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1 **Experimental and methodological framework for the assessment** 2 **of nucleic acids in airborne microorganisms**

3 **Running Title:** Methods in aeromicrobiology

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13 **Author contributions:** RP, MJ have made major contribution to the acquisition, analysis and
14 interpretation of the data. FR and OR helped with data acquisition and data analysis. PA
15 conceived and designed the study, and interpreted the data. PA and RP wrote the manuscript.

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17 **Keywords:** Atmosphere, aerobiology, bacteria, sample replication, contaminants

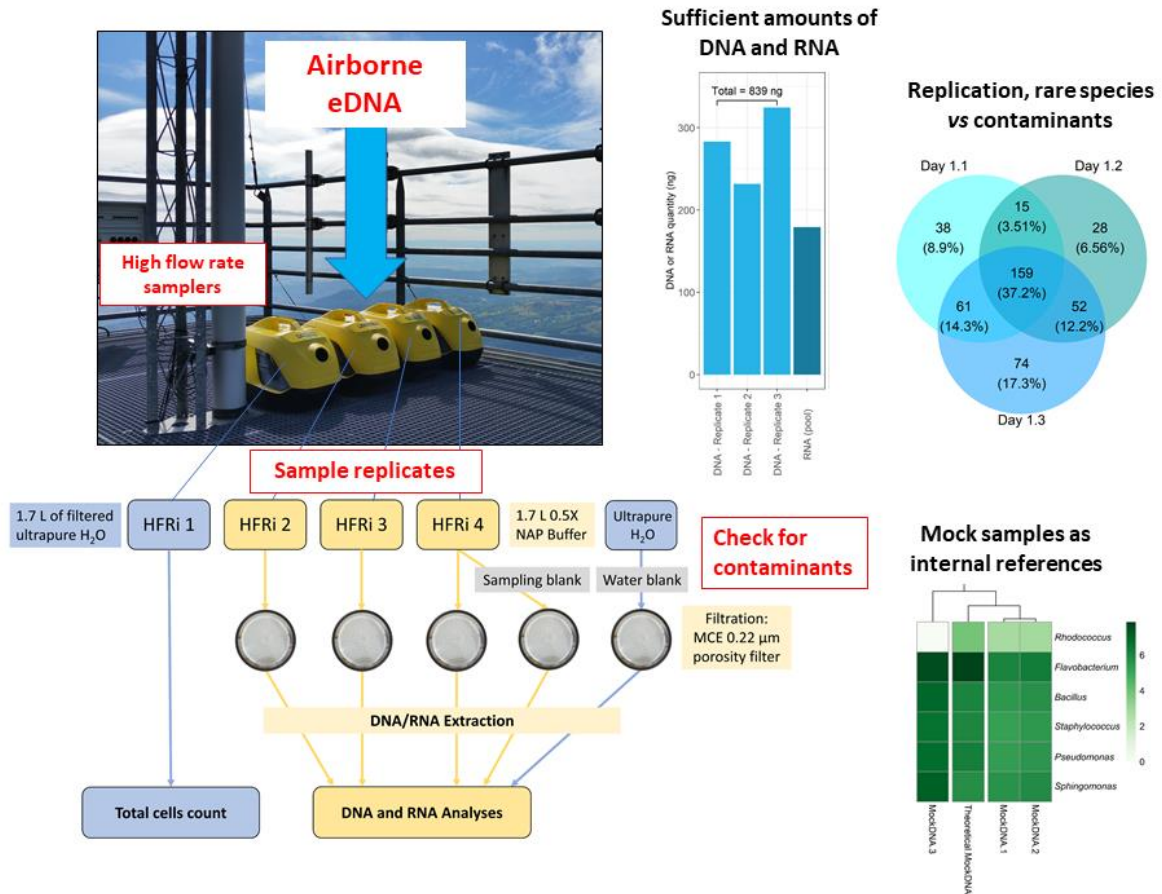
18 **Data Archiving Statement:** Demultiplexed sequencing files were deposited at the European
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 26 to RP.

27

28 **Graphical abstract:**



29

30

31 **Abstract**

32 Studying airborne microorganisms is highly challenging due to ultra-low and spread
33 biomass, and great spatial and temporal variabilities at short scales. Aeromicrobiology is still
34 an emerging discipline of environmental microbiology, and some of the basic practices
35 (replication, control of contaminants, *etc*) are not yet widely adopted, which potentially limits
36 conclusions. Here we aim at evaluating the benefits of such practices in the study of the
37 aeromicrobiome using molecular-based approaches, and recommend the following: (i) sample
38 at high airflow rate, if possible into a fixative agent, in order to be able to capture specific
39 situations ; (ii) replicate sampling and process samples individually to enable statistical analyses
40 ; (iii) check for contaminants at different steps of the analytical process, and account for their
41 potential stochasticity in sequence decontamination methods ; (iv) include internal references
42 to verify qualitative and quantitative aspects of the data, and (v) eventually investigate multiple
43 analytical procedures to identify potential impacts on the data. In our study, samples were
44 collected at a remote mountain site using high-flow rate impingers collecting airborne material
45 into nucleic acid preservation buffer. As high of ~75% of the sequences were shared between
46 independent triplicates, gathering 28 to 38% of the richness observed at the ASV level at a
47 given sampling date, which also emphasizes spatial heterogeneity at short scale due to rare taxa.
48 Thanks to replicates, daily variations in the diversity of bacteria could be distinguished
49 statistically, and the inevitable presence of contaminating sequences in controls could be
50 accounted for using established statistical methods. This work opens new perspectives and
51 notably paves the way to untargeted molecular methods in the exploration of aeromicrobiome's
52 composition and functioning.

53

54

55

56 Introduction

57 The atmosphere is exposed to emissions of biological material from surface ecosystems
58 and carries their DNA imprints. These can be lifted up to high altitudes and travel over long
59 distances up to continental scales (Després et al., 2012; Smith et al., 2013; Barberán et al.,
60 2015). Biological aerosols play roles as cloud condensation nuclei (CCN) and ice nuclei (IN),
61 and can have influence on cloud microphysics and precipitation (Zhang et al., 2021; Bauer et
62 al., 2003; Möhler et al., 2007; Patade et al., 2021). Bioaerosols also include microorganisms of
63 sanitary concern, such as pathogenic, opportunistic, or antibiotic resistant taxa (Rossi et al.,
64 2022; Fernstrom et al., 2013; Beattie and Lindow, 1995), and, regardless of the potential
65 hazards they may create, the fact that microbial cells can maintain metabolic activity (Krumins
66 et al., 2014; Amato et al., 2019; Šantl-Temkiv et al., 2017) raises questions about their
67 physiological properties and their role in atmospheric chemical processes (Wirgot et al., 2017;
68 Khaled et al., 2021; Joly et al., 2015).

69 Aeromicrobiology is still an emerging discipline, and the basics of recommended
70 practices in environmental microbiology are often neglected. The first prerequisite for a
71 meaningful analysis is to be able to distinguish target(s) from contaminants. These can originate
72 from handling, equipment, or reagents including commercial kits (Stinson et al., 2019; de
73 Goffau et al., 2018; Salter et al., 2014). Preventing contaminants involves, at the very least,
74 working under adequate sterile conditions, and checking them by taking control samples at
75 various stages of the analytical process. In addition, statistical comparison between diverse
76 environmental situations requires replicates (Prosser, 2010; Ji et al., 2019), which also help
77 detecting sporadic contaminants such as those brought by commercial reagents.

78 The greatest technical challenges in outdoor aeromicrobiology are related to the low
79 biomass (typically ~1 to 100 cells per liter of air), in particular in remote situations. This
80 imposes sampling for extended periods of time, or at high-flow rate, and preserving the *in-situ*

81 state of the material during and upon sampling (Burrows et al., 2009; Després et al., 2012; Šantl-
82 Temkiv et al., 2020). Sampling over long periods of time alters integrity and viability of
83 airborne biological material and living cells (*e.g.*, Manibusan and Mainelis, 2022). Moreover,
84 as microbial assemblages vary widely over short temporal and spatial scales, sampling may
85 have to be carried out over short periods of time (*e.g.*, a few hours or less) depending on the
86 objectives, for instance for capturing a specific situation. Meanwhile, sufficient quantities of
87 biological material must be collected to allow analyses, and ensure representativeness of the
88 samples through statistics. High-flow rate sampling solutions are therefore methods of choice,
89 and impingers, *i.e.*, liquid impactors, are considered as reference samplers for bioaerosols
90 (Dybwad et al., 2014; Rule et al., 2007). In addition of preserving cell integrity due to gentler
91 impaction than on solid surfaces, these allow the use of a variety of solutions for preserving
92 viability or nucleic acids, including RNAs (Kathiriya et al., 2021; Šantl-Temkiv et al., 2017;
93 Griffin et al., 2011; Camacho-Sanchez et al., 2013).

94 As analytical methods improve, deepest investigations are made possible, and methods
95 based on high-throughput sequencing of amplicons are now widely used to explore bacterial
96 and fungal diversity (Zhao et al., 2022; Tignat-Perrier et al., 2020b). With the advent of NGS
97 techniques as highly sensitive methods for investigating microbial diversity, new challenges
98 have emerged such as detection of trace contaminants, sequencing bias and artifacts (de Goffau
99 et al., 2018). Here, we propose an experimental procedure to study biological aerosols through
100 nucleic acid-based approaches in remote atmosphere, considering replication and accounting
101 for inevitable contaminants, whatever their origin. Several high-flow-rate impingers (HFRI)
102 filled with nucleic acid preservation (NAP) buffer as the sampling fluid were deployed in
103 parallel for molecular investigations. Controls for the presence of contaminants were made at
104 multiple steps of the experimental procedure, and quantitative aspects as well as sequence
105 annotation accuracy were verified using artificial “mock” communities as internal references.

106 Amplicon sequencing data indicated good reproducibility of the methods and allowed
107 distinguishing bacteria diversity from consecutive days with good statistical confidence. The
108 amounts of DNA and RNA collected opens unprecedented possibilities of direct sequencing of
109 metagenomes and metatranscriptomes from atmospheric samples.

110

111 **Materials and methods**

112 Drastic procedures were applied throughout the experimental process, including
113 systematic decontamination of the material used (pipets, *etc.*) with detergents (RNAse away,
114 ethanol 70% or diluted bleach), exposure to UVs, use of laminar flow hoods, systematic
115 filtration of all the liquids before autoclave, *etc.*

116

117 **Sampling setup with High-Flow-Rate Impingers (HFRI)**

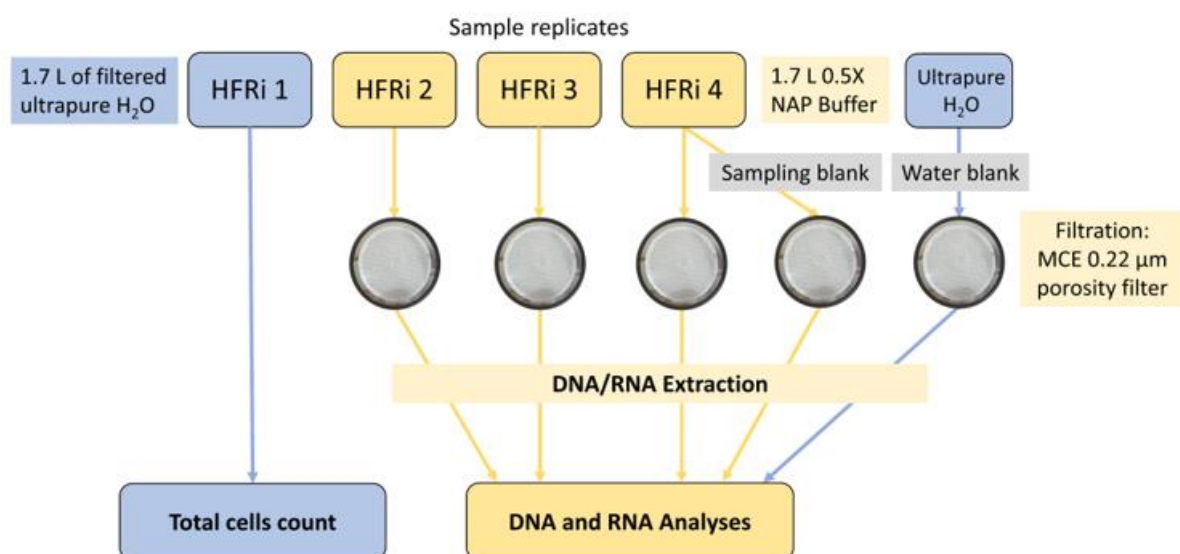
118 Sampling of aerosols was carried out at the summit of puy de Dôme mountain (1,465 m
119 a.s.l, France) using the facilities of the atmospheric station (Baray et al., 2020; Péguilhan et al.,
120 2021), during three consecutive days in July 2020. Samples were collected for 6 to 6.5
121 consecutive hours, corresponding to 708-770 m³ of air collected by each sampler at each
122 occasion, at ambient temperature ranging from 11 to 20°C and 48 to 61% humidity (**Table 1**).
123 More details on the meteorological context, including backward trajectories of the
124 corresponding air masses can be found at <https://www.opgc.fr/data-center/public/metadata>.

125

126 **Table 1:** Main characteristics of aerosol samples.

Sample identifier	Sampling date (dd/mm/yyyy)	Number of replicates	Sampling duration (h)	Air temperature (°C) [#]	Relative humidity (%) [#]	Wind speed (m.s ⁻¹) [#]	Microbial cell concentration (cell.m ⁻³) [*]
Day 1	07/07/2020	3	6.5	11.1	61	3.6	1.62×10 ³
Day 2	08/07/2020	3	6.1	14.2	53	3.1	1.72×10 ³
Day 3	09/07/2020	3	6.0	20.3	48	3.4	2.62×10 ³

127 [#] Average over the sampling period; ^{*}: inferred from concentration in the collection liquid and sampler's air flow
128 rate.



129

130 **Figure 1:** Schematic of the experimental procedure (HFRi: High Flow Rate impinger).

131 The overall sampling strategy is summarized in **Figure 1**. Four HFRi were used in
132 parallel from the platform of the roof of the atmospheric station. HFRi sampler is a commercial
133 Kärcher DS 5600 or DS6 vacuum cleaner (Kärcher SAS, Bonneuil sur Marne, France) that can
134 contain up to 1.7 L of collection liquid and operates at an airflow rate of $118 \text{ m}^3 \cdot \text{h}^{-1}$ (Šantl-
135 Temkiv et al., 2017). One of the samplers was dedicated to cell quantification by flow cytometry
136 and was filled with filtered ($0.22 \mu\text{m}$ mixed cellulose esters (MCE) membranes, 47 mm
137 diameter, Dominique Dutscher; Bernolsheim, France) and autoclaved ultrapure water as the
138 collection liquid. The other three HFRi were dedicated to nucleic acid analyses and were filled
139 with 0.5X nucleic acid preservation (NAP) buffer (see below for preparation). For all samplers,
140 the volume of liquid was checked individually every hour by weighing, and it was compensated
141 for evaporation with filtered autoclaved ultrapure H₂O when necessary, assuming unit density.
142 Immediately after sampling (on site), the collection liquid of each individual sampler dedicated
143 to nucleic acid analyses was filtered independently through $0.22 \mu\text{m}$ MCE membranes using
144 sterile filtration units (Thermo Scientific Nalgene), in a laminar flow hood previously exposed
145 to UV light for 15 min. The filters were then individually placed into 5 mL Type A Bead-Tubes

146 (ref. 740799.50, Macherey-Nagel), added with 1,200 μ L MWA1 lysis buffer and stored at -
147 80°C until nucleic acids extraction as specified in the corresponding section below.

148 Negative controls of the collection liquids and samplers were performed just before
149 sampling: 1.7 L of 0.5 X NAP buffer were poured into one of the HFRi tanks, left for 10 min
150 with agitation, and then collected in a sterile bottle; these are referred to as “sampling blanks”.
151 In addition, filtered autoclaved ultrapure water was used as a negative control to detect possible
152 contamination during sample processing after collection; these are referred to as “water blanks”
153 (**Figure 1**). All controls were processed and analyzed along with environmental samples.

154 NAP buffer was prepared following the instructions in Camacho-Sanchez et al. (2013).
155 This is composed of (final concentrations): 0.019 M of ethylenediaminetetra-acetic acid
156 (EDTA; Fisher BioReagents™), 0.018 M of trisodium citrate salt (Fisher Chemical) and 3.8 M
157 of ammonium sulfate (ACROS ORGANICS) dissolved in ultrapure water, and H₂SO₄ to pH
158 5.2. The NAP buffer was then filtered through Glass Microfiber filters GF/F (47 mm diameter,
159 porosity of 0.7 μ m; Whatman; Maidstone, United Kingdom) to remove impurities, aliquoted
160 and autoclaved as volumes of 1.7 L into 2-L glass bottles for subsequent direct use.

161

162 **Sampler decontamination procedure**

163 Ethanol and UVs are common decontamination procedures (Dommergue et al., 2019;
164 Archer et al., 2019; Šantl-Temkiv et al., 2017). Here the standard decontamination procedure
165 of the polypropylene HFRi’s tanks consisted in: (1) thorough rinse with H₂O then deionized
166 H₂O; (2) rinse and exposure to 2 L of 70% ethanol for 10 min; (3) exposure of the different
167 parts of the tanks to UVs (254 nm) for 10 min, within a laminar flow hood. The decontaminated
168 tanks were then stored in sterile autoclave bags until deployment to the field.

169 To evaluate the efficiency of our decontamination procedure, two sampling tanks were
170 intentionally contaminated with a culture of *Pseudomonas syringae* 32b-74 (see

171 **Supplementary Figure 1).** The strain was cultured in liquid R2A at 17°C for 3 days and then
172 centrifuged for 3 min at 13,000 g to recover cells. The supernatant was removed and the pellet
173 rinsed and resuspended in dH₂O, at a concentration of $\sim 2.3 \times 10^9$ cell mL⁻¹ estimated from OD₆₀₀.
174 Finally, 7.2 mL of the stock solution was diluted in 1.7 L of autoclaved ultrapure water to reach
175 a final solution at $\sim 10^7$ cell mL⁻¹, and poured into sampler's tank. Such cell concentration in the
176 collection liquid is much higher than what can be expected from sampling in natural context
177 (Šantl-Temkiv et al., 2017); a third sampler was left uncontaminated as a control. The samplers
178 were then emptied and subjected to decontamination, using either the standard procedure
179 described above, or just the thorough rinsing step with dH₂O, then refilled with 1.7 L of filtered
180 (0.22 μm porosity) autoclaved ultrapure water, as for actual sampling. Samplers were then
181 switched on for 10 minutes to ensure contact with all tank's parts, and subsamples of the
182 collection liquid were then analyzed for total cells count as detailed below in the corresponding
183 section. The autoclaved ultrapure water used was also analyzed without contact with the
184 samplers. Total cell concentrations in the liquid exposed to the samplers after intentional
185 contamination and decontamination were similar as those in uncontaminated controls (Mann-
186 Whitney test; *p-value* < 0.05). A simple thorough rinse with filtered ultrapure water thus
187 removed cells, and UV exposure ensured further decontamination.

188

189 **Total cell counts**

190 Total cells were quantified by flow cytometry from triplicate subsamples of 450 μL of
191 the collection liquid from the dedicated HFRi, fixed with 50 μL of 5% glutaraldehyde (0.5%
192 final) and stored at 4°C until analysis, using a BD FACS Calibur instrument (Becton Dickinson,
193 Franklin Lakes, NJ). Before analysis, samples were added with TE buffer (pH 8.0) and SYBR
194 Green I stain following the protocols in Amato et al. (2017). Negative controls consisted of
195 ultrapure water as the template.

196

197 **Nucleic acid extraction**

198 Environmental samples were processed within a laminar flow hood previously exposed
199 to UVs (15 min), and all bench surfaces, pipets etc. were decontaminated using RNase away
200 spray solution (Thermo Scientific; Waltham, USA). Three nucleic acid extraction kits designed
201 for DNA and RNA extraction were compared: DNeasy PowerWater kit (QIAGEN; Hilden,
202 Germany), NucleoSpin Soil, and NucleoMag[®] DNA/RNA Water kit for water and air sample
203 (Macherey-Nagel, Hoerdt, France), referred to as the “Water”, “Soil” and “Air” kits,
204 respectively. The “Water” and “Soil” kits, and the “Soil” and “Air” kits were compared as pairs
205 during two sampling events each, in triplicate using three independent samplers. After each
206 sampling event, the collection liquids were entirely and individually filtered through 0.22 µm
207 MCE membranes. The filters were then cut equally into two pieces for extraction using 2 of the
208 kits and stored at -80°C until processing. Extractions were performed following the
209 manufacturers’ protocols. In the case of the “Air” kit, slight adaptations were made from
210 manufacturer’s instructions: half MCE filters were placed into individual 5 mL Type A Bead-
211 Tubes (ref. 740799.50, Macherey-Nagel) and added with 1,200 µL MWA1 lysis buffer. After
212 the lysis step (5 min of bead-beating using a vortex), ~600 µL of lysate was processed following
213 the protocol adapted for 47 mm filter membranes. For DNA, the lysates were added with 1:50
214 volumes of RNase A (12 mg/mL, stock solution), incubated for 20 min at room temperature,
215 then eluted into 50 µL of RNase-free H₂O after another incubation for 5 min at 56°C. DNA in
216 the eluates was finally quantified using Quant-iT™ PicoGreen dsDNA kit (Invitrogen; Thermo
217 Fisher Scientific, Waltham, MA USA). For RNA, the lysates were added with rDNase and
218 processed as recommended. Purified RNAs were finally quantified by fluorimetry using
219 RiboGreen (Invitrogen; Thermo Fisher Scientific, Waltham, MA USA). In terms of quantity of
220 DNA recovered, the “Air” kit outperformed the “Soil” kit, which itself surpassed the “Water”

221 kit (see **Supplementary Figure 2**). The “Air” kit was therefore selected for further
222 investigations; it has the additional advantage of allowing parallel extraction of DNA and RNA.
223

224 **16S ribosomal gene amplification by PCR**

225 Amplification of the V4 region of the 16S rRNA gene of bacteria was performed from
226 genomic DNA extracts by multiplexed PCR, using the primers 515f (5’-
227 GTGYCAGCMGCCGCGGTAA-3’) (Parada et al., 2016) and 806r (5’-
228 GGACTACNVGGGTWTCTAAT-3’) (Apprill et al., 2015). The PCR mix was composed as
229 follows: each 50 µL reaction volume contained 2 µL of sample, 10 µL of 5X Platinum II PCR
230 Buffer (Invitrogen; Thermo Fisher Scientific, Waltham, MA USA), 5 µL of Platinum GC
231 Enhancer, 1 µL of 10 nM dNTPs (Sigma-Aldrich; Merck, Darmstadt Germany), 1 µl of 10 µM
232 forward and reverse primers, 0.2 µL of Platinum II Taq HS DNA pol (Invitrogen), and 29.8 µL
233 of Ambion™ Nuclease-free water (Invitrogen). PCR amplification conditions (35 PCR cycles)
234 are described on the “Earth Microbiome Project” website (<https://earthmicrobiome.org/>). All
235 amplicons (environmental samples and negative and positive controls) were purified using
236 QIAquick PCR Purification kit (QIAGEN; Hilden, Germany), pooled equimolarly and
237 sequenced on Illumina Miseq 2*250 bp (GenoScreen; Lille, France).

238

239 **Quality controls for taxonomic affiliation and biodiversity profiling**

240 Artificial mock samples prepared from pure cultures or DNA extracts were processed
241 as internal references, down to sequencing. An artificial atmospheric “mock” community was
242 obtained by mixing pure cultures of six bacterial strains isolated from cloud water and
243 representing a range of typical atmospheric bacteria (Amato et al., 2007; Väitilingom et al.,
244 2012; Lallement et al., 2017): *Pseudomonas syringae* PDD-32b-74 (GenBank ID for 16S rRNA
245 gene sequence: HQ256872), *Bacillus* sp. PDD-5b-1 (DQ512749), *Sphingomonas aerolata*

246 PDD-32b-11 (HQ256831), *Rhodococcus enclensis* PDD-23b-28 (DOVD00000000),
247 *Staphylococcus equorum* PDD-5b-16 (DQ512761) and *Flavobacterium* sp. PDD-57b-18
248 (KR922118.1). These were cultured separately in 10 mL of liquid R2A at 17°C until late
249 exponential phase (21-44h incubation). Genomic DNA were extracted either from pure cell
250 suspensions then mixed at known concentrations (“Mock DNA”), or from cell suspensions
251 mixed at known concentrations before DNA extraction (“Mock Cloud”) (**Supplementary**
252 **Figure 3; Supplementary Table 1**). The former allowed evaluating differences in DNA
253 amplification efficiency depending on taxa, while the latter evaluated in particular the
254 efficiency of DNA extraction.

255 For the “Mock DNA” samples, DNA extraction was performed following
256 manufacturer’s protocol of the QIAamp DNA Mini kit (QIAGEN, Hilden, Germany) with
257 minor changes: 1 mL of each culture was centrifuged at 14,000 g after 4 days of incubation and
258 the pellets were re-suspended in 180 µL of TE (1X), with 25 µL of lysozyme (50 mg/mL) and
259 5 µL of RNase (1 mg/mL). The mixture was vortexed and incubated 30 min at 37°C. Twenty
260 microliters of Protease K and 200 µL of Buffer AL were added. The mixture was vortexed
261 again and incubated first during 30 min at 56°C, then for 5 min at 95°C. DNA was finally
262 quantified in each individual extract using Quant-iT™ PicoGreen® dsDNA kit (Invitrogen;
263 Thermo Fisher Scientific, Waltham, MA USA) and “Mock DNA” aliquots were prepared by
264 mixing 2 µL of each extract, then stored at -80°C.

265 For the “Mock cloud” samples, the cell concentrations in individual cultures were
266 estimated by flow cytometry. The six strains were then mixed at known concentrations
267 (**Supplementary Table 1**) and 1 mL aliquots in 10% glycerol were stored at -80°C for further
268 use. DNA was extracted in triplicate for mixed cell suspensions using either NucleoMag®
269 DNA/RNA Water (Macherey-Nagel, Hoerd, France), *i.e.*, the kit denominated as “Air” in the
270 previous section, or QIAamp DNA Mini kit (QIAGEN; Hilden, Germany) (**Supplementary**

271 **Figure 3**). DNA extracts were stored at -80°C before further processing. The relative
272 abundances of 16S rRNA gene sequences in the extracts were estimated from total genomic
273 DNA quantifications and from the mean numbers of ribosomes in the corresponding genera, as
274 reported in the ribosomal RNA Database (rrnDB, v 5.7): 4.3 copies for *Rhodococcus*, 6.6 for
275 *Flavobacterium*, 8.7 for *Bacillus*, 5.7 for *Staphylococcus*, 4.8 for *Pseudomonas*, and 2.0 for
276 *Sphingomonas*.

277

278 **Bioinformatics data processing and statistics**

279 Amplicon sequence variants (ASVs) were obtained from raw reads with the package
280 *dada2* (v 1.20.0) (Callahan et al., 2016), using the functions *filterAndTrim*, *learnErrors*, *dada*,
281 *mergePairs*, *makeSequenceTable* and *removeBimeraDenovo* following authors guidelines.
282 Then, FROGS software (Bernard et al., 2021) was used to affiliate ASVs against SILVA v138.1
283 (Quast et al., 2013). When the BLAST assignment was questionable (*i.e.*, multi-affiliations,
284 percent identity $< 95\%$, or percent query coverage $< 98\%$), this was verified using the RDP
285 assignment and the EzBioCloud 16S rRNA gene-based ID database (Yoon et al., 2017;
286 <https://www.ezbiocloud.net/>, update 2021.07.07). ASVs affiliated to *Chloroplast* (46 ASVs;
287 13% of total sequences), *Mitochondria* (71; 1.6 %) or Archaea (5; 0.2%), and ASVs without
288 affiliation (87; 4%) were removed. The number of raw reads processed and remaining for
289 analysis after curation and rarefaction are indicated in **Supplementary Table 2**. Environmental
290 and mock samples were rarefied to 16,250 and 28,100 sequences, respectively, corresponding
291 to the sample of each category with the lowest number of reads, using *FROGS Abundance*
292 *normalization*. Blank samples were not rarefied. This left 22 and 556 ASVs in mock and
293 environmental samples for further analyses, respectively.

294 ASV abundance data were centered log-ratio (CLR)-transformed, as recommended by
295 Gloor et al. (2017) to account for their compositional nature. Data analysis was performed and

296 represented using the *R* environment (v 4.0.3) (R Core Team (2019). *R: A language and*
297 *environment for statistical computing.*, 2020). The *zCompositions* package (v 1.3.4) (Palarea-
298 Albaladejo and Martín-Fernández, 2015) was used to replace null counts in our compositional
299 data based on a Bayesian-multiplicative method (function *cmultRepl* using CZM method and
300 an input format in pseudo-counts) and to CLR-transform the abundance table (*clr* function).
301 Heatmaps and dendograms were obtained using the packages *pheatmap* (v 1.0.12) (Raivo
302 Kolde, 2019) and *ggdendro* (v 0.1.22) (Andrie de Vries and Brian D. Ripley, 2016). Principal
303 component analysis was carried out using the R package *factoExtra*, with ellipses depicting
304 95% confidence levels. The R package *decontam* (Davis et al., 2018) was used for identifying
305 and removing contaminants (referred to as “Method (iv)” in the corresponding result section).
306 Univariate statistical tests were performed using PAST v. 4.02 (Hammer et al., 2001).

307

308

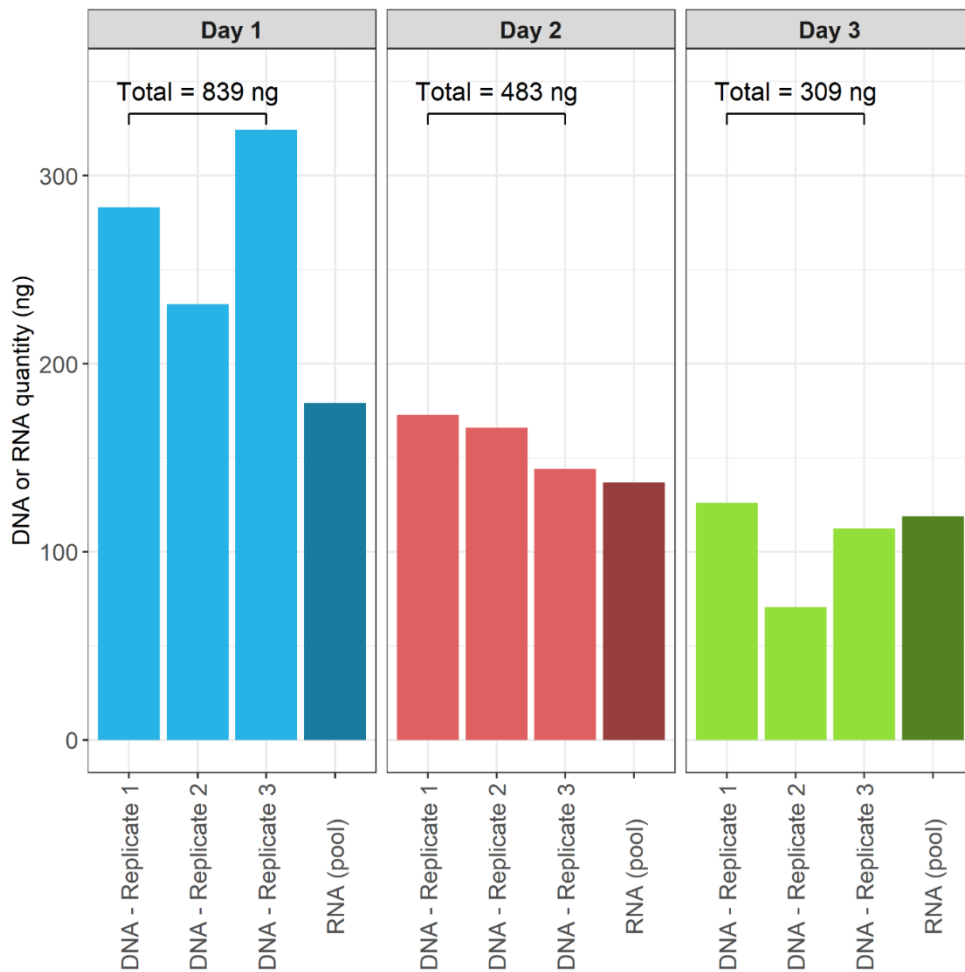
309 **Results and discussion**

310 Total cells in the air samples averaged $(1.98 \pm 0.55) \times 10^3$ cell m⁻³ of air (**Table 1**); these
311 are typical values at puy de Dôme station (Vaïtilingom et al., 2012). In total, 424 ASVs could
312 be detected on Day 1, 378 on Day 2, and 348 on Day 3. The main bacterial phyla identified
313 belonged to Proteobacteria (Alpha- and Gamma-; e.g., *Sphingomonas*, *Methylobacterium*,
314 *Massilia*, *Pseudomonas* and *Bradyrhizobium*), Firmicutes (e.g., *Bacillus*), Actinobacteria (e.g.,
315 *Nocardioides*), and Bacteroidota (e.g., *Hymenobacter* and *Pedobacter*), which are commonly
316 reported in the atmosphere (Bowers et al., 2012; Tignat-perrier et al., 2019). Day 1 was
317 characterized by high abundance of *Sphingomonas* (3.2 % of the sequences), over
318 *Hymenobacter* (1.1 %) and *Pseudomonas* (1.0 %), while Day 3 was more evenly dominated by
319 *Sphingomonas* (1.8%), *Bacillus* (1.6 %) and *Methylobacterium* (1.2 %) (see **Supplementary**
320 **Figure 4, and Supplementary Table 3**).

321

322 **The recovery of high amounts of DNA and RNA opens new perspectives**

323 The amounts of DNA extracted from the collection liquids ranged from 70.5 ng (Day 3,
324 replicate 2), to 324.5 ng (Day 1, replicate 3), with low variations between replicates (CV<30%).
325 In total, 309 to 839 ng of DNA and 118.8 ng to 179.1 ng of RNA were available for analyses
326 (**Figure 2**). These quantities are sufficient to allow direct sequencing of DNA and cDNA using
327 current high throughput methods, which opens unprecedented opportunities of metagenomics
328 and metatranscriptomics studies.



329

330

331 **Figure 2:** DNA and RNA concentrations in environmental air samples.

332

333 Metagenomics and metatranscriptomics approaches have proven their strength in the
334 understanding of microbial functioning in environments like oceans (Salazar et al., 2019;
335 Gifford et al., 2011). In the air, nucleic acids are in general obtained from filter samples (Be et
336 al., 2015; Tignat-Perrier et al., 2020a; Gusareva et al., 2019), which prevents relevant
337 assessment of transcriptomes. To our knowledge the very few studies reporting
338 metatranscriptomes sequences from atmospheric samples so far involved targeted or untargeted
339 pre-amplification (PCR or MDA) (Amato et al., 2019; Womack et al., 2015; Klein et al., 2016;
340 Amato et al., 2017).

341

342 **Internal references allow evaluating quantitative aspects**

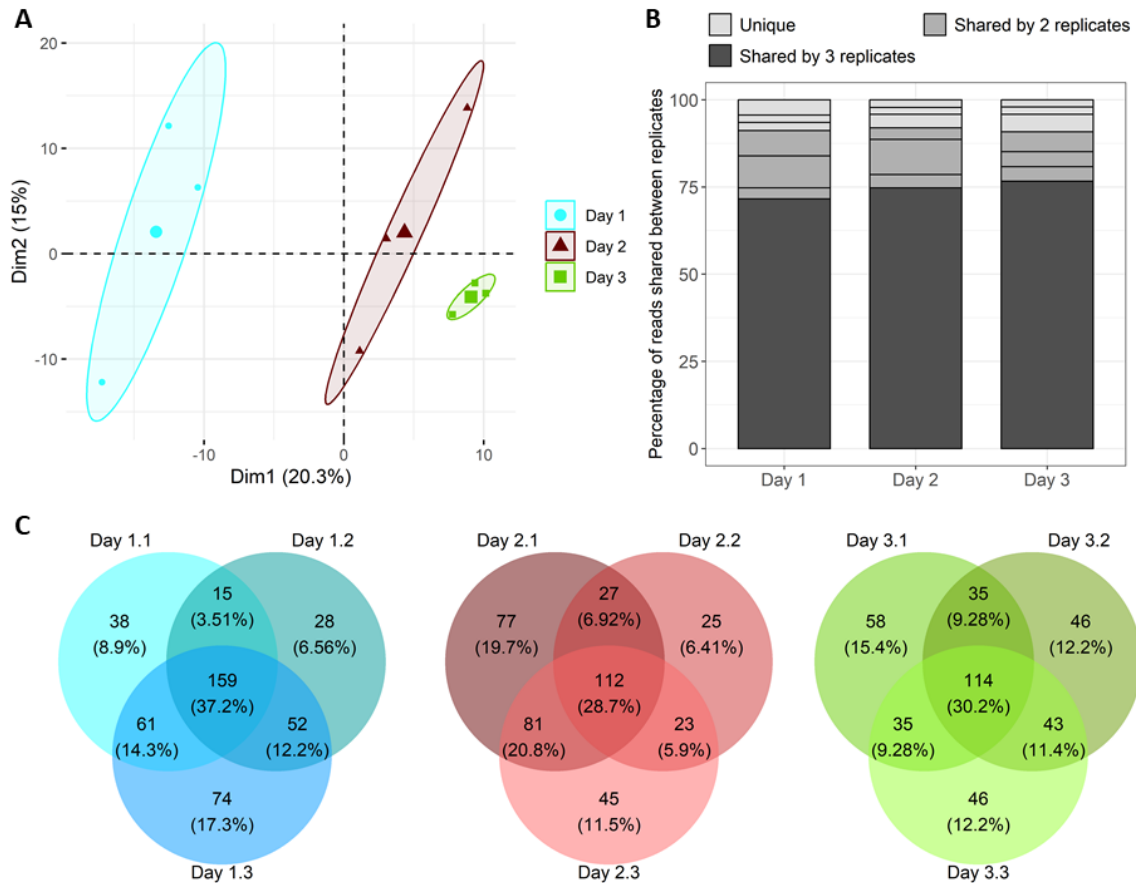
343 Mixed cell suspensions (“Mock cloud”) and DNA mixes (“Mock DNA”), composed of
344 cultures and DNA extracts of isolates from clouds, were processed as internal references. These
345 included a range of bacteria typically reported in atmospheric samples: affiliated with
346 *Pseudomonas syringae*, *Bacillus* sp., *Sphingomonas aerolata*, *Rhodococcus enclensis*,
347 *Staphylococcus equorum* and *Flavobacterium* sp.. In all cases, clustering analysis followed
348 expectations and grouped replicates with their respective theoretical taxa distribution
349 (**Supplementary Figure 5**). Mock DNA samples data supported that PCR and sequencing
350 processes were efficient at maintaining the relative distribution of taxa from DNA mixes. In
351 Mock cloud samples, *Staphylococcus* was found overrepresented at the expense of *Bacillus* as
352 compared to expectations based on cell counts, in particular when using QIAamp extraction kit.
353 The primer pair used for 16S rRNA gene amplification (515F-806R) has been shown to perform
354 better than many other current ribosomal primers in detecting a wide range of bacteria taxa
355 (Abellan-Schneyder et al., 2021) and could not be incriminated. It is likely, rather, that cell
356 counts by flow cytometry tended to underestimate the actual relative abundance of
357 *Staphylococcus* in the original cell suspensions as this forms cell agglomerates, while *Bacillus*
358 was to some extent recalcitrant to DNA extraction due to the presence of spores (Knüpfer et al.,
359 2020). This indicates that specific taxa, in particular among Firmicutes, can present distortions
360 in their relative abundance in sequence datasets compared with actual abundance in samples.

361 The few other sequences sporadically present in positive controls at very low abundance
362 (<50 reads; <0.05% of the total reads in samples; **Supplementary Table 4**) may inform about
363 the presence of contaminants and/or sequencing artifacts. Moreover, aliquots of both mock
364 sample types were archived at -80°C for further use as references to compare data from distinct
365 sequencing runs and studies.

366

367 **Replicate sampling allows statistics**

368 The data demonstrate good reproducibility of the methods (**Figure 3**); it allowed
 369 distinguishing the airborne bacteria diversity of 3 consecutive days with very similar
 370 environmental conditions by principal component analysis (PCA) (**Figure 3A**).



371
 372 **Figure 3:** Distribution of ASVs and sequences among sample replicates. **A:** Principal
 373 component analysis based on ASV's relative abundances (ellipses depict 95% confidence level
 374 areas); **B:** Proportions of sequencing reads retrieved in 1 (unique), 2 or 3 sample replicates; **C:**
 375 Venn diagrams showing the occurrence (presence/absence) of ASVs among sample replicates.

376
 377 Bacterial assemblages were very uneven, composed of few abundant taxa accompanied
 378 by numerous sporadic (low-abundance) ones. Most sequences were consistently retrieved
 379 between sample replicates (71.6% to 76.8% depending on the sampling date; **Figure 3B**),
 380 representing a core assemblage gathering 28.7% to 37.2% of the richness (**Figure 3C**). In turn,

381 only ~3% of the sequences were specific, *i.e.* retrieved in only one of the 3 replicates of each
382 sampling date, but they contributed relatively large proportions (6.4% to 19.7%) of the observed
383 species richness in a sampler. Low-abundance taxa thus largely contributed to the variability
384 observed between replicates and sampling dates, which is common in such datasets as pointed
385 earlier in a range of ecosystems from air and lakes to skin and gut (Shade et al., 2014). With
386 our setup, taxa's rarity directly related to their chance to be captured by one or more samplers.
387 The fact that a relatively large fraction of the total richness observed on a given sampling date
388 was specific (~33 to 40%) emphasizes the high spatial heterogeneity at short scale of the
389 atmospheric environment, as regularly documented (Fierer et al., 2008), which is caused by a
390 high proportion of rare taxa. The multiplicity of potential sources to the material collected and
391 their respective strengths in emitting microorganisms can generate such variations despite
392 overall very similar environmental conditions. Rare taxa can be important components of the
393 material circulating in the air, for ecological and/or sanitary reasons, and they must not be
394 neglected (Jalasvuori, 2020; Barberán et al., 2014; Leyronas et al., 2018; Pascoal et al., 2021;
395 Pester et al., 2010; Rossi et al., 2022; Lynch and Neufeld, 2015).

396 Thanks to the individual processing of replicate samples, we could statistically
397 discriminate sampling dates. Nevertheless, given the large number of potential explanatory
398 variables involved respect to the limited number of samples assessed, it would be highly
399 hazardous to try explaining the variability observed between sampling dates, so such attempt is
400 not proposed. A more complete assessment of the extended dataset in relation to environmental
401 variables can be found in Péguilhan et al. (2023).

402

403 **Account for the inevitable presence of contaminants**

404 Processing negative controls is crucial in environmental microbiology to ensure data
405 robustness, in particular where the biomass is low and subjected to strong short-scale variations

406 such as in the atmosphere. As many contaminants can be brought by air itself (other than from
407 the target environment) during sample handling and processing, detecting them is particularly
408 challenging in aeromicrobiology (Šantl-Temkiv et al., 2022). Moreover, rare taxa can easily be
409 confounded with stochastic trace contaminants from kits and reagents, or sequencing artefacts
410 (de Goffau et al., 2018; Šantl-Temkiv et al., 2020; Glassing et al., 2016; Salter et al., 2014).

411 The amounts of nucleic acids recovered from controls, *i.e.* 1.7 L of unexposed deionized
412 water (“water blanks”) or of NAP buffer exposed to the samplers (“sampling blanks”) were
413 well below the amounts obtained from environmental samples: over 10 sampling blanks
414 performed between July 2019 and September 2020 (including some which are not presented
415 here, collected in the frame of other studies), the total amount of DNA ranged from 2.8 to 9.6
416 ng (7.45 ± 2.1 ng; mean \pm SE), while it remained under detection limits for water blanks. From
417 both control types, slight PCR products could be generated, and these were processed down to
418 sequencing. This points toward the difficulty to maintain background signals at low level when
419 using DNA amplification and high-throughput sequencing methods. Stinson et al. (2019)
420 proposed to treat commercial reagents with DNase in order to remove potential contaminants.

421 The number of raw sequencing reads was much fewer in controls than in environmental
422 samples as expected from lower amounts of DNA, with medians of ~4,000 *versus* ~88,000
423 reads, respectively (Mann-Whitney test, $p = 0.001$; **Supplementary Table 2**). Both water and
424 sampling controls types exhibited much lower richness and diversity than environmental
425 samples. Among controls, more raw reads could be obtained from unexposed water than from
426 the collection liquid after exposed to the samplers, and they tended to be richer (Chao1 index).
427 This confirms the effectiveness of sampler decontamination procedures and suggests that
428 contamination occurred randomly during sample processing rather than during field work; it
429 also indicates the absence of core contamination from the reagents and material used.

430 A total of 89 ASVs could be detected in controls, including 18 to 47 ASVs in water
431 blanks and 24 to 29 ASVs in sampling blanks; 54 of them (~61%) were also detected in
432 environmental samples. These were affiliated with a large diversity of taxa identified as
433 frequent contaminants in commercial reagents (Stinson et al., 2019; Salter et al., 2014; Glassing
434 et al., 2016) and also typically dominant in atmospheric samples (Väitilingom et al., 2012;
435 Amato et al., 2017), such *Sphingomonas*, *Pseudomonas*, *Hymenobacter*, and *Methylobacterium*
436 (see **Supplementary Table 5** for complete list).

437 The stochasticity of contaminants (Stinson et al., 2019) makes them difficult to detect
438 in complex datasets. In our study, most ASVs in controls (56 out of 89; 63%) occurred only
439 once, and only 3 were recurring, affiliated with *Sphingomonas*, *Pseudomonas*, and
440 *Burkholderia*: (cluster_4, cluster_2 and cluster_174, respectively). Cluster_4 was present in all
441 the samples processed in this study, including positive (“Mock”) controls; cluster_2 was present
442 in at least one replicate of each sampling date, in various proportions; cluster_174 was absent
443 from environmental samples. This latter was therefore most likely associated with reagents or
444 sequencing procedures.

445 The most conservative way to account for contaminants in samples is to exclude them
446 totally from environmental datasets, regardless of their relative abundance (it would be
447 irrelevant to subtract read numbers or proportions), although this is likely to remove also true
448 members of the environment studied. Besides, less drastic, more elaborated statistical
449 procedures have been proposed to account for both the prevalence and frequency of
450 contaminants in such datasets (Davis et al., 2018), and so better consider stochasticity aspects;
451 this requires replicates. In order to test the influence of sequence decontamination methods on
452 richness and diversity, 4 treatments were applied to non-rarefied environmental datasets: (i)
453 strict removal of all the ASVs detected in water blanks regardless of their relative abundance;
454 (ii) strict removal of all the ASVs detected in sampling blanks; (iii) strict removal of all the

455 ASVs detected in water and/or in sampling blanks; (iv) probability-based method cumulating
 456 the frequency and prevalence methods of the R package *decontam* (Davis et al., 2018).

457

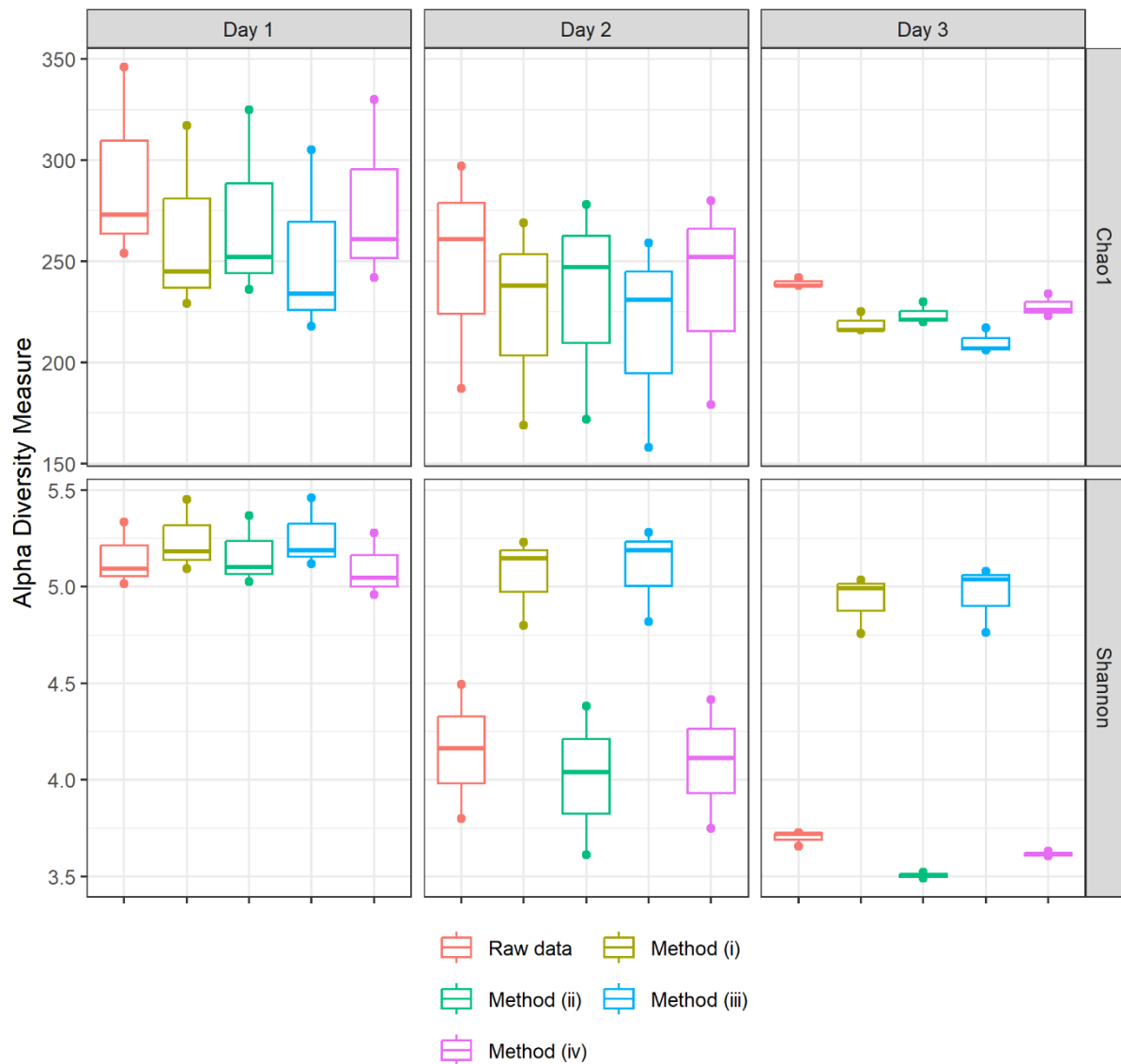
458 **Table 2:** Proportions of reads and ASVs removed from environmental datasets from
 459 decontamination methods (see text for details on the methods).

Sample	Initial data (non-rarefied)		Method (i) (water blanks)		Method (ii) (sampling blanks)		Method (iii) (water + sampling blanks)		Method (iv) (probability)	
	Number of reads	Number of ASVs	% reads removed	% ASVs removed	% reads removed	% ASVs removed	% reads removed	% ASVs removed	% reads removed	% ASVs removed
Day 1.1	18823	273	24.07%	10.26%	16.66%	7.69%	31.07%	14.29%	2.75%	4.40%
Day 1.2	16250	254	23.22%	9.84%	16.46%	7.09%	31.41%	14.17%	3.24%	4.72%
Day 1.3	24856	346	22.55%	8.38%	14.97%	6.07%	29.03%	11.85%	2.99%	4.62%
Day 2.1	27670	297	38.23%	9.43%	12.94%	6.40%	44.86%	12.79%	2.97%	5.72%
Day 2.2	19027	187	45.99%	9.63%	12.66%	8.02%	53.82%	15.51%	1.56%	4.28%
Day 2.3	24406	261	44.14%	8.81%	12.27%	5.36%	49.63%	11.49%	1.63%	3.45%
Day 3.1	29709	242	45.88%	7.02%	9.41%	4.96%	51.68%	10.33%	1.50%	3.31%
Day 3.2	24392	238	48.38%	9.24%	11.30%	7.56%	55.12%	13.45%	3.23%	6.30%
Day 3.3	23014	238	48.94%	9.24%	10.72%	7.14%	54.94%	13.03%	2.92%	5.04%
		Mean	37.93%	9.10%	13.04%	6.70%	44.62%	12.99%	2.53%	4.65%
		<i>Standard error</i>	<i>11.41%</i>	<i>0.95%</i>	<i>2.52%</i>	<i>1.07%</i>	<i>11.05%</i>	<i>1.59%</i>	<i>0.74%</i>	<i>0.97%</i>

460

461

462 The proportions of reads and ASVs removed with each method and their influence on
 463 richness and biodiversity on environmental data are presented in **Table 2** and **Figure 4**,
 464 respectively. All methods showed very good consistency between replicates. These all
 465 necessarily decreased richness in samples, by ~5% to ~13% in average depending on the
 466 methods (**Table 2**). The strict methods (*i*, *ii* and *iii*) led to the removal of higher proportions of
 467 reads than ASV, contrarily to the statistic method, and strongly increased biodiversity index in
 468 samples, by up to more than 1 point in the cases of Day 2 and Day 3 (**Figure 4**). In turn, the
 469 statistic method (*iv*) did not alter biodiversity indexes.



470

471 **Figure 4:** Influence of decontamination methods on environmental samples' richness and
472 biodiversity indexes.

473

474 The decontamination solutions that can appear the most conservative at first sight can
475 thus counterintuitively lead to increase biodiversity in environmental samples and smooth
476 temporal variability, so result in erroneous conclusions. In addition of strengthening statistics
477 aiming at deciphering alpha- and beta- diversity of airborne microbial assemblages, replication
478 also enables more meaningful decontamination methods to be applied.

479

480 **Conclusion**

481 We used an analytical framework involving some of the basic recommended practices
482 in environmental microbiology (replicate, check and account for contaminants, include internal
483 references) to atmospheric samples, and demonstrate that these can logically benefit to
484 aerobiology as well in many aspects. Replicated sampling at high air-flow rate for short periods
485 of time into nucleic acid preservation buffer allows capturing close atmospheric situations that
486 can be distinguished statistically using high throughput sequencing methods. Replication is also
487 necessary to account for the stochastic and inevitable presence of contaminants, and so to ensure
488 confidence to taxa's presence and abundance in environmental samples. Finally, replicating
489 also allows pooling to access larger amounts of material if necessary, which opens new
490 perspectives for metagenomics and metatranscriptomics investigations of the aeromicrobiome.
491 Analyses of the alpha- and beta- diversity of microbial assemblages in air masse, and short-
492 scale and specific atmospheric variations (*i.e.*, day-to-day or day/night variations, clouds,
493 pollution events, etc) will be assessable with good confidence using this framework.

494

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