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A review of the sampling efficiency of rotating-arm impactors used in aerobiological studies

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A review of the sampling efficiency of rotating-arm impactors used in aerobiological studies

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Correct sampling of airborne biological particles is the most critical step in aerobiological studies. It is common not to take account of the difference between the true atmospheric concentration, and the apparent concentration, as measured with rotating-arm impactors. The difference can be quantified by the sampling efficiency (E_s). I demonstrate that such differences can lead to substantial errors in many fields of aerobiology. Because of the continuing mis-use of such aerobiological samplers I present a review of concepts and an examination of previous experimental and theoretical attempts to ascertain E_s . I take the example of the widely-used rotorod sampler.

Commonly used theories cannot fully account for demonstrated variations in sampling efficiency when particle diameter and ambient wind speed vary. This is caused by: the complicated air flow patterns that develop around the rotating I-rods of a rotorod sampler; lack of particle retention; and, the varying densities and shapes of aerobiological particles. Other considerations indicate that, when used outdoors, atmospheric turbulence may also affect sampling efficiency.

To resolve these problems, a pragmatic approach is proposed wherein the rotorod is calibrated over a range of wind speeds, particle sizes and possibly turbulent intensities. A repeated measures design would allow a determination of sampler precision. The determination of precision, in addition to accuracy, is viewed as a crucial consideration that aerobiologists should consider in their work. This approach to calibration should, ideally, be enacted through international aerobiological standard measures or be done at calibration centres, and instrument calibrations should be made traceable to these standards.

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Quantifying airborne biological particles forms the basis for aerobiological research in areas such as seed production in agricultural crops and forestry (e.g., Dark 1971, Di-Giovanni & Kevan 1991); airborne pathogens of plants, animals and humans (Gregory 1973, Cox & Wathes 1995); and spray dispersal of biocontrol and other agents (e.g., Crabbe et al. 1994). Among the various methods commonly used to obtain a representative sample of aerobiological particles (see reviews in Dimmick & Ackers 1969, Gregory 1973, Ogden et al. 1974, Raynor 1979, Solomon 1984, Henningson & Ahlberg 1994, Lacey & Venette 1995) one of the most common for outdoor use is the rotating-arm impactor sampler exemplified by the rotorod-type samplers (commercially available as the Rotorod® Sampler, Sampling Technologies Inc., Minnetonka, MN, USA).

The development of the rotorod sampler by investigators at Stanford University was documented by Webster (1963) and Leighton et al. (1965). The device was originally designed to recover fluorescent tracer material from the atmosphere during various meteorological experiments. In the course of these investigations, it was discovered that the rotorod sampler also collected particles of biological origin. A modified device was introduced for sampling pollen grains and fungus spores in the 1960's (Magill et al. 1968) and the sampler became widely used in the fields of clinical allergy and plant pathology. A recent publication, for example, reported that

approximately 300 rotorod samplers are presently operating in the United States for routine aeroallergen monitoring (Frenz & Lince 1997).

Some versions of the rotorod sampler collect pollen grains and fungus spores on two transparent, rectangular rods (I-rods) that rotate through the atmosphere (Figs. 1, 2). Particles are retained on the rods with the aid of a silicone coating medium (e.g., G-697, General Electric Co., Waterford, NY, USA) applied to the upwind surface. Other

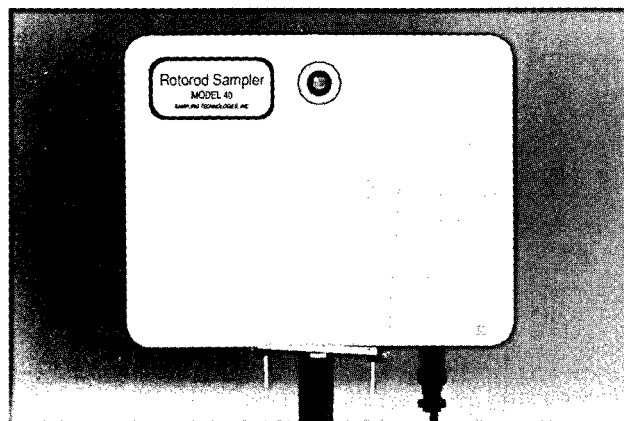


Fig. 1. The commercially available model 40 Rotorod sampler.

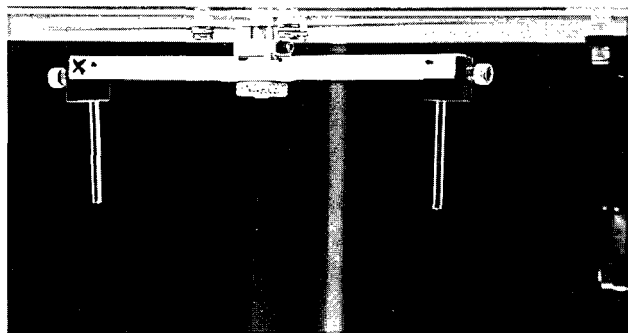


Fig. 2. Close-up of the model 40 Rotorod sampler showing the I-rod sampling surfaces.

versions of the rotorod use thin, metal rods or the edges of microscope slides, but the principle of operation is similar in all cases. In routine use, the atmospheric concentration of particles in the vicinity of the sampler is obtained by enumerating the particles collected on the I-rods and dividing those values by the volume of air swept out by the rotation of the I-rods (Sampling Technologies Inc. 1989). However, not all particles contained within the volume of revolution of the I-rods will be collected. This lack of collection is fairly well known as a phenomenon within aerobiology (e.g., Ogden et al. 1974) and yet very few workers account for this when determining airborne concentration. Most workers use the final estimate of the airborne particle concentration as if it were an accurate and precise representation of the true particle concentration (Edmonds 1972). As I will show, this is not borne-out by experimental or theoretical evidence.

In general, a measure of deviation of the estimated concentration (C_{est}) from the true airborne concentration of particles (C_{true}) is given by the sampling efficiency, E_s , of the sampler. This is a measure of the accuracy of the instrument. Simply, $E_s = C_{est}/C_{true}$, and varies between 0–100% for rotary-impaction type instruments (values greater than 100% are possible with suction-type samplers). It is well known that E_s varies with the physical characteristics of the sampler as well as with environmental conditions. If one hopes to obtain an accurate and precise estimate of C_{true} one needs to know the correct value of E_s , and its variability, for the instrument used and the environmental conditions at the time of sampling. If the variability (precision or standard deviation) of E_s is known, in addition, then one can place confidence intervals around one's estimate of C_{true} . This, to my knowledge, is not normally done in aerobiology and yet, as I will show later, is an extremely important concept that should be brought into aerobiology (Hirst 1995).

In this paper, I will; firstly, introduce the theoretical and physical considerations underlying sampling efficiency, with emphasis on impaction efficiency; secondly, I will present previous work demonstrating that E_s varies substantially with particle size and ambient wind speed and in a way that

is not easily predictable using impaction theory; thirdly, I will put forward a number of possible reasons for the incoherence between measurement and theory; fourthly, I will discuss the implications of ignoring corrections for sampling efficiency; and lastly, I will present a proposal for a more pragmatic measurement approach which can incorporate various aerobiological study philosophies.

SAMPLING EFFICIENCY OF ROTARY-TYPE SAMPLERS

In order to understand how the accuracy and precision of E_s varies, one needs to understand the important factors affecting E_s . The main factors are:

- (1) The impaction efficiency (E_i) to the collector rods (i.e., the ratio of particles impacting the rods to the number of particles populating the rods' equivalent area in the atmosphere);
- (2) The retention and bounce-off of the impacted particles (Gregory 1973, Raynor 1979, Paw U 1980, Gagnon & Comtois 1992);
- (3) Particle counting and identification errors (e.g., Frenz et al. 1996).

I will focus, primarily, on E_i because variation in particle retention and counting errors are relatively difficult to quantify, and more importantly, because variation in these two factors can be more simply accounted for in experiments I will suggest later.

The theory behind the impaction efficiency for these types of samplers has been reviewed many times (e.g., Harrington et al. 1959, Noll 1970, Edmonds 1972). The E_i is a function of an inertial parameter of the sampled particle called the Stokes number, St , and the Reynolds number of flow (Re_f), a measure of the ratio of inertial to viscous forces around the sampling surface. The relationship can be expressed as:

$$E_i = f\left(St = \frac{\rho_p d^2 u}{18nL}; Re_f = \frac{uL}{\nu}\right) \quad (1)$$

(Harrington et al. 1959, Noll 1970, Chamberlain 1975) where ρ_p is the density of the particle, d is the aerodynamic diameter of the particle, u is the velocity of the air carrying the particle on to the sampling surface, n is the dynamic viscosity of air, ν is the kinematic viscosity of air ($=n/\rho_{air}$) and L is the width of the obstacle. The aerodynamic diameter of a particle is the diameter of a unit density, perfectly spherical and smooth sphere whose settling velocity is equal to that of the particle of interest. The Stoke's number can also be written as:

$$St = v_s u / Lg$$

(Gregory 1973) where v_s is the settling velocity of the particle in still air and g is the acceleration due to gravity. Therefore, if v_s , u and L are known, a value for E_i may be calculated if the relationship between E_i and St is known (and variations in Re_f are assumed negligible) as utilized for fungal spore impaction on crop leaves by Aylor (1982).

The functional relationship between impaction efficiency and St and Re_f has been estimated from theory (Glauert 1940, Langmuir & Blodgett 1945, Brun & Mergler 1953

[quoted in Ogden & Raynor 1967], Galovin and Putman 1962 [quoted in Noll 1970]) for various flow conditions and also experimentally in aerosol science research (e.g., May & Clifford 1967). It has been customary, in theoretical studies, to establish the empirical relationship between E_i and St at constant values of Re_f . Typically, Re_f values are chosen which are typical of turbulent ($Re_f > 1000$), intermediate ($1000 > Re_f > 100$) and laminar ($Re_f < 100$) flow conditions. This is done because it is known that these three flow conditions cause quite different impaction conditions for airborne particles. However, as will be shown in the next section, Re_f around the rotorod I-rods is usually greater than 100 (defined as potential flow in Chamberlain [1975]). Therefore, variations in E_i due to Re_f will be relatively minor compared to variations due to St .

The above sources provide theoretically- or experimentally-derived families of curves of E_i versus St for different Re_f values. They indicate, as equation 1 shows, that high wind speeds and large particles result in high efficiencies and therefore less difference between C_{est} and C_{true} . If one assumes negligible error due to lack of retention of particles on the sampling surface, or due to counting error, these relationships could be used to estimate E_s , and its variation. However, in order to test the applicability of the above assumptions to the rotorod, independent measurements of the sampling efficiency of the rotorod sampler are required.

PREVIOUS DETERMINATIONS OF SAMPLING EFFICIENCY

Independent estimates of E_s may be obtained by comparison of values of C_{est} , obtained from the rotorod test instrument, and C_{true} , obtained by a calibration standard sampler. These comparisons may be made either in wind tunnel facilities or outdoors. Results of such studies are presented in Table I.

Theoretical estimates of E_i were calculated using the following procedure:

1. Wind speed, u , was calculated in a different way from previous workers. Here I took account of the variation in the velocity of air relative to the sampling surface of the rotorod as it rotated through 360° . For the 180° of up wind travel, the average wind speed encountered by the sampling surface (u_{rel}) is calculated from;

$$u_{rel} = u_{rr} + (2/\pi)u_{amb}$$

where u_{rr} is the linear velocity of the sampling surface (usually $\sim 1080 \text{ cm s}^{-1}$) assumed constant, and u_{amb} is the velocity of the surrounding air (column 5 in Table I). Similarly, for down wind travel;

$$u_{rel} = u_{rr} - (2/\pi)u_{amb}$$

2. Re_f was calculated (as in eqn. 1) assuming $v = 0.152 \text{ cm}^2 \text{ s}^{-1}$, L taken from specific instrument descriptions (but usually $\sim 0.15 \text{ cm}$) and u_{rel} used from above. In all cases, for both up wind and down wind travel Re_f calculated using u_{rel} was greater than 290.
3. St was calculated (as in eqn. 1) separately for up wind and down wind components of the I-rod rotation. ρ_p was assumed to be unity, d was assumed equal to the physical

pollen or spore diameter or estimated as shown in Table I (column 4) and n was taken as $1.83 \times 10^{-4} \text{ g cm}^{-1} \text{ s}^{-1}$.

4. E_i was derived from fig. 4 (p. 163) of Chamberlain (1975) using curve A for potential flow ($Re_f > 100$) in all cases. Up wind and down wind E_i values were averaged to produce the figures given in Table I (column 7).

To summarize the patterns indicated by experimental evaluations of E_s indicated in Table I:

1. There is marked variation in E_s with variation in u and d .
2. At constant u , E_s increases as the size of the particle increases (Carter 1961, McGill et al. 1968).
3. For smaller particles, as u increases, E_s increases (Carter 1961, Aylor 1993).
4. For larger particles, as u increases, E_s decreases (Carter 1961, Ogden & Raynor 1967).
5. No clear pattern emerges from the work of May et al. (1976).

The theoretical estimates do not correspond exactly with the measured values in either absolute value or trend of the data. Although the estimates are within approximately 10–15% for the studies of McGill et al. (1968), May et al. (1976) and Aylor (1989), the variations in measured E_s with u are greater than theoretical for the studies of Carter (1961) and Ogden and Raynor (1967). Certainly the assumption of previous workers (Harrington et al. 1959, Ogden et al. 1967, Solomon et al. 1968, Noll 1970, Raynor 1979, Aylor 1993), that the high linear velocity of the rotating I-rods rendered insignificant any variation in ambient wind speed, is not corroborated.

NON-IDEAL SAMPLING BY ROTATING-IMPACTOR TYPE SAMPLERS

If the theoretical estimates presented in Table I had been close to measured values, it would provide a relatively simple method to correct C_{est} values. However, in some cases they were not. It is instructive to examine some of the possible reasons why in order to convince ourselves that the proposal for calibration work (next section) is more pragmatic than using a theoretical approach to calibrate the rotorod.

The effect of the vortices and wake produced by the rotation of impaction arms on the rotorod may cause a local breakdown in streamlined airflow, thus largely invalidating the theoretical models for impaction efficiency and empirical relationships measured under specialized conditions (e.g., as used in May & Clifford 1967). Ogden and Raynor (1967) tested the roto-slide for these effects by modifying the roto-slide, constructing a cross-arm twice the normal length but operating at one-half the normal rotational speed, thus having the same linear speed at the sampling surfaces. Results indicated that the efficiency was improved somewhat but the scatter in the experimental points and the variation with wind speed were greater and thus the modification was not recommended. Attempting to model the affects of this turbulent wake would be difficult. Noll et al. (1985) chose the rotational speed of their modified rotary impactor so as to minimise the wind speed needed to provide fresh (unsampled) air to each sampling surface and eliminate the effect of the wake from one rotating sampling surface on the following.

The modified Noll rotary impactor is similar to the rotorod except that the axis of rotation is kept parallel to the ambient wind direction by attachment to a wind vane; the device resembles a propeller-vane anemometer. At 320 RPM the sampling surfaces rotated at 10.2 m s^{-1} (similar to contemporary rotorods) and a wind velocity of 0.54 m s^{-1} was needed to provide fresh air and prevent the wake of one sampling surface impinging upon the following. McCartney et al. (1997, Fig. 3) recently published schematic diagrams of smoke plume photographs of a rotorod-type sampler in operation. Smoke flow patterns indicated that air is drawn into the axis of rotation of the sampling rods from below and above, and then "ejected" by the sampling rods. Similar observations were also made by Aylor (1995). This specific airflow pattern would again suggest that streamlined flow of particles on to the collecting rods is unlikely to be occurring (see also Solomon et al. 1968, Batchelder 1977).

In addition, errors may be caused by non-retention of particles. Bounce-off may explain the observations by Carter (1961) and Ogden and Raynor (1967) for larger particles; particle retention on the sampling surfaces is inversely proportional to the kinetic energy of the particle upon impact above a threshold energy (Aylor & Ferrandino 1985). For the impaction of *Lycopodium* spores and ragweed pollen on to non-sticky glass cylinders and wheat stems, Aylor and Ferrandino (1985) found that substantial rebound occurred at energies above a threshold energy of approximately 10^{-6} to 10^{-5} ergs ($1 \text{ erg} = 10^{-7} \text{ J}$). The reduction in E_s due to bounce-off may have been negligible for the smaller particles, used in the rotorod tests, whose kinetic energy may never have exceeded the specific threshold. Thus E_s was found to increase as wind speed increased for smaller particles; e.g., ascospores of *Mycosphaerella pinodes* in the work of Carter (1961) or ascospores of *Venturia inaequalis* (Cooke) G. Wint.

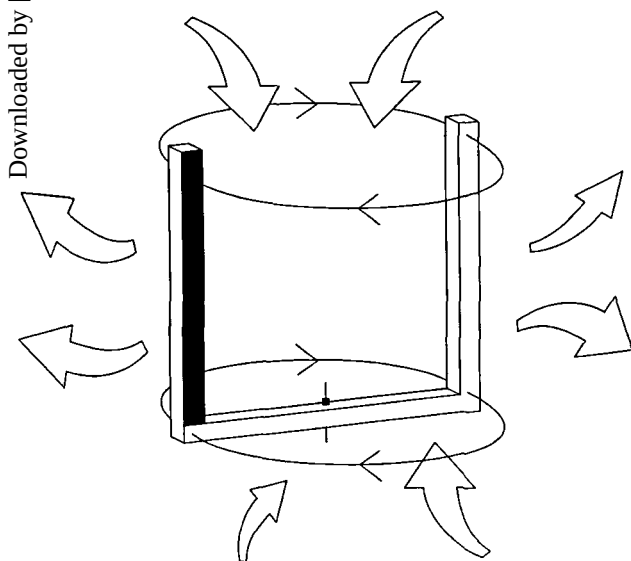


Fig. 3. Schematic diagram of sampling surface of rotating-arm impactors showing air movement into sampler (based on smoke photographs taken in a wind tunnel at IACR-Rothamsted, UK). [Reprinted from Journal of Aerosol Science, 28, McCartney et al., Sampling in plant pathology, pp 349–364, Copyright (1997), with permission from Elsevier Science].

in the work of Aylor (1993) but not for the larger particles. Lack of retention efficiency and bounce-off has also been mentioned in some other studies (Gregory 1973, Raynor 1979, Paw U 1980, Gagnon & Comtois 1992) but there have been no experimental or theoretical investigations of this for the rotorod. Aylor and Ferrandino were able to regress the relative retention of the particles they used against their kinetic energies. However, threshold energies for bounce-off and the relationships between relative retention and kinetic energies are likely to be different for the grease-covered I-rods of the rotorod sampler, although one could guess that the threshold energies are likely to be higher. It is possible, as mentioned above, that these higher threshold energies were exceeded by the larger particles used by Carter (1961) and Ogden and Raynor (1967), and that the ensuing loss of larger particles due to bounce-off exceeded increases in E_s due to larger particle size.

Previously determined relationships between E_i and St were derived using or assuming spherical, unit density particles, i.e., particles whose aerodynamic diameter was likely close to their nominal diameter. Many pollen and spores are not spherical nor possess unit densities (Gregory 1973). Substitution for the correct aerodynamic diameter in the St can correct for this, and aerodynamic diameters for various pollen and spores can be derived if, for example, their settling velocity is known (Di-Giovanni et al. 1995). Alternatively, correction for shape-factors (Chamberlain 1975, McCartney 1990, Lacey 1991), and the particular density of the pollen or spore of interest is also possible. However, in practise, all these correction methods are difficult to apply given the relative lack of such data. For example, in Table I, a nominal value of $7.5 \mu\text{m}$ diameter was used to calculate theoretical E_i for *Bacillus subtilis* clumps, and yet it is obvious that there was likely much variation in the sizes and aerodynamic diameters represented in such a loosely defined category. This is likely the reason that the theoretical E_i overestimated E_s by such a large amount (43.3%).

The normally turbulent airflow, as can be quantified by turbulent intensity i , in the outdoor environment has been shown to affect the sampling efficiency of suction-type samplers (Weiner et al. 1988). However the affect of turbulence on sampling has not been approached theoretically (Green & Lane 1964 p. 194) and no comprehensive experimental tests have been carried out on the rotorod.

IMPLICATIONS OF SAMPLING VARIATION FOR AEROBIOLOGICAL WORK

The implications of varying sampling efficiency are fairly obvious. If changes in u cause changes in sampling efficiency, then a simple difference in u from one day to the next will cause an apparent change in concentration when no true change may have occurred when sampling outdoors. Using Carter's (1961) data, for example, if using the rotorod to measure the airborne concentration of ascospores similar in size to *M. pinodes* ($12\text{--}15 \times 6\text{--}8 \mu\text{m}$), and if the average wind speed during sampling were $1\text{--}2 \text{ m s}^{-1}$ on one day but $4\text{--}5 \text{ m s}^{-1}$ the next, then an apparent two-fold increase in concentration would be measured when in fact no true change in concentration had occurred.

Table I. Results of previous investigations into the effect of varying wind speed and/or particle size on the sampling efficiency (E_s) of rotary-impaction type samplers and the corresponding theoretical estimate of impaction efficiency (E_i) for each experiment.

Bracketted figures in columns 5 and 6 (particle diameter and ambient wind speed, respectively) are the nominal values used in the theoretical calculations of E_i . See text for explanation of theoretical calculations.

Author(s)	Calibration standard	Particle types	4 d (μm)	5 u (m s^{-1})	E_s -exp (%)	E_i -theor. (%) (E_s-E_i)	Notes
Carter (1961)	Isokinetically operated Cascade Impactor	Ascospores of <i>Mycosphaerella pinodes</i>	12–15 × 6–8 (10.5)	1–2	50	63 (–13)	Wind tunnel comparisons in turbulent airstream
			12–15 × 6–8 (10.5)	4–5	90	63 (+27)	
		<i>Lycopodium clavatum</i>	30	1.5	80–85	93 (~ –10.5)	
			30	9	60–65	91 (~ –28.5)	
Ogden and Raynor ^a (1967)	Filter-sampler operating isokinetically	Ragweed pollen	21.4	'near zero' (0.0)	68	90 (–22)	Wind tunnel comparisons
			21.4	10	49	73 (–24)	
Mcgill et al. (1968)	Millipore filter operating isokinetically	<i>Bacillus subtilis</i> spores	0.5 × 1.0 (0.75)	0.995	0.5	~0 (~ +0.5)	Wind tunnel comparisons
		<i>Bacillus subtilis</i> clumps	5.0 to 10 (7.5)	0.995	0.7	44 (–43.3)	
		<i>Calvatia gigantea</i> spores	4–5 (4.5)	0.995	19.3	18 (+1.3)	
		Paper Mulberry pollen	11–13 (12.0)	0.995	54.9	69 (–14.1)	
		<i>Puccinia graminis</i> spores	14 × 24 (19.0)	0.995	89.5	84 (+5.5)	
May et al. (1976)	Suction sampler operating isokinetically in a portable wind tunnel	Liquid drops	50	1–6 (3.0)	86	96 (–10)	Field comparisons. No variation attributable to u found
		Liquid drops	30	1–6 (3.0)	85	92 (–7)	
		Liquid drops	20	1–6 (3.0)	93	83 (+10)	
Aylor (1989)	Suction traps; 100% efficient for u between 0–2.3 m s^{-1} . ^b	<i>Lycopodium</i>	30	~0–3 (1.5)	80	93 (–13)	Field comparisons
Aylor (1993)	Burkard sampler assumed 90% efficient and corrected for anisokinetic sampling	Ascospores of <i>Venturia inaequalis</i> (Cooke) G. Wint.	NA	0.1–0.15	~21	NA	Indoor comparisons
			NA	0.6–2.3	32	NA	Field comparisons

^aOgden and Raynor (1967) tested a Rotoslide, a variant of the rotorod that used microscope slid edges ($L=0.1$ cm) as the trapping surface.

^bBainbridge and Stedman (1979) measured the efficiency of the same suction traps in a wind tunnel by comparison against a cascade impactor (May 1945) operated isokinetically. Tests were conducted using spores of *Lycopodium clavatum* and *Erysiphe graminis* and efficiency did not vary with wind speed up to speeds of 2.3 m s^{-1} but their results (fig. 1, p.190 therein) suggest some consistent variation with particle size. The average of the tests indicated an average efficiency for the suction trap of close to 1.0. However, reference to the original developers of the same suction trap (Gregory et al. 1961) reveals that the efficiencies (tested against a cascade impactor operated isokinetically and using spores of *Lycopodium*) at 0.82, 1.95, 3.6 and 6.1 m s^{-1} were 54, 74, 85 and 119% respectively. The reason for these contradictory results between the two sets of investigators is not known. However, in general, the usage of the suction trap in wind tunnel studies allows more control over inlet velocity versus ambient wind speed making isokinetic sampling achievable.

Similarly, one must only compare variations in atmospheric concentration for particles of the same size; differences in size also cause differences in sampling efficiency and thus an apparent difference in concentration where there may not be. For example, if wind speed were constant ($\sim 1 \text{ m s}^{-1}$) and one were measuring *B. subtilis* spores and *Puccinia graminis* spores with the same rotorod sampler, then the apparent difference in concentrations would be ~ 180 -fold when no true difference in concentration exists. In many aerobiological studies, the same sampler is used to capture a range of particle types and sizes. The same may possibly be said for differing turbulent intensities in the atmosphere, as they may also affect sampling efficiency when sampling outdoors (May 1945) for suction type devices (Wiener et al. 1988), although May et al. (1976) briefly states that turbulence does not seem to affect the rotorod.

Of particular interest, therefore, would be the difference in apparent concentration induced by these factors without a change in true concentration. That is, if the difference in C_{est} measured from one day to the next is less than that possible due to a change in wind speed alone, one can presume that the difference is within "sampling error" and therefore non-significant. Similarly, if one measures concentration gradients in space (horizontally or vertically) or time, and the gradients are particularly subtle, one must ask the question "when is a difference a significant difference." It becomes obvious, then, that an assessment of sampler precision (as may be quantified by standard error) becomes just as crucial a sampler characteristic as accuracy is.

In much past work, it is likely that variations in C_{est} have been attributed to the various atmospheric variables thought to affect pollen and spore dispersal or describe concentration gradients with height. In physical aerobiology studies, it is likely that concentration gradients in the vertical or horizontal may have been misinterpreted; concentration differences that were thought significant may not have been; in other words, type I errors may have been committed. This may be especially true where gradients are particularly subtle, as in long-distance dispersal type studies. In probabilistic, pollen-forecasting type studies, statistical relationships may have been determined between C_{est} and atmospheric variables. Given the now obvious sampling instrument interaction, some false significant correlations between meteorological parameters (i.e., wind speed) and C_{est} may have been derived. Overall, it is difficult to think of a field of aerobiology that would not be fundamentally affected by the above considerations.

ESTIMATING SAMPLING EFFICIENCY AND SAMPLER ERROR

To summarize past work, firstly, it is known that no presently used particle collector is (nor is likely to be) 100% efficient for aerobiological sampling, nor is the sampling efficiency invariant. Secondly, previous efficiency tests of rotorods sampling aerobiological particles were not comprehensive, i.e., they did not cover a range of d , u , or turbulent intensity (i) allowing the relationship between Re_r , St and E_s to be fully elucidated and generally applicable. In a number of cases unexpected results (i.e., decreasing efficiency with

increasing wind speed) were derived. On the other hand, these instruments are among the most practical instruments available for routine sampling work. It is difficult to envisage alternative instruments that are as practical and yet more efficient considering present technology. Rather than propose yet another aerobiological sampler, instead I propose a more pragmatic approach wherein the limitations of these sampling techniques are accepted, and effort is directed to finding the associated error involved with each estimate of airborne concentration, as also proposed by May et al. (1976) and Hirst (1995). In essence, I propose a calibration system not unlike that used for meteorological instruments wherein calibration standards or calibration centres are available worldwide, and the calibration of various instruments (or type of instrument) be traceable to the international standards.

Most sampler efficiency (or calibration) determinations are carried out by simultaneously comparing particle capture rates of the sampler of interest versus a standard sampler in a series of wind tunnel tests (Henningson & Ahlberg 1994). A suitable standard sampler should be aerodynamically non-intrusive (*sensu* Braaten et al. 1993); optical particle analyzers (Mitchell 1995) may therefore be appropriate. Resulting determinations of the relationship between E_s and the major independent variables (d , u and perhaps i) that affect E_s would allow calibration of the rotorod for use with different particle sizes, turbulent intensities and wind speeds. Variations due to retention efficiency and counting error will be subsumed into the estimate for sampling efficiency although errors due to mis-identification of particles will not. Inter-sampler variation can be quantified by repeating tests for a randomly selected number of instruments supplied by the manufacturer.

The crucial element will be to design the experiment incorporating repeated measures such that the standard error of the E_s can be derived (May et al. 1976, Banks & Di-Giovanni 1994). Essentially, one can design an experiment where E_s for the rotorod can be related, by multiple-regression (or some other suitable multivariate technique), to u , i and d . The resultant regression line will be the calibration curve used to convert C_{est} to C_{true} . In addition, the standard error of the estimate, and thus the 95%CI (or 95% prediction interval), can be calculated. Therefore the two characteristics of accuracy and precision are quantified in such a way as to allow users to quantitatively test concentrations differences for statistical significance.

However, use of such a calibration curve requires co-located information on u and i (it is assumed that d is easily estimated by most aerobiologists). If an instrument user only measures u for example (in addition to d) and not i then one can de-stratify the calibration data to produce a regression of E_s on u and d alone. However, it will be likely that the standard errors of such an estimate will be wider than when the more detailed regression equation is used. If, as is likely in most cases, the user does not measure u or i , the only regression line usable will be the univariate regression of E_s versus d , using all the calibration data pooled. This will likely have even wider standard errors associated. Thus more experimental effort will be required to differentiate more subtle differences in concentrations; this is a compromise.

ise that aerobiologists must bear in mind when designing their experiments.

In practise, it is likely that a series of calibration equations will have to be developed for each major type of aerobiological sampler, including Hirst-type samplers. This will allow each user to choose the calibration equation suitable for their own study aims. If regional daily pollen counts are required, for example, for pollen forecasting purposes, the only independent variable available may be *d*. In that case, the user will apply the appropriate calibration equation and will probably inherit rather large standard errors. On the other hand, if a user is measuring vertical concentration gradients of pathogenic spores over a crop field, they may have, at hand, data on *u* variation with height and *i*. In that case the researcher would choose the most precise calibration equation employing those additional independent variables, in order to obtain the most precise concentration estimates, and thus allowing the significance of even subtle gradients to be assessed.

SUMMARY

I have reviewed theoretical aspects and experimental measurements of the impaction and sampling efficiency of rotary-type impaction samplers. Commonly used theories cannot fully account for variations in sampling efficiency with particle diameter and ambient wind speed. This is perhaps caused by the complicated air flow patterns that develop around the rotating l-rods of a rotorod sampler, non-retention of particles, lack of particle sphericity and differences from unit density. Other considerations indicate that, when used outdoors, atmospheric turbulence may also affect sampling efficiency.

Despite the above, most users of these types of instruments do not correct for varying sampling efficiency. Not correcting for varying sampling efficiency can result in large errors in the estimate for atmospheric concentration. Such errors will result in spurious scientific interpretations.

On the other hand, development of an "ideal" sampler for outdoor sampling is not within the reach of current technologies; no sampler presently used is perfect. Instead I propose that these instruments, and in particular the commonly-used rotorod sampler but also other types of samplers, be extensively tested and calibrated. This would enable users to correct for varying sampling efficiency, and more importantly, estimate the standard error of the concentration estimate. Use of the standard error will allow users to quantitatively test for significant differences in concentration. These calibrations should ideally be used as standard procedure by aerobiologists, and be derived from internationally-recognized calibration procedures.

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