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Airborne pollen records and their potential applications to the conservation of biodiversity

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Abstract The magnitude and complexity of the current erosion of plant biodiversity call for the development of interdisciplinary tools that enable an early detection of its effects and the establishment of effective management strategies. Indeed, plant sciences face the complex task of identifying the ecological information needed for the conservation challenge. Along this line should be placed the approach of aerobiology to gather the essential information for the development of plant recovery guidelines. In this work, we aim to discuss the potential role of airborne pollen monitoring in providing relevant data for the protection of plants and its potential applications to the management of plant diversity. To this end, we review three study cases where aerobiological monitoring can provide significant insights on conservation science. The

present study is a contribution to plant conservation biology through long-term aeropalynological sampling, on the basis that pollen records constitute a suitable indicator for evaluating resource conservation of vegetation responding to environmental fluctuations. In view of its position between botany and meteorology, the contribution of aerobiological knowledge to biodiversity conservation can be very relevant and should be explored thoroughly.

Keywords Plant conservation · Climate change · Biogeography · Pollen counts · Pollen transport · Genetic diversity

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The erosion of plant biodiversity is currently recognized as one of the mainstream subjects of study in the field of botany (Hilton-Taylor 2000; Pitman and Jørgensen 2002; Callmender et al. 2005; López-Pujol et al. 2006). Many papers have concentrated on this event since 1973, when the first International Symposium on the Threatened Vegetal Species was held at Arc-et-Senans (France), particularly focusing on the estimation of the fraction of the global flora threatened with extinction (Davis et al. 1986; CPC 1991; Akeroyd 2002). The most commonly cited figure for it shows that 13 % of the world's flora is under threat of extinction (Walter and Gillett 1998; Bramwell 2002). Nevertheless, this estimation is known to be a serious underestimate, taking into account that every year

some 2.000 new plant species are described and that biodiversity in many parts of the world, especially in tropical latitudes, remains poorly known (Brummitt and Bachman 2010). Considering these assumptions, it has been recently suggested that as many as approximately half of the 420.000 world plant species may be qualified as threatened by extinction under the International Union for Conservation of Nature (IUCN) criteria (Pitman and Jørgensen 2002). The results of the first report of the IUCN Sampled Red List Index situate this rate in 21.5 %, highlighting also that 33 % of the world's species remain insufficiently known to be able to carry out proper conservation assessments (Brummitt and Bachman 2010).

Several authors across natural and social sciences have underlined the urgent need of broader interdisciplinary collaborations to put global change research on a more productive trajectory (Lambin 2005; Campbell et al. 2009). Indeed, plant diversity conservation is not the exception. Plant conservation science faces with the complex task of identifying the information on the ecology of species and evaluating their respective causes and risks of threat. Extensive biological research is required for the implementation of useful conservation strategies and the establishment of a protection framework for plant biodiversity. In other terms, the conservationist community urgently needs input from biologists in order to have a greater interaction among the stakeholders involved in the global biodiversity challenge (Lowry and Smith 2003; Smith et al. 2004). Along this line might be placed the approach of aerobiology to collect part of the biological information necessary for the development of plant recovery guidelines. Fifty years ago, aerobiology emerged as a primarily study of seasonal atmospheric diffusion of spores and aeroallergens over long distances associated with respiratory diseases (Comtois and Isard 1999). Nowadays, medicine and the study of the allergenic activity of pollen are still the most important applications of aerobiology. However, in the recent years, aerobiology has proved to be a multidisciplinary science, deriving towards other fields of study such as agriculture, biogeography, atmospheric pollution, plant pathology or ecology (Benninghoff 1991; Orlandi et al. 2005a; Carisse et al. 2008; García-Mozo 2011; Tormo et al. 2011).

Aerobiological analysis enables the detection of airborne pollen and spores, thus providing information on plant phenology, potential crop production and

related diseases, plant distribution and the health and/or risks for some species in terms of allergies. Pollen sampling is increasingly used to enlarge biogeographical and ecological information, which appears to be crucial for the protection of plant biodiversity (Valencia-Barrera et al. 2001; Cariñanos et al. 2010a; Womack et al. 2010). The contributions of aerobiology to the fields of biogeography and ecology are numerous and diverse. Aerobiological monitoring allows the detection of short term and minor changes in the ranges of species and their phenology, which are considered to be very sensitive indicators of environmental changes within time (Peñuelas et al. 2002; Walther et al. 2002; Parmesan and Yohe 2003; García-Mozo et al. 2010a, 2010b). This has taken a particular importance in the context of climate change (Bakkenes et al. 2002). In this context, previous studies have addressed the response of anemophilous vegetation to global warming from an aerobiological perspective, taking into account that pollen can be considered as a climatic indicator (Frei 1998; Newnham 1999; Clot 2003; Cariñanos et al. 2004; Recio et al. 2009; García-Mozo et al. 2010b).

The analysis of airborne pollen released during the pollination season can provide very relevant information on local and regional plant status (Trigo et al. 2006; Alba et al. 2008; Cariñanos et al. 2010b). Long-term pollen databases allow charting the dynamics, behaviour and response of different plant species to the many components of global change. Nevertheless, aerobiological data have been rarely used for conservation purposes (Fernández-Llamazares et al. 2012a; Cariñanos et al. 2013). This situation should be readdressed because practical conservation requires the adoption of an integrated strategy involving all the appropriate techniques and approaches (Falk 1990). As Pitcher and Pauly (1998) note, understanding environmental change and facing the current global environmental crisis is and must be inherently interdisciplinary. In this sense, the contribution of aeropalynology can be very relevant, in view of its position halfway between botany and meteorology. For instance, aerobiological monitoring can contribute to conservation science, most notably through support of underlying taxonomic studies, monitoring of the health of the atmosphere and the collection of pollen samples and their preservation in pollen banks (Heywood 1995). So in the context of long-term aeropalynology emerges the present article, which

reviews all the current and potential applications of aerobiology to the field of biological conservation, aiming to open a new path for aerobiologists and palynologists to make their breakthrough in the conservation area. To this end, we: (a) present three study cases from Spain highlighting the importance that pollen sampling can have in terms of plant conservation; and (b) provide insight into the potential research lines that could lead to a real and constructive engagement between aerobiologists and conservation managers and scientists.

1 Study case 1: Aerobiological monitoring and invasion ecology

The pollen dispersal modelling constitutes an important tool for the study of invasion ecology, which has received considerable attention in the recent years (Laaïdi et al. 2003; Belmonte and Vilà 2004; Taramarcaz et al. 2005). In this sense, the prediction of which species will become bioinvasers (Křivánek and Pyšek 2006) or the design of appropriate management and control strategies for certain species are currently some of the most significant fields of study. Early detection of the introduction of an invasive harmful plant taxon is possible through a systematic monitoring of the airborne pollen concentrations and can be decisive to the prevention of its expansion, making the difference between employing offensive strategies against the species (eradication) or defensive ones (Rejmánek et al. 2005).

The Aerobiological Network of Catalonia (Xarxa Aerobiològica de Catalunya, XAC) is monitoring since 1983 the atmospheric pollen concentrations of Catalonia (NE Spain) in order to make a follow-up of the possible risk of respiratory allergies, but also the distribution of certain species throughout the region. In the XAC database, more than eighteen non-native taxa have been recorded, from which up to 50 % can be considered allergenic (Belmonte and Vilà 2004). Of course, biological invasions can have important aerobiological consequences, as sometimes they entail the dispersal of new aeroallergens (Asero 2002; Confalonieri et al. 2007). In this study case, we have concentrated in one paradigmatic case of this phenomenon: the dispersal of *Ambrosia* L. pollen type. *Ambrosia* is a genus of plants of the Asteraceae family widely studied in aerobiology due to its highly

allergenic pollen. It is abundantly distributed in North America and is becoming frequent in continental Europe, where it has been expanding in the recent years and is considered a bioinvader (Mabberley 1987; Dana et al. 2003), due to its enormous spread potential and its huge pollen production.

Up until the 1970s, *Ambrosia* weeds were just one among the several noxious weeds in agricultural fields, but nowadays the spreading rate of the genus is much higher. Noticeable increasing trends of both amounts (Annual Pollen Index, API) and daily concentrations of *Ambrosia* pollen have been detected in most part of the European aerobiological stations in regions such as Burgundy, France (Laaïdi and Laaïdi 1999), Poland and Croatia (Cvitanovic et al. 2004), Central Northern Italy (Cecchi et al. 2007) or the Ticina canton, Switzerland (Peeters 2000). In recent years, *Ambrosia* has crossed the border of the Pyrenees reaching Spain, the last bastion left to conquer in Europe (Fernández-Llamazares et al. 2012b). The API (sum of the mean daily counts of the whole year) of *Ambrosia* pollen in Catalonia has increased significantly right from the beginning of the measurement in 1983 until now. The API of *Ambrosia* pollen measured at a specific station can be considered a first estimate of how much an area is infested by this species (Skjøth et al. 2010). Thus, it can be assumed that a high presence of *Ambrosia* in the territory will increase pollen emission in the area, and therefore, the amount of pollen recorded will be also bigger. The increases on the pollen counts are particularly clear in Bellaterra and Barcelona. It is important to note that these aerobiological stations are located in areas where *Ambrosia* seems to be expanding and appears to be most abundant (Belmonte et al. 2000).

Although the concentrations of *Ambrosia* pollen type in Catalonia are still low, the species poses a serious environmental problem, aggravated by the fact that its pollen is highly allergenic and can constitute a menace to public health. The high spreading rates of the genus in the territory threatens to change the ecological functions of the affected Catalan ecosystems. For example, the spread of *A. coronopifolia* Torr. et A. Gray in the sandy dunes of the Delta del Llobregat Natural Park, close to Barcelona, has a great impact on the nesting habitat of *Charadrius alexandrinus* L., an emblematic bird species of Catalonia, and on the dune vegetation of the Mediterranean littoral, with endangered species such as *Stachys*

maritima Gouan being replaced (De Roa et al. 2009). Therefore, since the aerobiological data reveal that this genus has found in Spain an ideal habitat for its expansion, it is time to alert policy makers and start facing its management, particularly in Catalonia. The Catalan Government should think towards the eradication of the species before its expansion is too wide to manage. It is important to take into account that even though the species spreads through seed culture, a clear way of expansion is roads, mainly those concerning rails and roads. In this sense, the role of the regional aerobiological networks is crucial to anticipate the threat of an expansion of the genus beyond the Catalan borders. Nowadays, other invasive taxa that can be followed aerobiologically in different regions comprise *Ailanthus* Desf., *Eucalyptus* L'Hér., and *Myoporum*, Banks & Sol. Ex G. Forst.

2 Study case 2: Gene flow through pollen and forest management strategies

Fagus sylvatica L. is considered at present to be the most common economically important broadleaved tree species in Europe, representing approximately 10 % of European forests (Paule 1995). It is widely distributed across Central Europe, including the northern Spanish mountain borders (Pyrenees, Cantabric range) and some isolated locations in the inner Iberian Peninsula (north of the Sistema Ibérico, Sistema Central Montseny, Guillerries and Ports de Beseit), where it forms dense forests in mountain slopes over 500 and 2,000 m (Rocha Afonso 1990). This species has been the subject of many scientific studies related to the gathering of fossil data to understand the palaeoecological history of this tree (Björkman 1996; Bradshaw 2004; Lindbladh et al. 2008), as well as intensive genetic surveys using nuclear markers (Gömöry et al. 1999; Comps et al. 2001; Hasenkamp et al. 2011), among others.

Fossil and genetic data have revealed unexpected perspectives on the history of *Fagus*, clarifying the relationships between past geographical distribution of this species and its modern genetic distribution (Magri et al. 2006). This might facilitate the conservation and sustainable management of the genetic resources of this emblematic tree species (Paule 1995). Magri et al. (2006) evaluated the genetic consequences of long-term survival of *Fagus* in refuge areas and the

postglacial spread from palaeobotanical data (400 fossil pollen sites and 80 plant-macrofossil sites) and genetic data (450 and 600 modern populations analysed for chloroplasts and nuclear markers, respectively). In angiosperms, chloroplast markers are inherited only maternally (Liepelt et al. 2002), so we refer only to the results published by Magri et al. (2006) on isozyme data (nuclear markers). These results established a geographical distribution of isozyme groups throughout the Pyrenees, France and Catalonia, showing a higher allelic richness in the region than in the rest of Europe. Nuclear markers indicate that most of the *Fagus* populations of Central, Eastern and Northern Europe have a very homogenous genetic structure. However, for Southern and Western Europe, particularly in the Pyrenees Mountains, the results indicated a heterogeneous genetic structure, with separate populations over the territory.

This genetic diversity can be studied from a palynological perspective, taking into account that for most plant species, pollen plays an important role in shaping the genetic structure of populations (Burczyk et al. 2004), being responsible for gene flow (Ellstrand 1992; Ennos 1994) and contributing to the spatial distribution of the species (Schmidt-Lebuhn et al. 2007; Sharma and Khanduri 2007; Smouse et al. 2001). The study of gene dispersal by pollen has relevant implications for plant biogeography and plant conservation biology. Therefore, a proper understanding of pollen dispersal is crucial for the management and conservation of plant species in increasingly fragmented landscapes. This aerobiological approach regarding pollen is similar to the study of plant dispersal through seeds. Bullock et al. (2012) modelled the spread of 6 British wind-dispersed plants under future wind speeds in the framework of climate change, finding lower spread rates for almost all species. Such results have not yet been found in terms of pollen spread, but aerobiological studies on this subject are starting to emerge, taking into consideration that pollen dispersal is a crucial process in the life cycle of wind-pollinated plants, such as *F. sylvatica*, a highly outcrossing wind-pollinated species. Belmonte et al. (2008) analysed the role of long-distance transport in determining the concentration of airborne *Fagus* pollen observed in the pollen records from six stations across Catalonia. To discriminate between the long-range transport of *Fagus* pollen and the influence of local pollen, they hypothesized that

long-distance transport would be indicated by simultaneous peaks at the majority of the Catalan monitoring stations, taking into account that *Fagus* plants are not present around most of them.

The results obtained by Belmonte et al. (2008) showed that *Fagus* pollen can occasionally be transported very far from its source forests. The application of a source-receptor model to pollen data from the period 1997–2006 enabled the identification of the probable source regions of *Fagus* pollen. The model suggested a broad provenance area between Northern Italy, Switzerland, Northeastern France and Southwestern Germany, a region extensively covered by *Fagus* forests. This long-range transport could have consequences for the understanding of modern pollen genetic diversity. The high allelic richness of *F. sylvatica* at the Pyrenees could be explained by the episodes of long-range transport of *Fagus* pollen. The problems traditionally faced in species delimitation and phylogeny reconstruction may be due in part to a combination of weak reproductive barriers and the large distances that can be covered by genetic information as a result of wind pollen dispersal (Schmidt-Lebuhn et al. 2007). In other terms, pollen transport plays a crucial role in the gene migration of anemophilous trees, and the study of the pollen dispersal source areas can give some clues for the future expansion or reduction in *Fagus*, i.e. information on how the management of forest genetic resources could be done.

Gene flow is an important force in both plant conservation genetics and plant evolutionary biology, and its potential role should be considered in any plant conservation management programme (Ellstrand 1992). Research on gene flow has lagged because gene flow rates have been historically considered to be irrelevant and highly restricted (Levin 1981). However, now that gene flow through pollen has been recognized to occur frequently (Ellstrand and Hoffman 1990; Muona 1990; Belmonte et al. 2008), its importance in conservation has to be reassessed. In this sense, conservation biology should address this issue taking into account that gene flow by pollen might be either beneficial or detrimental for a plant population (Ellstrand 1992). On the one hand, genetically isolated populations could result in inbreeding depression but, on the other hand, hybridization may lead to the extinction of other populations through the disruption of local adaptive differentiation (Beardmore 1983;

Simberloff 1988). Considering *F. sylvatica*, this has many implications in conservation, especially when we consider that, because of mediaeval devastation and forest management practices, many of the former natural *Fagus* forests in Europe have been replaced by coniferous stands and that the remaining ones are small and fragmented in many places (Schubert et al. 2001). Therefore, seeding and planting plays a major role for enlarging the *Fagus* forest area in ongoing forest conservation programmes (Hasenkamp et al. 2011). Recently, large forest blowdowns put additional pressure to seed on plant providers. This means that large amounts of forest reproductive material, especially seeds, are needed. However, besides quantity, also the quality of the material in terms of genetic diversity and origin has to be considered. Moreover, the seeds should provide the genetic preconditions for best possible adaptation to the respective local conditions (Konnert 1995; Vollrath 2005). But gene conservation can be attained also through pollen pools. The storage of reproductive material in the form of pollen is another *ex situ* approach to conservation (Eberhart et al. 1991). The purpose of gene conservation is straight forward, and its significance is supported in the framework of the adaptation towards climate change. If the necessity of replacement of the Northern European populations by the southern ones occurs, in the case of climate change, it is fundamental to secure that genetic resources will be available (Muhs and Von Wuehlich 1993).

It is not customary to take into account the storage of pollen as a component of plant conservation strategies. Nevertheless, there are many situations where the availability of stored pollen would be a useful form of germplasm at the service of endangered plants (Heywood 1995), a largely neglected approach that was once pioneered by Cerceau-Larrival (1989) and Gbili (1992). The available information on the storage characteristics of the pollen of most species is scarce, and further research is largely needed in order to determine which pollen types are desiccation-tolerant and their different responses to low temperatures. In any case, if natural vegetation follows the same path of degradation of the twentieth century, infrequent techniques such as long-term pollen storage will be increasingly needed to conserve germplasm at the gates of global plant conservation.

3 Study case 3: Aerobiology within climate change research

If palaeopalynological records have been used during years to rebuild former climates and characterize the different climate changes of the geological eras—and, therefore, its implications in terms of vegetation—, nowadays, aerobiological data series stand as a powerful tool to study the climate and its associated variability (Emberlin et al. 1997; Damialis et al. 2007; Stach et al. 2008). Many recent studies are focused on examining if the pollination interannual trends keep a relation with the climate variability indexes (D'Odorico et al. 2002; Avolio et al. 2008; Smith et al. 2009; Orlandi et al. 2013), based on the fact that in anemophilous vegetation, the presence of pollen in the atmosphere is a consequence of the phenological state of flowering (García-Mozo et al. 2006; Tormo et al. 2011). Given the fact that the sexual reproductive phase in plants might be particularly vulnerable to the effects of global warming (Hedhly et al. 2009), pollen counts can act as a very sensitive indicator of climate change and the distributional changes of vegetation in response to global warming (Newnham 1999; Clot 2003; Fernández-Llamazares et al. 2013). In this study case, we focus on the aerobiological impacts on mountainous vegetation, studying the pollination trends in the Vielha station, located on the Vall d'Aran, at the Catalan Pyrenees.

High mountains have been signalled as one of the habitats the plant diversity of which could be most rapidly and intensely affected by an increase in global temperatures, according to different projected scenarios (Theurillat 1995; Nualart 2003; Thomas et al. 2004). The decrease in the climatic space suitable for the mountainous flora has already caused reductions and simplifications in the floristic ensembles of some mountainous areas in Catalonia, especially significant because of the high endemism rates of these habitats (Beguiria et al. 2003; Thuiller et al. 2005). In this sense, many plant species seems to experiment a range shift due to local climatic conditions variation in response to climate change (Thuiller 2004; Dawson et al. 2011). According to Peñuelas and Boada (2003), the mediterraneisation of the cold temperate domains of the Montseny Massif, part of the catalan pre-coastal range, is an evidence of the influence that climate change can elicit to the vegetation of high mountains. When comparing the actual distribution of the vegetal

covers in the mountain and the one in 1945, a progressive substitution of the ecosystems of cold temperate climate by Mediterranean ecosystems is observed. *F. sylvatica* has migrated to higher elevations (1,600–1,700 m), being replaced by *Quercus ilex* L. and *Q. suber* L. at medium elevations (800–1,400 m). Similar situations have been recorded in other mountainous regions throughout Europe (Meshinev et al. 2000; Kullman 2001; Pauli et al. 2001), which leads to the prediction that this phenomenon can be induced for other mountainous regions such as the Pyrenees, where other ecological effects of climate change are starting to be witnessed (Camarero and Gutiérrez 2003; Sanz-Elorza et al. 2003).

Even though the magnitude and complexity of the impacts of climate change call for more detailed monitoring of the vegetation in order to corroborate the expected responses and predict the unexpected ones. In this sense, aerobiological data can be very useful to make a follow-up of the biogeographical response of vegetation to climate change (Rasmussen 2002; Emberlin et al. 2007a; Recio et al. 2009). For the moment, there are no comparable results in terms of pollen dispersal to those which have been found and are presented here. Although the pollen data series of Vielha are not very long to study such complex phenomena, some early effects of climate change are starting to be observed at an aerobiological level. One of the most relevant changes is a general increase in the pollen emissions of several taxa (Spieksma et al. 1995; Frei 1998; Teranishi et al. 2000). The greater biomass productivity associated with the increase in the atmospheric CO₂ concentrations is also shown in the anthers of the flower, with an increment of the pollen production of the plant, as it has been demonstrated experimentally (Ziska and Caulfield 2000; Wan et al. 2002; Wayne et al. 2002). Regarding this, the aerobiological records of Vielha seem to indicate a similar trend, although the evidences are still a bit premature considering the great fluctuations of the Mediterranean climate, responsible for the high inter-annual variability of the atmospheric pollen concentrations (Osborne et al. 2000). Nevertheless, for certain taxa such as *Corylus* L. and *Pinus* L., a significant increase on the API is being observed (Fernández-Llamazares et al. 2013).

Climate change exerts an influence on the pollen production mainly through the CO₂ concentrations (Levetin and Van de Water 2001; Beggs 2004), but also

through meteorological variables such as temperature and precipitation. Temperature is one of the factors that influence the most the development of the flower buds of trees (Chuine et al. 1998; Laaidi 2001; Galán et al. 2005; Orlandi et al. 2005b; García-Mozo et al. 2008). An increase in the temperatures can accelerate the development of buds and flowers, as well as its pollen production. For example, the API of *Corylus* pollen keeps a significant correlation with the mean daily minimum winter temperatures, having a stronger intensity of pollination in warmer years. The same situation is described for precipitation, since pollen production also relies on the accumulated rainfall in the previous months before the pollination season take place (Emberlin et al. 2000, 2007b). Thus, airborne pollen can act as a rainfall indicator. For example, in the case of the *Pinus* pollen, the API and the precipitation accumulated during winter and early spring show a significant relation of direct dependence, having a greater pollen production in rainy seasons. In this sense, shifts on the temporal distribution of rainfall could have many implications on the floral development of mountainous pines and the subsequent increase in seed production and new plant development.

The length and timing of the phenological cycle of plants is also of great importance for the conservation of mountainous forests, since a general advance in the flowering of many tree species is being recorded throughout Europe (Jäeger et al. 1996; Emberlin et al. 2002, 2007b; Bortenschlager and Bortenschlager 2005; Menzel et al. 2006). This advance could make them more vulnerable to late frosts, which can have many implications in terms of forest management. In this sense, ecological restoration should incorporate criteria for the prevention of the numerous effects of climate change, taking into account, for instance, tolerant species to climate change trends in restoration of plant covers. In conclusion, airborne pollen records can constitute a suitable biological indicator for evaluating physiological behaviour and resource conservation of vegetation responding to environmental fluctuations, particularly important in the context of climate change.

4 Concluding remarks

The role of airborne pollen monitoring in providing relevant data for the protection of flowering plants and its possible applications to the management of plant biodiversity are still underestimated and poorly

documented. This situation should be readdressed through long-term pollen sampling, with a special focus on natural areas, which have often been disregarded by aeropalynology. For instance, since pollen records are a biological indicator of an adequate plant reproductive development, they could be potentially used to identify the success and efficacy of the Programs of Recovery of Threatened Flora. The analysis of the historical series of pollen records placed near natural areas could be an effective tool to visualize the effects of different programmes of plant recovery on the pollen incidence. Under the current scenario of increasing temperatures and global environmental change, such an approach will surely become more necessary for the conservation challenge.

It may be argued that one of the reasons why aerobiological data have often been neglected in conservation schemes is related to the lack of basic research on the topic. A review of the literature suggests that barring few exceptions, aerobiologists have only recently turned their attention on how pollen records could contribute to conservation science (e.g. Belmonte et al. 2008; Cariñanos et al. 2013). In this article, we present three study cases showing evidence that, when aerobiological records are coupled with insights from other disciplines—such as meteorology or cartographical analysis, for instance—such knowledge is likely to be very helpful for the design of plant conservation initiatives that are more suited to biological requirements. This should augment the prospects for aerobiological sampling within the field of plant conservation, if aerobiology is to advance as a discipline.

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