100 µg g^{-1} DW); orange dots intermediate levels (20 µg g^{-1} DW≤x≤100 µg g^{-1} DW) and green dots low levels (<20 µg g^{-1} DW).

4. AIR QUALITY IN URBAN AGGLOMERATIONS IN EUROPE

EuroBionet, the "European Network for the Assessment of Air Quality by the Use of Bioindicator Plants" (www.eurobionet.com) was set up in 1999. In this network of 12 cities and regions in eight European countries, bioindicator plants were used for monitoring air quality and promoting environmental awareness. Communal administrations and research institutes from Edinburgh (GB), Sheffield (GB), Copenhagen (DK), Düsseldorf (D), Nancy (F), Lyon (F), Barcelona (E), Valencia (E), Ditzingen (D), Klagenfurt (A), Verona (I) and Glyfada (GR) took part in the project (Figure 4). Within these cities, local bioindicator networks with more than 100 monitoring stations in total were established and operated over three years. At these stations accumulative and sensitive bioindicator plants (tobacco, rye grass, spiderwort/*Tradescantia* and curly kale) cultivated according to highly standardised procedures were exposed to ambient air in order to assess and to demonstrate the effects of ozone, sulphurous compounds, heavy metals, polycyclic aromatic hydrocarbons and mutagenic substances. The scientific investigations were accompanied by an intensive programme of public relations and environmental education (Klumpp et al., 2004).

Figure 4. Map of Europe showing the partner cities of the network.

The experiments provided numerous data on the spatial and temporal distribution of the effects of air pollutants both within local networks and at the European level. A clear gradient of ozone-induced effects from northern and northwest Europe to southern and central Europe became evident using tobacco plants (*Nicotiana tabacum* cv. Bel-W3). The strongest ozone-induced leaf injuries were observed at the exposure sites in Lyon and Barcelona, while in Edinburgh, Sheffield, Copenhagen and Düsseldorf only weak to moderate ozone impact was registered (Figure 5).

Evaluation of data on ambient ozone concentrations revealed that in the majority of the cities the international threshold and target values for protecting vegetation were exceeded. The Tradescantia micronucleus test for assessing mutagenic effects using *Tradescantia* clone #4430 was carried out for the first time successfully over such a large geographical area. Signs of a raised genotoxic potential were found at sites with high levels of car traffic (Klumpp et al., 2004).

The experiments showed that local 'hotspots' of heavy metal pollution could be verified using the standardised grass culture (*Lolium multiflorum italicum*), and that it was also possible to document the small-scale distribution of the pollution load and short-term changes in emission status. Overall, impact by sulphur and heavy metals was classified as low to moderate, and limit values for feedingstuff were adhered to at most stations. Comparably high heavy metal pollution, however, was noticed in Spanish cities, but a clear drop in lead levels was registered during the course of the project (Figure 6). Antimony proved to be particularly characteristic of traffic-influenced sites. The enrichment of different polycyclic aromatic hydrocarbons (PAH) in curly kale (*Brassica oleracea acephala*) revealed a clear differentiation between urban and reference stations (Klumpp et al., 2004). Overall, the contents lay at an intermediate concentration level typical for urban agglomerations. Furthermore, the studies showed that bioindicator plants are outstandingly useful tools for environmental communication and education as they make the noxious effects of air pollution visible to the everyday life of citizens (Ansel et al., 2004).

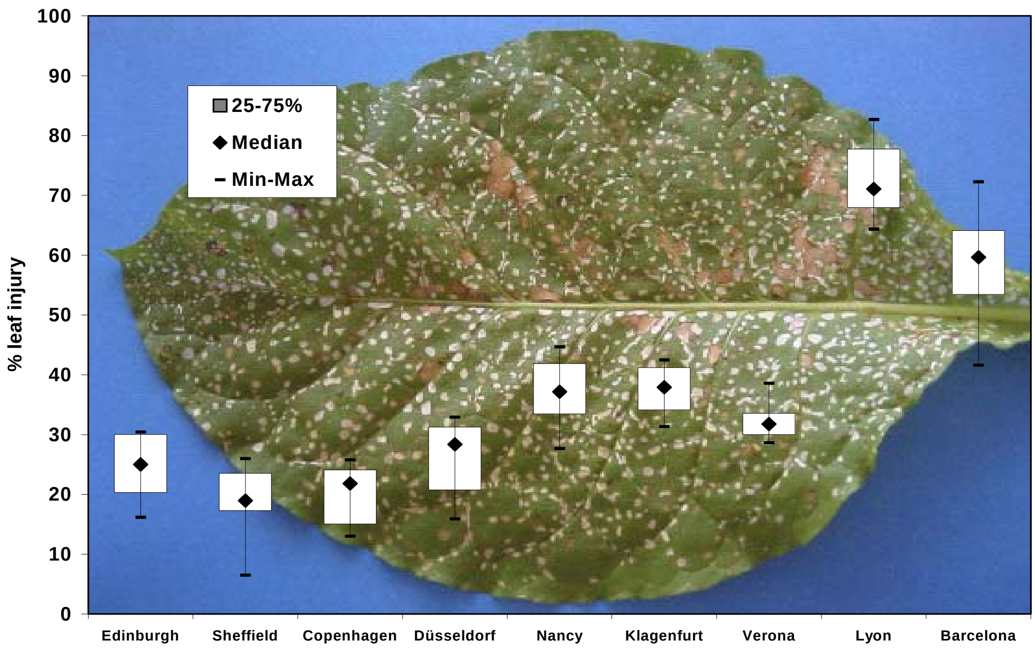

Figure 5. Mean leaf injury degree of tobacco Bel–W3 exposed in nine partner cities of the EuroBionet during eight consecutive bi-weekly periods in 2001.

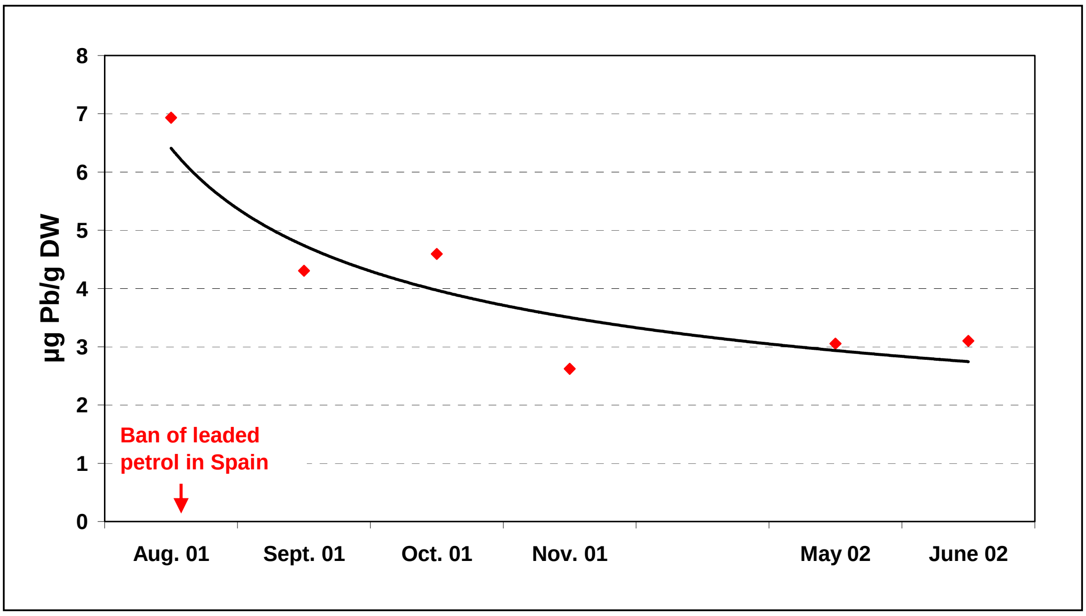

Figure 6. Fall in lead contents of grass cultures (in µg g^{-1} DW) in the Valencia monitoring network after final ban of leaded petrol in Spain in summer 2001.

5. CONCLUSIONS AND PERSPECTIVES

Bioindicators do not measure **ambient pollutant *concentrations***, but indicate **air pollution *effects*** on organisms. They show an integrated response to different pollutants over time and space even in the presence of complex pollutant mixtures. In doing so, they integrate all external (e.g., weather, soil, pests, simultaneous action of other pollutants) and internal factors (e.g., developmental stage, age, nutritional status) in the sense of an overall risk allowing for the estimation of the risk potential concerning the objects to be protected. They may disclose not only acute, but also chronic effects and may concentrate toxic substances to an amount that makes chemical analyses easier. If the bioindicator species is relevant to the food chain, limit values for pollutants can be taken into account.

Many of these attributes render biomonitoring an appropriate means to detect and to monitor air pollution effects thus supplementing information gained from conventional monitoring and modelling. Hence, bioindicators may be employed in i) source-related air pollution monitoring, ii) regional and national/multi-national surveys, iii) ecological long-term monitoring, iv) control of compliance with threshold values, v) environmental impact assessment, vi) air pollution control plans, vii) risk assessment concerning human health or contamination of the food chain, and viii) licensing procedures for new industrial installations, among others. Moreover, biomonitoring may provide data on the presence of phytotoxic levels of air pollutants and their geographical and temporal distribution particularly in developing countries and remote areas where continuous physico-chemical air monitoring is commonly inexistent due to the lack of financial, technical and human resources. Finally, it has been demonstrated that bioindicators are an excellent tool for environmental communication and that they are outstandingly useful in environmental education and awareness raising.
Besides 'traditional' pollutants like sulphur dioxide, ozone, fluoride, heavy metals and some hydrocarbons for which well established bioindication methods already

exist, new problems from 'emerging pollutants' will pose a challenge for biomonitoring in the years to come. The increased environmental concentrations of noble metals (like platinum and palladium) which are released as abrasion from catalytic converters are just one prominent example. Other compounds of current interest are a variety of organic substances, including POPs and endocrine disruptors, which constitute a high potential risk for human health. Environmental monitoring of such compounds may be achieved by using accumulative indicators (e.g., standardised grass culture) or through monitoring of the associated mutagenic effects, e.g., by the *Tradescantia* method. Finally, the constantly high deposition rates of nitrogenous compounds like NOx and NHy require modified bioindication methods, which can be employed in local or national monitoring programmes.

Apart from local and regional pollution, long-range transport of air pollutants is giving rise to hemispherical or even global pollution problems with steadily increasing levels even in remote regions far from emission sources (Prather et al., 2003). Such dimensions of air pollution are being addressed by international conventions like the UNECE *Convention on Long-range Transboundary Air Pollution* (www.unece.org/env/lrtap/) or the *Malé Declaration on Control and Prevention of Air Pollution and its Likely Transboundary Effects for South Asia* (www.rrcap.unep.org/issues/air/maledec/). Similarly to European initiatives using bioindicator plants for the assessment of air quality in urban (EuroBionet) and rural areas (ICP Vegetation, icpvegetation.ceh.ac.uk), steps towards supra-regional monitoring programmes using conventional monitoring, passive samplers and/or bioindicators will become necessary to obtain detailed information on the geographical pattern of air pollution problems and their potential impact on agricultural production, biodiversity and human health in developing countries in Latin America, Africa and Asia. Activities like those proposed by the RAPIDC Programme (www.rapidc.org) may serve as an example for this process.

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