

1 **Room-level Ventilation in Schools and Universities**

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Room-level Ventilation in Schools and Universities

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Supporting Information

Mountain West University

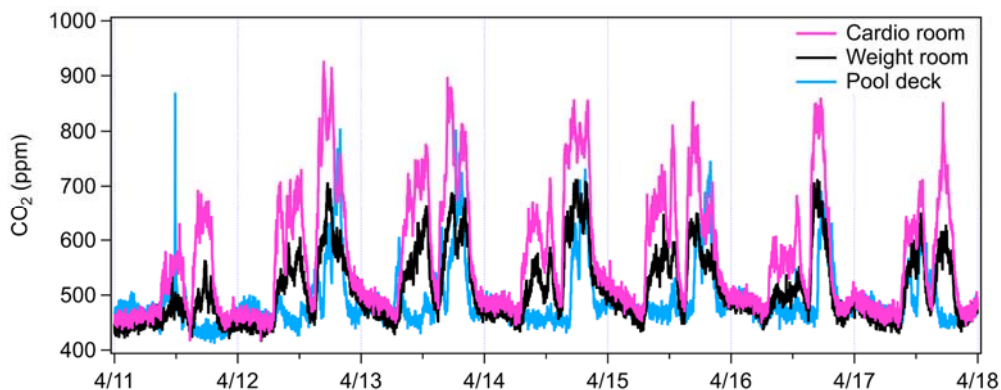


Figure S1: CO₂ concentrations for a one-week period in three areas of the Mountain West University campus gym.

Figure S1 shows the time series of CO₂ concentration in three areas of the campus gym. The average concentrations match observations shown in Figure 12a. Having access to CO₂ information at high resolution, especially if in real-time, however, shows trends in usage that are not observable from broader averages. Figure S1 shows a very repeatable daily cycle matching differences in room usage. The cardio and weight rooms are used more heavily, with daily peaks in the late morning and early evening. A drop in CO₂ concentrations can be seen at 1:00 PM when the gym closes for an hour. Having access to passive CO₂ data like this can be an efficient, non-invasive way not only to record gym usage, but to verify that occupancy is well-matched to HVAC strategies. In this example, the data shows that concentrations rarely exceed 800 ppm in the cardio room, and never significantly above 700 ppm in either the weight room or on the pool deck. These results suggest a ventilation strategy generally well-matched to the usage of rooms.

Simultaneous passive CO₂ and PM₁ monitoring results from one private music practice room are shown in Figure S2. As described in the main text, the correlation between PM and CO₂ in this space was poor.

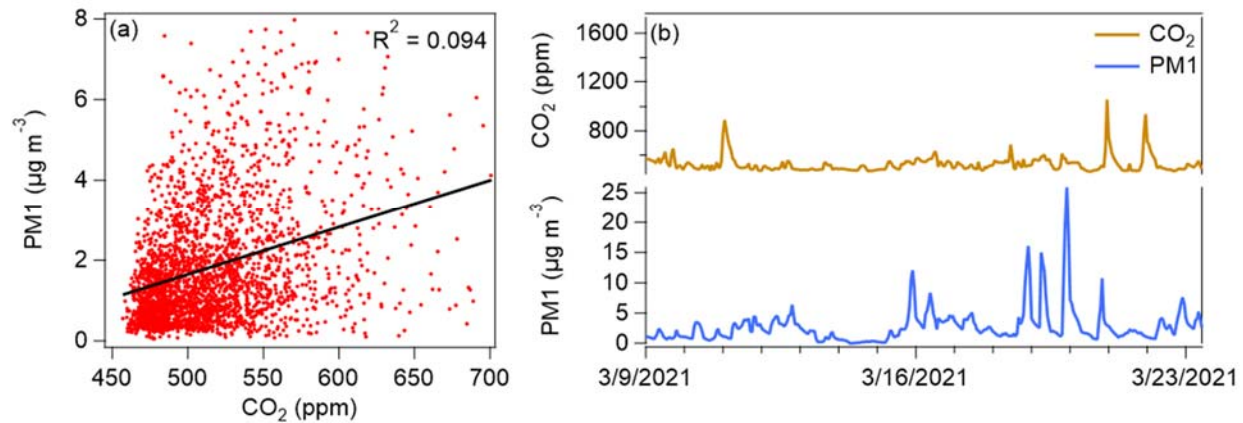


Figure S2: Comparison of PM₁ and CO₂ concentrations in a private music practice room of the Mountain West University. Data shown as 1-hour averages from November 1 - April 23. Time series (b) shown for a 2-week period as an example of lack of correlation.

North East University B

The testing space was ~600 ft² with an 11-foot ceiling (6,600 ft³). The room had single pane glass windows on both long walls of the room and furnishings included wood tables, lamps, and chairs. The room had no mechanical ventilation but had a passive air transfer grille and wall radiators with recirculating blowers below the window bays. Significant efforts were taken to create as clean, enclosed, and air-tight a space as possible to minimize influences from air infiltration/exfiltration and resuspension of dust from books, furnishings, and flooring.

The AFVU unit consisted of flexible supply and exhaust ductwork, an energy recovery element, main blower fan, MERV 14-rated filter, and a ducted supply air register (Figure S3). The device was operated as an air handling unit, delivering air to the space and exhausting a portion of room air back outdoors. As configured for testing, the AFVU provided 125 CFM of outdoor air and 645 to 670 CFM of total supply air, comparable to or higher than applicable ASHRAE ventilation standards (ASHRAE 2019) and typical of mechanical ventilation systems on campus. This unit was placed in the corner of the test space with an elevated discharge (8 ft above the floor) through an upward angled grille – this configuration was demonstrated to be optimal for PM removal efficiency based on testing in the library space (data not shown). The AFVU was purposefully designed to operate on standard 120 V power for widespread deployment, with a fan motor rheostat to provide a range of total delivered airflows. Since the AFVU operates at equal volumetric airflows of outdoor supply and exhaust air, its deployment was not expected to impact room pressurization.

To simulate continuous PM generation as would occur in an occupied classroom, two new candles were placed on a table in the center of the room and were burned for 15 minutes. PM number concentration was measured at the four sampling locations (S1-S4, Figure S4). This test was performed twice; once while operating only the AFVU and again with only the HEPA recirculating air cleaner operated at 320 CFM. The variation in PM levels across the test space

are shown in Figure S4. The AFVU and commercial cleaners produced noticeably different results with continuously burning candles. With the AFVU running, PM concentrations reached a maximum of $\sim 30,000$ particles/cm³, then decreased by about 33% in 15 minutes. When the AFVU was turned off, PM concentrations increased at all sampling locations while the candles were burned. In contrast, when the commercial air cleaner was running, PM levels remained high at two of the four sampling locations (S1 and S3).

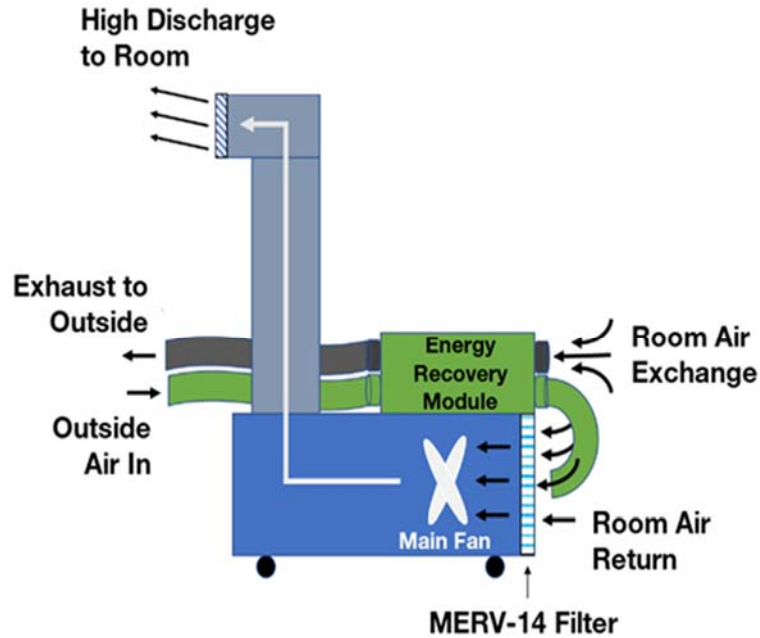


Figure S3. Schematic diagram of the air filtration ventilation unit designed for use in naturally ventilated spaces for North East University B.

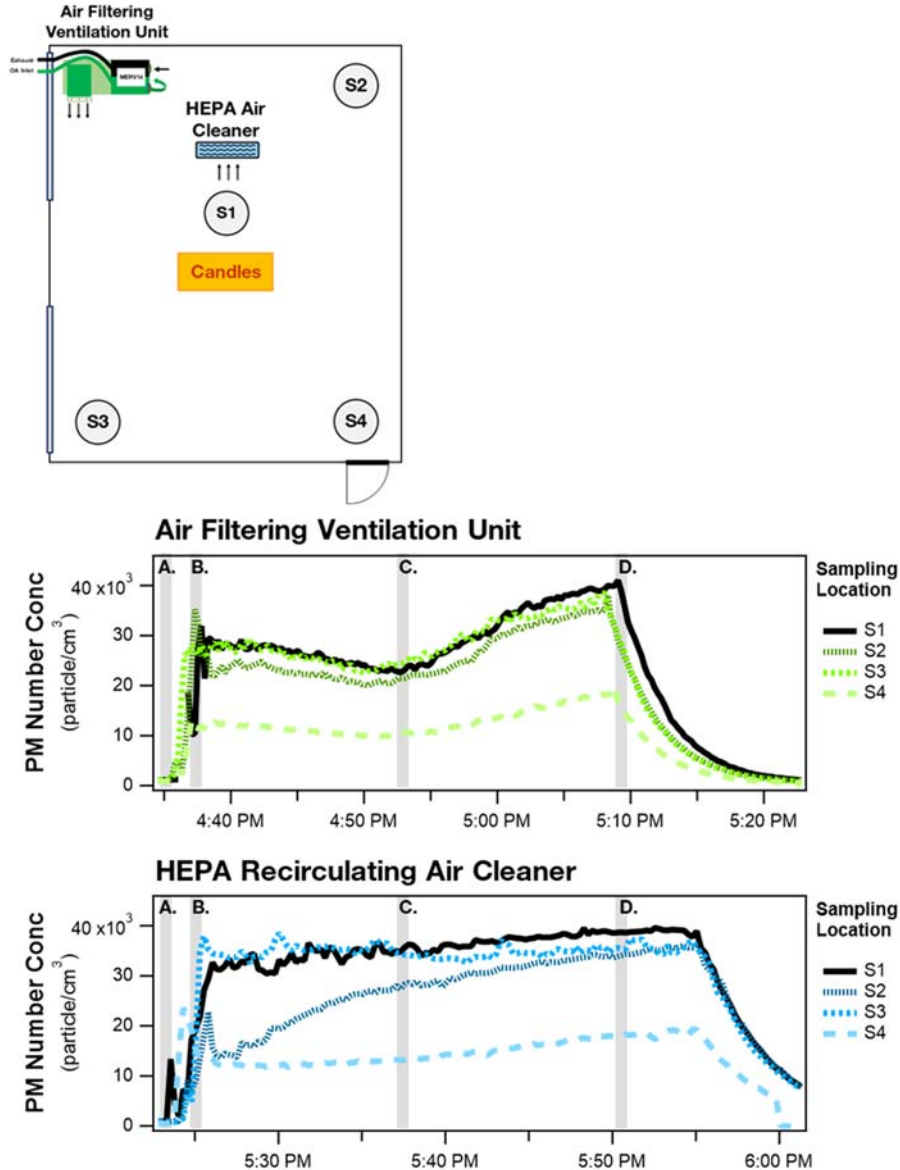


Figure S4. Evaluation of the spatial distribution of PM in a naturally ventilated library test space in North East University B using different filtration/ventilation approaches. *Top:* The plan view indicates the location of candles used for continuous PM generation, the PM sampling locations (S1-S4), and the two supplemental filtration/ventilation devices that were individually evaluated: an air filtering ventilation unit and a commercially available air cleaner. *Bottom:* PM number concentration measured at the four sampling locations across the test space for each filtration/ventilation approach. Time point A indicates when candle burning was started, time point B shows when the AFVU or HEPA-recirculating air cleaner was turned on, time C notes the time when these devices were turned off, and time D indicates the time candles were extinguished and the recirculating HEPA-filtered blowers started operation.

References

ASHRAE Standing Standard Project Committee 62.1, ANSI/ASHRAE Standard 62.1-2019, Ventilation for Acceptable Indoor Air Quality (2019)

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57
58 **Abstract**

59 Ventilation is of primary concern for maintaining healthy indoor air quality and reducing the spread
60 of airborne infectious disease, including COVID-19. In addition to building-level guidelines,
61 increased attention is being placed on room-level ventilation. However, for many universities and
62 schools, ventilation data on a room-by-room basis are not available for classrooms and other key
63 spaces. We present an overview of approaches for measuring ventilation along with their
64 advantages and disadvantages. We also present data from recent case studies for a variety of
65 institutions across the United States, with various building ages, types, locations, and climates,
66 highlighting their commonalities and differences, and examples of the use of this data to support
67 decision making.

68
69 **Keywords**

70 Ventilation; HVAC; Indoor Air; Schools; Sensors

71
72 **1. Introduction**

73 Adequate ventilation with air free of harmful air pollutants is essential to maintaining a healthy
74 indoor environment. In modern buildings, particularly in the U.S., this is usually accomplished by
75 providing indoor spaces with a combination of outside and recirculated, conditioned, and filtered
76 indoor air via a mechanical heating, ventilating, and air conditioning (HVAC) system. Although
77 critical discussions of ventilation are usually focused on buildings with mechanical HVAC, in many
78 parts of the U.S. it is common for schools and university buildings to have only natural ventilation,
79 which means ventilating via passive flow of outdoor air through windows, doors, and other
80 openings. Natural ventilation is typically encountered in older buildings in the Northeast or in more
81 temperate climates in the West. The ventilation design standard of the American Society of
82 Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) for education-related buildings
83 ranges from 4.3 liters per second per person ($L s^{-1} person^{-1}$) of outdoor air for a lecture classroom
84 to 8.6 $L s^{-1} person^{-1}$ for a science laboratory (ASHRAE 2019). Many schools and universities in the
85 U.S. do not meet this minimum standard (Corsi et al. 2021). Inadequate ventilation may result
86 from: malfunctioning (or improperly configured or scheduled) air handling equipment, excessive

87 air recirculation, inadequate natural ventilation, or simply by design to save on energy costs
88 associated with heating or cooling.

89
90 Outbreaks of COVID-19, influenza, and other infectious diseases have been connected to
91 inhalation of virus-laden respiratory aerosol in inadequately ventilated indoor spaces (Li et al.
92 2007, Miller et al. 2021, Greenhalgh et al. 2021, Corsi et al. 2021). Ventilation has well-
93 documented benefits for reducing airborne infectious disease transmission, as well as other
94 negative health and education outcomes (Fisk 2017, Wargocki et al., 2020, Corsi et al. 2021).
95 Masking, improved ventilation, reduced occupancy, physical distancing, and other efforts to
96 mitigate the spread of COVID-19 in the U.S. during the 2020-2021 flu season also led to dramatic
97 reductions in other airborne illnesses such as influenza (Centers for Disease Control and
98 Prevention, 2021).

99
100 In the wake of COVID-19 pandemic shutdowns, safe reopening of schools and universities for in-
101 person instruction, and sustainable maintenance of safe conditions, has become an international
102 priority. Since inhalation of respiratory aerosols containing infectious material is a key route of
103 transmission for SARS-CoV-2 and other airborne pathogens (Greenhalgh et al. 2021), gathering
104 of students and educators in school facilities with insufficient ventilation poses a public health risk.
105 Since aerosol transmission is significant at both short- and room-scale distance, ventilation and
106 filtration, along with distancing and mask wearing, are important components of layered risk
107 reduction (Corsi et al. 2021). A correlation between improvements in ventilation and air filtration
108 in schools and lower rates of COVID-19 incidence has been shown (Gettings et al. 2021).

109
110 In addition to building-level guidelines, e.g. that HVAC filters should be upgraded, outdoor air
111 dampers should be opened entirely when weather permits, and demand-control ventilation should
112 be disabled (ASHRAE 2020), increased attention is being placed on room-level ventilation and
113 air cleaning. The Harvard Schools for Health group (Jones et al. 2020) and others (Corsi et al.
114 2021, Levinson et al. 2021) recommend classrooms meet a minimum of 3 outdoor-air supplied
115 air changes per hour at standard occupancy and room sizes, and that this should be augmented
116 with air cleaning (i.e., filtration or ozone-free upper-room germicidal ultraviolet light) for a total of
117 4-6 air changes per hour of outdoor plus filtered air. These recommendations are consistent with
118 the minimum ventilation rates recommended by ASHRAE (ASHRAE 2019). In spaces with known
119 ventilation issues, steps may be taken to increase the fraction of outdoor air that is supplied,
120 improve the filtration efficiency of the recirculated air, or provide filtration on a room level.
121 However, there is an overall lack of room-level ventilation data in educational spaces in the U.S.
122 that would allow such planning. There are a number of reasons for this data gap, including that,
123 while recommended guidelines exist for room-level ventilation (ASHRAE 2019), in many locations
124 strict requirements only exist for special room types such as wet-chemical laboratories and
125 auditoriums, or for buildings with special certification (U.S. Green Buildings Council, 2019). Room-
126 level ventilation can be difficult to quantify as it can fluctuate with weather, season, room
127 occupancy, etc. (Turner et al. 2012, Persily 2016, Korsavi et al. 2020). Moreover, conventional
128 ventilation metrics and codes were designed to address different risks than those posed by
129 infectious diseases. In particular, standard ventilation codes ensure enough fresh air is supplied
130 to flush the exhalation and other bio-effluents of a specified number of occupants, generally

131 assumed to be identical in their emissions and respiratory intake. Mitigating the spread of
132 infectious disease, however, introduces an additional demand -- to flush a room's air quickly
133 enough to reduce the risk of occupants inhaling airborne pathogens generated by even *one*
134 infected individual.

135
136 The direct flow measurement techniques used by building managers and engineers to
137 characterize ventilation rates in mechanically ventilated buildings cannot be applied to naturally
138 ventilated spaces. Other approaches for characterizing ventilation may require technical expertise
139 for execution or data interpretation, or specialized instrumentation, which reduces accessibility.
140 As educators, administrators, and building managers plan for safe operations in the wake of
141 COVID-19, there is a need for practical approaches for characterizing ventilation on the room
142 level, as well as support for small-scale, short-term decision making, e.g., with respect to opening
143 windows and doors and running fans, air conditioners, or supplemental air cleaning.

144
145 Here, we describe efforts taken by this group of scientists and educators using different
146 approaches to characterize ventilation in educational spaces in different U.S. locations in
147 collaboration with facilities managers, administrators, and other decision makers. We discuss our
148 findings, best practices, and lessons learned.

149 150 **2. Methodology**

151 In this section, we describe practical approaches for characterizing ventilation on a room level in
152 universities and schools, highlighting their advantages and disadvantages. The approaches
153 discussed are summarized in Table 1. Broadly, these can be classified as direct flow
154 measurements, controlled-release studies, and passive in situ monitoring. Note that ventilation
155 rates, especially in naturally ventilated spaces, are highly dependent on factors including but not
156 limited to environmental conditions (indoor-outdoor temperature difference, wind speed, etc.) and
157 occupancy.

158
159 We have used the approaches summarized in Table 1, alone and in combination, to characterize
160 ventilation on a room level in classrooms and other educational spaces. They require
161 instrumentation of varying levels of sophistication, ranging from low-cost (anemometer/velocity
162 probe, nondispersive infrared (NDIR) CO₂ sensors, low cost PM_{2.5} sensors) to research-grade.
163 Some instrumentation may serve multiple purposes, for example, NDIR CO₂ sensors can be used
164 for controlled-release experiments as well as passive monitoring. Operation of the instruments
165 and execution of the measurements requires varying levels of training. The use of lower-cost
166 sensors allows measurement in several rooms simultaneously, or use of several monitors in a
167 single room to assess spatial variability in tracer concentrations (mixing). Passive monitoring with
168 user-friendly sensors will be more accessible to nonspecialists than other techniques such as
169 balometry and controlled release experiments, and may be used as part of a long-term strategy
170 for indoor air quality management.

171
172 The ventilation metrics discussed here are summarized in Table 2. Ventilation rate is generally
173 expressed as air volume per unit time (and sometimes per occupant). Mitigating the spread of
174 airborne disease requires different metrics. Since the goal is to minimize the steady-state

175 **Table 1.** Summary of approaches for characterizing ventilation on a room level

Approach	Technique	Advantages	Disadvantages
Direct Flow	Balometer or anemometer	<ul style="list-style-type: none"> Accepted method, accessible to building managers Measures total flow of recirculated + outdoor air 	<ul style="list-style-type: none"> Inconclusive measurements in spaces with no mechanical ventilation Not possible to separate outdoor and recirculated air exchange rates with this measurement alone
Controlled Release	CH₄ or C₂H₆	<ul style="list-style-type: none"> Indicates outdoor air exchange rate, gives results for spaces with no mechanical ventilation Low natural background High sensitivity Few indoor sources, occupancy does not interfere with measurements 	<ul style="list-style-type: none"> Generally requires research instrumentation Flammable gas
	CO₂	<ul style="list-style-type: none"> Gives results for spaces with no mechanical ventilation Low-cost, reliable sensors readily available Non-flammable, readily available gas 	<ul style="list-style-type: none"> Requires empty room since CO₂ emission from the occupants interfere with measurements Potential for interference from recirculated CO₂
	noninfectious aerosol particles	<ul style="list-style-type: none"> Dispersion experiments provide insight into airflow patterns, movement of aerosol within a space 	<ul style="list-style-type: none"> Technically challenging to generate and detect aerosols Loss of particles to surfaces, filtration, and resuspension must be accounted for
Passive	CO₂	<ul style="list-style-type: none"> Collect data during normal facility operation, occupancy No expertise required Directly shows the impact of human exhalation on indoor air 	<ul style="list-style-type: none"> Uncontrolled conditions complicate interpretation of the results Other CO₂ sources (vehicles, cooking, recirculated air) may cause interference
	PM_{2.5}	<ul style="list-style-type: none"> Provides valuable indoor air quality data during normal facility operation Characterize impact of indoor air pollution sources 	<ul style="list-style-type: none"> Uncontrolled conditions complicate interpretation of the results Respiratory particles are greatly outnumbered by 'background' PM Loss of particles to surfaces, filtration, and resuspension must be accounted for

176
177
178

Table 2. Ventilation parameters and their definitions

Parameter	Units	Definition
Ventilation rate	L s ⁻¹ or L s ⁻¹ person ⁻¹	Volumetric rate of delivery or Volumetric rate of air delivery, per occupant
Air changes per hour (ACH)	h ⁻¹	Rate at which room air is replaced by recirculated and outdoor air and equals volumetric ventilation rate normalized to room volume
Tracer air changes per hour (ACH _T)	h ⁻¹	ACH as determined by measuring the decay of a tracer species
Balometer air changes per hour (ACH _B)	h ⁻¹	ACH as determined via balometry measurements
τ	h	Air change timescale

179
180 concentration of pathogens exhaled by an infected individual within a room's air, relevant metrics
181 capture how frequently the room's air is flushed, regardless of the number of occupants.

182
183 **2.1 Direct flow measurements.** Direct measurements of air flow in ducts are the most basic and
184 commonly accepted method (ASHRAE 2017) for measuring ventilation on a room scale. As a first
185 pass, or when resources are low, a simple check using tissue paper may be used to determine if
186 air flow exists and identify malfunctioning air handling equipment. In more sophisticated
187 measurements, a balometer (essentially a portable hood that measures volumetric flow rate from
188 supply grilles) or velocity probe is used to measure flow into and out of the room through supply
189 and return grilles. For more information, see ASHRAE (2017). Air changes per hour (ACH, h⁻¹),
190 or the rate at which room air is replaced, can be calculated from balometer measurements by
191 dividing the incoming volumetric air flow rate by the room volume. This is also commonly referred
192 to as the air exchange rate. ACH calculated using direct flow measurement data will include both
193 recirculated and outdoor air. An obvious major disadvantage of the direct-flow approach is that it
194 cannot be used for spaces without mechanical ventilation, nor can it be used to test the impact of
195 opening doors and windows. For naturally ventilated spaces, another approach is needed.

196
197 **2.2 Controlled release.** Another family of approaches for characterizing ventilation in indoor
198 spaces involves releasing a fixed quantity of an inert tracer substance and observing its decay
199 with time (Charlesworth 1988, Persily 1988, Persily 2016). A major advantage of controlled-
200 release measurements is that this approach provides ventilation data for naturally ventilated
201 spaces as well as mechanically ventilated ones. These experiments provide an ability to
202 quantitatively test ventilation scenarios to support policy decisions. Controlled-release
203 experiments measure the total ventilation, which could include some infiltration or exfiltration as
204 well as airflow through design openings (windows). Tracer substances employed may include
205 gases such as CO₂, CH₄, C₂H₆, volatile organic compounds (VOCs), SF₆, or particulate matter
206 (PM). Note that, for some gas tracers, particularly VOCs, reactive or deposition loss is possible.
207 In PM tracer studies, particle deposition or filtration must be accounted for. Resuspension of
208 deposited particles is also possible and should be considered in the data analysis. If humans or
209 their activities emit the tracer substance (e.g., in the case of CO₂ or PM) indoors, or if the tracer
210 may be considered harmful to health at the levels used for the test, the room must be unoccupied
211 during the measurement. Occupancy and furnishings may also affect air flow, e.g. by enhancing
212 mixing or obstructing air flow. Fans should be used to disperse the tracer species throughout the
213 space, and mixing should be verified with measurements in different locations throughout the
214 space. Under the assumption of well-mixed conditions and no sources of emission, the mass
215 balance for a substance in a given space is described as follows:

216
217
$$\frac{dC}{dt} = -\frac{1}{\tau}(C - C_{background}) \quad (1)$$

218
219 where C is the concentration of the tracer substance in the room, t is time, τ is the air change
220 timescale, and $C_{background}$ is the background concentration of the tracer substance in the room

221 when ventilation is operated at a specified condition but no tracer substance has been released.
 222 By introducing a corrected concentration variable, $\hat{C} = C - C_{background}$, Eq. (1) simplifies into:

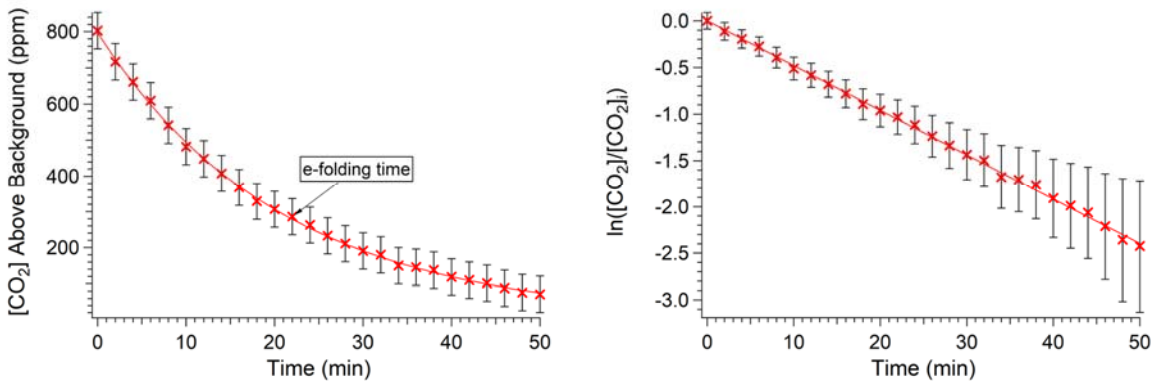
$$224 \quad \frac{d\hat{C}}{dt} = -\frac{1}{\tau} \hat{C} \quad (2)$$

225
 226 Thus, τ can be determined as the inverse slope of the linear regression line of natural logarithm
 227 of \hat{C} versus time. Note that if sources of the tracer compound are present, $C_{background}$ may vary with
 228 time, resulting in nonlinearity of this relationship. Once exponential decay is confirmed, analysis
 229 can be simplified by calculating τ as the e-folding time, or the time for the peak concentration to
 230 be reduced by a factor of e . We define ACH_T (ACH as inferred from tracer decay observations)
 231 as follows:

$$232 \quad ACH_T = \frac{1}{\tau} \quad (3)$$

233
 234
 235 Figure 1 shows typical data from a controlled-release CO_2 experiment exhibiting exponential
 236 decay, consistent with equation (2).

237
 238



239
 240 **Figure 1.** Data from a controlled-release CO_2 experiment at North East University A. The decay
 241 is exponential as shown in the corrected concentration profile ($C - C_{background}$) on the left. ACH_T
 242 is calculated either from the e-folding time or via a linear fit to the log-linear plot. See the Results
 243 section for more details.

244
 245 ACH_T may differ from ACH determined via flow measurements. In naturally ventilated or
 246 mechanically ventilated spaces with no recirculation or other air exchange between rooms,
 247 $C_{background}$ is the outdoor concentration of the tracer and ACH_T can be interpreted as the rate at
 248 which room air is replaced with outdoor air. This is also true for mechanically ventilated spaces
 249 with recirculation as long as there are no sources of the tracer elsewhere in the building. The
 250 potential exists for interference in CO_2 decay measurements in a densely occupied building with
 251 air recirculation or other sources of mixing between rooms. CO_2 transported from occupied rooms
 252 would result in an elevated CO_2 baseline reading and potentially interfere with measured decay
 253 rates. (Note that, at the time of writing, the background outdoor CO_2 concentration in North

254 America is ~415 ppm (NOAA, 2021)). Similarly, small natural gas leaks can cause interference
255 when CH₄ or C₂H₆ is used as the tracer and a sensitive detector is used. Simultaneous
256 measurement of the tracer in the recirculated air is recommended in those cases. ACH_T
257 measurements can be complemented with direct flow measurements for a more complete picture.
258 For PM decay studies in such a scenario, if HVAC filtration effectively removes PM from
259 recirculated air, ACH_T is the sum of the outdoor and filtered air change rates, and $C_{background}$ would
260 be lower than the outdoor PM concentration.

261
262 The choice of tracer substance depends on a number of factors, including the availability of the
263 substance and a suitable detector for the measurement, and the technical complexity of the
264 measurement. Despite the potential for interference described above, CO₂ gas is a widely used
265 tracer for controlled-release experiments. The gas itself is non-flammable and non-toxic at low
266 levels. It is available in gas cylinders from specialty gas or food service suppliers, or in the form
267 of dry ice or canisters for limited studies or demonstrations. Low-cost (~USD \$100-200) NDIR
268 CO₂ sensors are readily available and can be repurposed for in situ monitoring after the
269 experiment. CH₄ and C₂H₆ studies have several advantages over CO₂ in that (i) these gases are
270 not emitted by humans so the presence of occupants in the room or elsewhere in the building
271 does not interfere with the test (ii) these gases have a comparatively low natural background
272 concentration (1 ppm for CH₄), allowing high sensitivity in large rooms. However, one
273 disadvantage is that higher-cost (~USD \$48,000) research-grade instrumentation is required for
274 sensitive, low noise, high-frequency measurements of CH₄ and C₂H₆. Lower-cost and lower-
275 sensitivity NDIR methane sensors do exist and could potentially be a more affordable alternative,
276 but we have not tested them. SF₆ has similar advantages to CH₄ and C₂H₆, but it has fallen out of
277 use in recent years as it has become recognized as a potent greenhouse gas. N₂O and several
278 halocarbon gases have also been previously used (Persily 1988, Persily 2016).

279
280 Controlled-release experiments using dispersion of non-infectious particles may provide insight
281 into airflow patterns and movement of aerosol within a space. This information is especially
282 relevant in the context of COVID-19-related ventilation concerns. Many tracer particle types are
283 possible, including soot from a combustion source, organic aerosols, e.g. from a fog machine,
284 inorganic salt aerosols such as NaCl, or engineered particles with special properties such as
285 fluorescence (Tang et al. 2020). The technical challenges of generating and detecting well-
286 characterized aerosols make this more of a research exercise. There may also be challenges in
287 securing permission for measurements and communicating the data, due to misunderstandings
288 about infectious vs. noninfectious aerosols and safety concerns about inhalation. Information can
289 be inferred about particle dynamics in the space if different PM sizes are measured. We found
290 that building activities which result in periodic aerosol release (i.e., disinfectant fogging) present
291 an opportunity for a 'natural experiment' if appropriate detectors are in place. Low-cost PM
292 sensors may be appropriate for these measurements although there is some concern about the
293 data quality for many of the instruments on the market (Singer and Delp 2018) and attention must
294 be paid to their calibration.

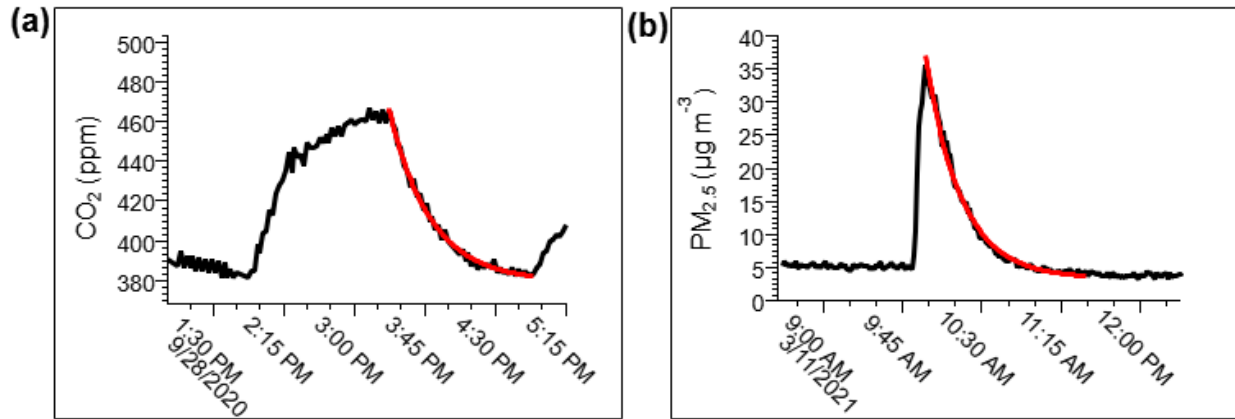
295
296 In addition to the considerations listed above, when analyzing the decay of tracer particles, one
297 must account for the particle dynamics that remove PM from air that are not related to ventilation,

298 such as surface deposition, as well as, possibly, resuspension. Therefore, tracer particle decay
299 rates represent total aerosol removal from the room rather than purely room ventilation or ACH.
300 Further research needs to be done investigating size dependence of aerosol decay as well as
301 how aerosol decay directly compares to decay of other tracer gases and room ACH. However,
302 the decay rates found by analyzing in situ $PM_{2.5}$ levels, analogous to the total time that aerosols
303 are suspended in the air, may more directly represent the potential time of exposure to particle
304 contaminants under 2.5 microns (including resuspended SARS-CoV-2-containing aerosols) than
305 would a tracer gas-calculated ACH.

306
307 **2.3 In situ monitoring.** A third approach for characterizing ventilation in indoor spaces is the
308 placement of sensors for one or more trace species in a space, for passive monitoring during
309 normal facility operation (Rudnick and Milton, 2003; Batterman 2017; Peng and Jimenez, 2021).
310 Tracers which are emitted by humans (e.g. CO_2 , aerosol, volatile organic compounds) and
311 therefore will fluctuate with occupancy are especially appropriate. This approach is attractive in
312 that it requires relatively little technical expertise and does not disrupt operations. Collecting data
313 during normal occupancy provides a direct measure of the impact of human exhalation on indoor
314 air. Passive CO_2 data can also be useful as a real-time proxy of occupancy that shows daily usage
315 schedules, and may reveal unexpected trends in room usage. In the best case, the real-time data
316 can be linked into publicly visible outputs to support decision making. Long-term in situ monitoring
317 of CO_2 can be accomplished with the same low-cost sensors used for controlled-release
318 experiments, reducing capital investment.

319
320 In situ monitoring during events such as in-person classes, which can lead to a buildup of CO_2 ,
321 and fogging events which occur when a room is disinfected with a cleaning aerosol spray, allow
322 for calculation of the room ACH_T . This approach is demonstrated in Figure 2 using data from the
323 two classrooms at the South East University. CO_2 decay after an in-person class is shown in panel
324 A. Note that occupancy in the building was low during the period of these measurements so no
325 interference from CO_2 in other rooms is observed. ACH_T was estimated using Equations 1 and 2,
326 analyzing the in situ buildup in CO_2 levels during room occupancy and the resulting exponential
327 CO_2 decay after the occupants left the room. $PM_{2.5}$ data for a fogging episode in another
328 classroom is shown in panel B. $PM_{2.5}$ levels in the room varied no more than 1-5 ug/m^3 during
329 class time, indicating that the concentration of aerosols produced by fogging (an order of
330 magnitude higher) should not be greatly affected by potential particle resuspension or
331 accumulation during the monitored decay. ACH_T was calculated from in situ PM data following
332 the same exponential decay model. For additional details see the Results section.

333
334 The main limitation of the in situ approach is that uncontrolled conditions complicate interpretation
335 of the results. Direct quantification of ventilation parameters is difficult with this method. Usually,
336 the tendency of the tracer levels to stay within a range (e.g., 600-800 ppm CO_2) is taken as an
337 indicator of sufficient or insufficient ventilation. Sometimes, transient events, such as a gathering
338 of people in a space, may cause temporary buildup of the tracer, allowing observation of its decay
339 and calculation of the air change timescale as described in the previous section. Interference may
340 be caused by other sources of CO_2 , such as cooking or vehicles in a garage or near an air intake.
341 As in controlled release CO_2 experiments, interference from CO_2 recirculated or otherwise mixed



342

343 **Figure 2.** Data from the South East University demonstrating the use of in situ data for calculation
 344 of ACH_T . (a) Room A CO_2 profile and exponential decay fit (in red) during class time. This room
 345 has mechanical ventilation (recirculating indoor air and outdoor air, with a MERV 13 filter between
 346 circulation cycles). ACH_T was calculated to be $2.3\ h^{-1}$. (b) Room B $PM_{2.5}$ profile and exponential
 347 decay fit (in red) during a fogging event. This classroom has mechanical ventilation and a portable
 348 air cleaner with a high-efficiency particulate air (HEPA) filter. ACH_T was calculated to be $2.8\ h^{-1}$.

349

350 from other spaces in the building may also be an issue. For this reason, ideally, CO_2 should be
 351 measured in the supply air as well as room air.

352

353 In situ monitoring of aerosols may lead to confusion in the COVID-19 context since respiratory
 354 particles are greatly outnumbered by ‘background’ PM indoors, as well other particles generated
 355 by human activities such as resuspended floor dust, skin flakes and clothing fibers. Therefore,
 356 number-based monitoring would not allow detection of a respiratory aerosol signature. Detection
 357 of virus-containing respiratory particles requires advanced sampling methods and
 358 instrumentation (Lednicky et al., 2020). Selective monitoring of a subset of the indoor aerosol
 359 (e.g., Bhangar et al. 2014), or analysis of the particle size distribution data may reveal subtle
 360 trends linked to human emissions, but will require further research.

361

362 **3. Results**

363 Here we describe ventilation studies conducted by this group using the methods described in the
 364 previous section. Controlled-release methods were used in a university and a secondary school
 365 in Southern California, two universities in the Northeast with facilities with a range of ages, and
 366 two K-12 school districts in Coastal California. Passive sampling was used in a university in the
 367 Southeast U.S. and one in the Mountain West. These institutions are referred to herein using
 368 pseudonyms.

369

370 **3.1 North East University A.** Controlled-release CO_2 experiments were performed between
 371 August-December 2020 in nine buildings across two of the University’s campuses, located in a
 372 dense urban area within a three mile radius. Relatively newer buildings with mechanical
 373 ventilation (built 1961-1996) and older buildings (built 1897-1911) were studied. The older

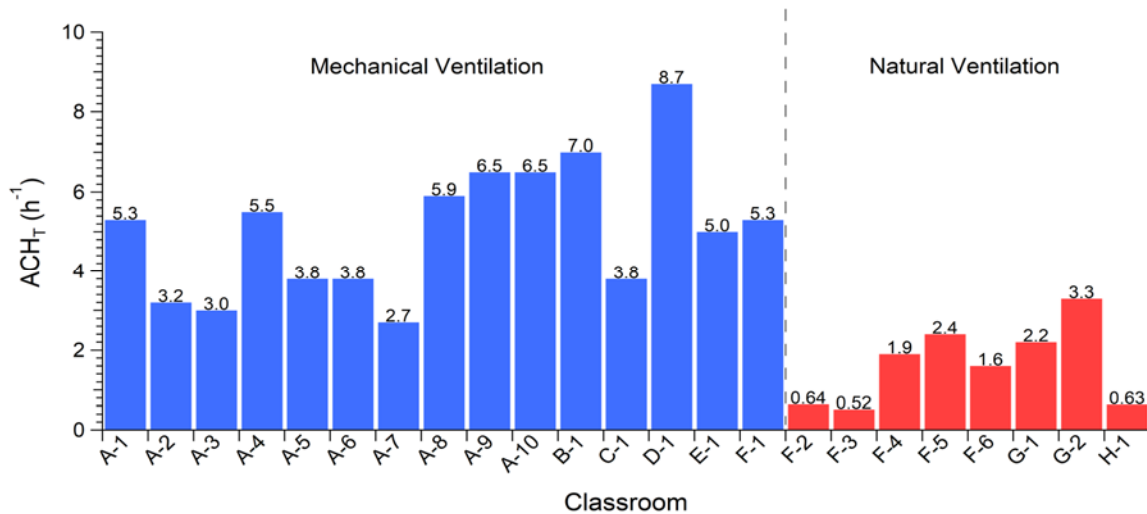
374 buildings were originally constructed with steam heat and natural ventilation but were later fully
375 or partially retrofitted with mechanical ventilation. In buildings with partial mechanical ventilation,
376 certain parts of the building relied only on natural ventilation. Classrooms to be studied were
377 initially prioritized based on an informal survey of faculty and student recollections of thermal
378 comfort and perceived air quality. Once the method was established and trust was developed with
379 campus facilities and administration, the scope of the measurements was expanded to include a
380 broad survey of classrooms, conference rooms, and elevators.

381
382 The spaces were unoccupied during and immediately before each test. A baseline CO₂ reading
383 was taken before initiation of each experiment. Experiments were performed by releasing
384 compressed CO₂ (TechAir) into each room with fans for mixing until a level of 1000-1500 ppm
385 was reached as measured using calibrated NDIR CO₂ sensors (Aranet4, Aranet) which were
386 connected via Bluetooth to an Apple iPhone XR running Aranet software. The primary sensor was
387 located close to the center of the space, while three auxiliary sensors were placed near the
388 corners. Once the CO₂ reading reached the target level and the room air was well-mixed (i.e.
389 auxiliary sensor readings within 250 ppm of primary sensor reading), the operator then exited the
390 room and observed the decay of CO₂ to the baseline via the Aranet software. CO₂ levels in each
391 case exhibited exponential decay consistent with equation (2) (cf. Figure 1, Methodology section).

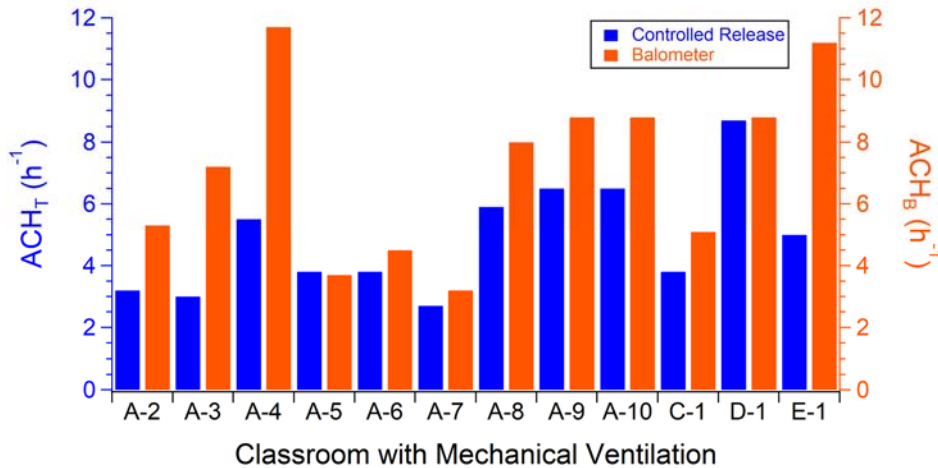
392
393 The differences between the measured baseline level ($C_{\text{background}}$) and the outdoor background
394 readings preceding the experiments were within the sensitivity of the sensor (<50 ppm) for all but
395 one classroom. This is consistent with the fact that the measurements were performed at a time
396 of very low occupancy in the buildings. For the one exception observed, $C_{\text{background}}$ was 83 ppm
397 higher than the outdoor CO₂ concentration. In this specific case, the experiment was conducted
398 immediately following a controlled-release experiment in the adjacent classroom.

399
400 Results for classrooms are summarized in Figure 3. In the newer and retrofitted buildings,
401 ventilation was generally satisfactory, with $2.7 \text{ h}^{-1} \leq \text{ACH}_T \leq 8.7 \text{ h}^{-1}$ for classrooms. Some problem
402 areas with ACH_T substantially lower than 3 h^{-1} were identified in classrooms with natural ventilation
403 in older buildings. The data were shared with campus facilities and administration, resulting in the
404 installation of portable HEPA filter units in classrooms with $\text{ACH}_T < 3 \text{ h}^{-1}$ across campus.

405
406 In parallel with the tracer measurement effort, an independent engineering firm conducted
407 balometer measurements at the supply inlets of some of the mechanically ventilated classrooms
408 that we characterized. Measurements were not made on the same days, so differences in weather
409 conditions (indoor-outdoor temperature difference, wind speed, heating/cooling load, etc.) and
410 HVAC operation on those days may be a source of discrepancy (Batterman 2017). Comparison
411 between results of the controlled-release measurements and balometer measurements is shown
412 in Figure 4. The buildings had been set for maximum air intake before these measurements were
413 made, and there was relatively low occupancy due to remote study and COVID-19 related
414 occupancy restrictions at the time of the measurements. Ventilation was satisfactory for all of the
415 rooms in this measurement set, by both measures (ACH_T and $\text{ACH}_B \geq 3 \text{ h}^{-1}$). The two sets of
416 measurements exhibited general agreement for most of the compared classrooms. However,



417
 418 **Figure 3.** Summary of ACH_T as measured via CO₂ decay rate in controlled-release experiments
 419 in classrooms for a university in the Northeastern U.S. (North East University A) with a mix of
 420 mechanical and natural ventilation.
 421
 422
 423
 424



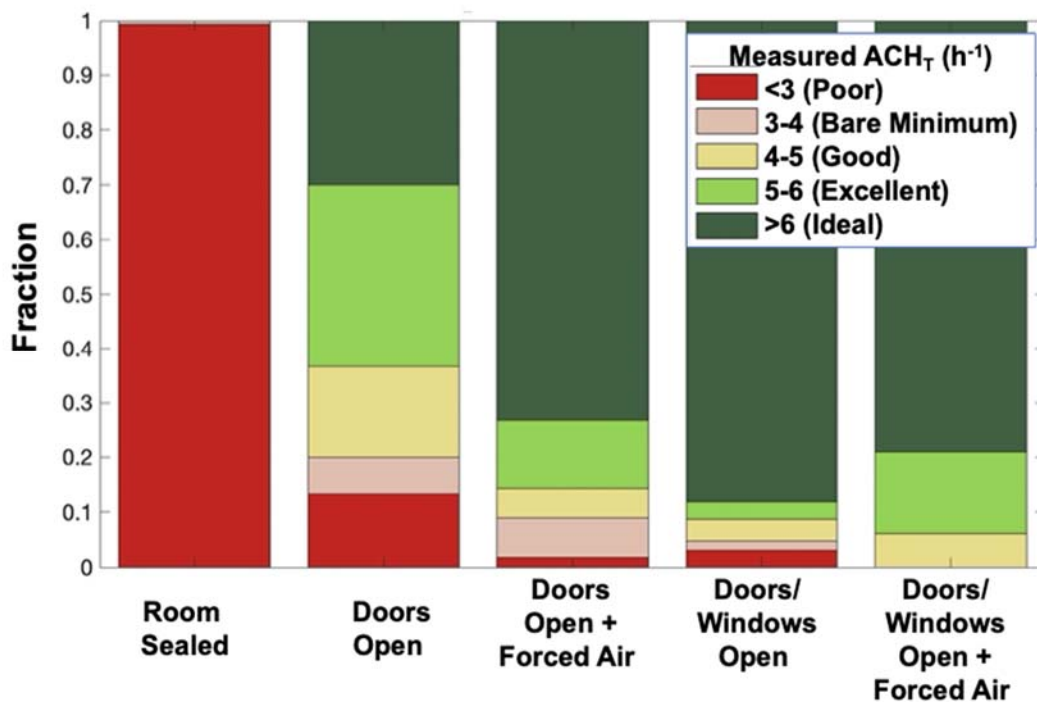
425
 426
 427 **Figure 4.** Comparison Between the Controlled Release CO₂ Decay Rate and Balometer Air
 428 Change Measurements for North East University A.
 429
 430

431 there were significant disparities, up to 6.2 h⁻¹ among the remaining 25% of the classrooms, where
 432 the balometer results were substantially greater than the controlled-release results. The low
 433 baseline CO₂ concentrations that we observed, consistent with the low building occupancy,
 434 allowed us to rule out recirculated CO₂ as a major contributor to the observed differences. Some
 435 discrepancies may be attributable to the fact that the balometer measurements and controlled-
 436 release studies in each classroom were made 2-4 weeks apart during the summer-autumn

437 transition, so cooling and heating conditions varied. HVAC settings were also changed during this
438 time period. In one case, a relatively high ACH_B as compared to ACH_T alerted the facilities manager
439 that outdoor air intake to the building had not yet been increased, and adjustments were made.
440 Besides the classroom measurements, tracer measurements were also conducted in ten
441 conference rooms and four elevators in four different mechanically ventilated buildings. Two out
442 of the ten conference rooms had inadequate ventilation ($ACH_T < 3 \text{ h}^{-1}$) and were subsequently
443 equipped with HEPA filter units by facilities. All of the four stationary elevators were well-ventilated
444 ($ACH_T > 5 \text{ h}^{-1}$), even reaching values as high as 21 h^{-1} .

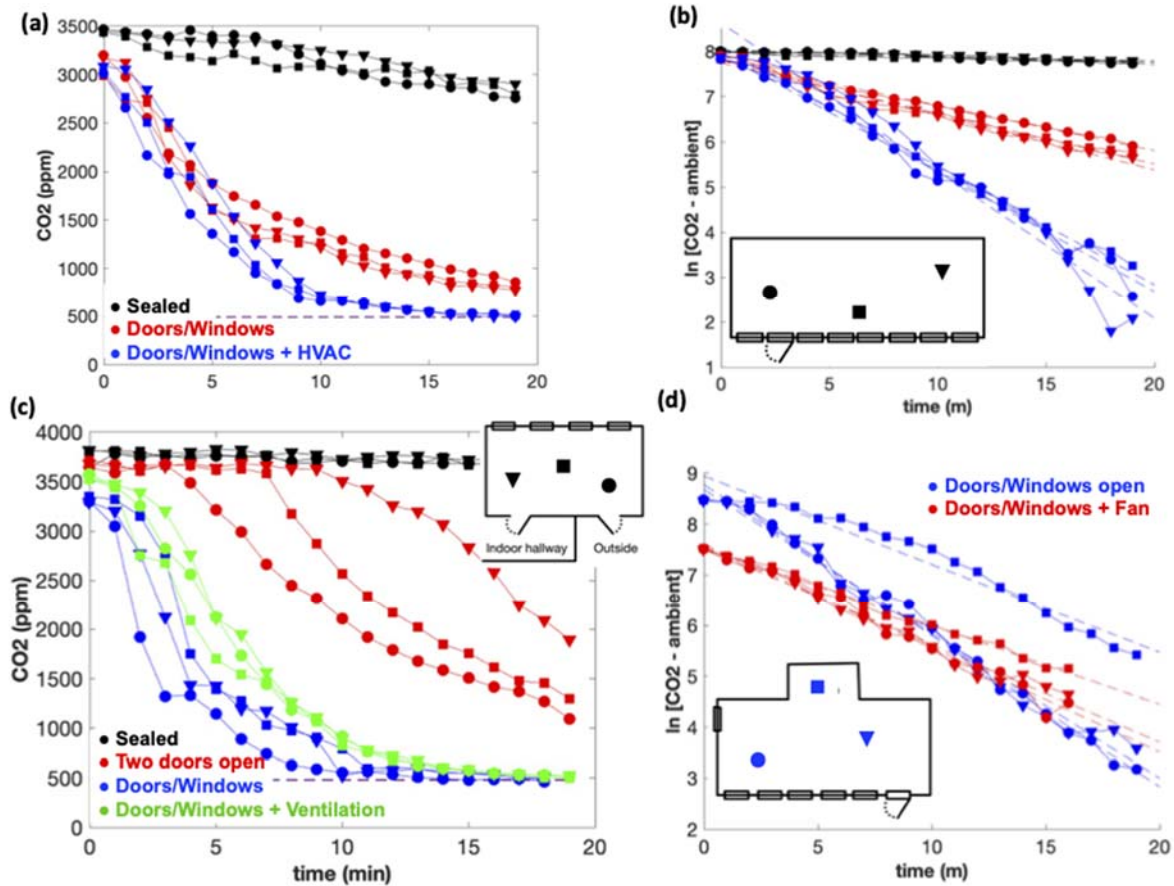
445
446 **3.2 Coastal California K-12 Schools** Controlled release of CO_2 experiments using the same
447 methodology as described above for North East University A were performed in 50 classrooms
448 across two K-12 school districts in Coastal California, which included preschool, elementary,
449 junior high and senior high schools. These neighboring districts are in a temperate zone where
450 the majority of classrooms were designed with natural ventilation. Many of these classrooms
451 therefore had large windows and most had exterior hallways so classroom doors open directly to
452 the outside, enabling cross-flow. Researchers trained facilities personnel to conduct CO_2 decay
453 measurements using Aranet4 NDIR CO_2 sensors. Facilities personnel then performed
454 experiments and sent CO_2 data to the researchers for analysis. Measurements were performed
455 during January-March 2021. Within each school, the architecture consisted of many similar
456 classroom arrangements and architectures. Therefore, in each school, only a selection of
457 representative classrooms were measured. In each of those classrooms, CO_2 monitors were
458 placed at three separate locations with respect to the windows and doors. ACH_T was measured
459 first in the “sealed” room with doors and windows closed and HVAC turned off (if available). Once
460 CO_2 returned to background levels, the controlled-release experiment was then repeated under a
461 variety of other conditions: 1) windows open, 2) windows and doors open (usually on different
462 walls leading to cross flow), 3) with the ventilation system on (when available), and 4) with a fan
463 facing out of a doorway or open window. Experiment (4) was only performed in rooms that were
464 suspected by facilities personnel to have ventilation issues. The results are summarized in Figure
465 5. Measurements were taken only on relatively calm days without unusually high wind speed,
466 though a few schools located on coastal bluffs are generally breezy. This led to a dataset of
467 approximately 460 measurements across 50 classrooms.

468
469 As observed in North East University A, CO_2 levels showed simple exponential decay in the
470 majority of rooms and conditions, and were accurately fit as described in the Methodology section.
471 Representative curves are shown in Figure 6. As seen in Figure 5, none of the classrooms studied
472 had $ACH_T > 3 \text{ h}^{-1}$ with closed windows and doors. Unsurprisingly, opening one or two exterior
473 doors increased the overall ventilation rate dramatically; opening windows in addition to exterior
474 doors led to $ACH > 5 \text{ h}^{-1}$ in $>90\%$ of classrooms measured. Panels (c) and (d) on Figure 6 highlight
475 the additional insight and information that was made possible by using multiple sensors to
476 simultaneously measure CO_2 levels in different locations within each room. In most cases (panels
477 a-b), there is no difference in ACH_T measured at different locations within the room. However,
478 some other rooms showed a positional lag, where CO_2 levels in some locations stayed constant
479 for several minutes after the room was opened, before beginning to decay. Figure 6(c) shows
480



481
 482 **Figure 5.** The results of CO₂ decay measurements in Coastal California K-12 Schools under
 483 different room conditions. ACH_T is binned and color-coded following the ventilation categories of
 484 Jones et al. (2020). Dataset represents approximately 460 measurements in 50 classrooms (3
 485 sensors per room, 3-4 measurement conditions per room).

486
 487
 488 data from a room that showed very little CO₂ decay when the doors and windows were sealed.
 489 Once two doors were opened, the front, middle, and back of the room still showed no decay for
 490 the first 4, 8, and 11 minutes. The onset of decay traveled from one open door towards the other
 491 over approximately ten minutes, more reminiscent of a plug flow than the continuously-stirred,
 492 well-mixed assumption that leads to eq (2). In this room and others, opening windows or adding
 493 mechanical ventilation typically reduced or eliminated this lag. Another example, shown in Figure
 494 6(d), shows differences in air turnover rates measured within a classroom containing a small
 495 alcove set off from the main classroom area. CO₂ decay within the alcove lagged sensors in the
 496 main classroom by a few minutes with the door and windows open. While the main room had a
 497 high air turnover frequency (~17 h⁻¹), the alcove was lower (~10 h⁻¹). Placing a fan at the door,
 498 directed outwards, eliminated the lag in the alcove. Curiously, the added fan actually lowered the
 499 general room ACH (17 h⁻¹ to 13 h⁻¹, alcove from 10 h⁻¹ to 9 h⁻¹), suggesting that the door served
 500 as a natural inlet for airflow, which the fan's orientation opposed. Despite these spatial
 501 heterogeneities, air turnover was well above target in all locations measured. In a less well-
 502 ventilated space, problem zones such as the alcove could be addressed via use of portable air
 503 cleaners.
 504



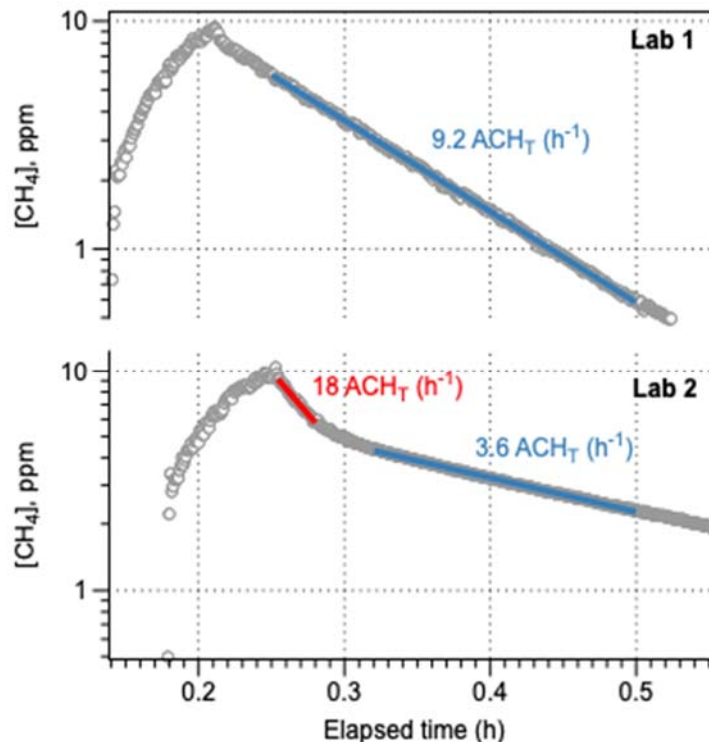
505
 506 **Figure 6.** (a) CO₂ decay measured in three different locations of a Coastal California classroom,
 507 under three conditions: closed doors and windows (black), open doors and windows (red) and
 508 open doors and windows plus HVAC (blue). The dashed line indicates ambient CO₂ level,
 509 measured separately. (b) Log-linear plot of data from panel (a); ACH determined from slopes
 510 obtained from linear regression fits (dashed). No difference appears between different locations
 511 within the room. (c) Room with non-exponential decay and positional lag. (d) Classroom with an
 512 'alcove'.

513
 514
 515 **3.3 Southern California University.** Controlled release of methane (CH₄), combined with a
 516 portable, scientific-grade methane and ethane detector (Picarro GasScouter, a mid-IR cavity-
 517 ringdown spectrometer) was employed to measure fresh-air ventilation rates in 21 buildings
 518 across the campus from July 2020 through April 2021. Tested buildings were mostly large,
 519 monolithic, multistory buildings whose construction spans the past 100 years, and comprise a
 520 mixture of laboratory, classroom, meeting, and office spaces. All buildings are mechanically
 521 ventilated, and most of the buildings have operable windows. The high data quality (rapid sample
 522 rate, low noise) of this sensor allows shorter experiments as well as more confident interpretation
 523 of subtle features in decay curves. These advantages are balanced by the substantial cost of the
 524 instrumentation; in our case it was also being used for other research studies. Methane (1% in N₂
 525 to exclude the possibility of ignition) was added to a room using a 700 cfm shop fan to boost the
 526 ambient concentration to 10-20 ppm, then decay was monitored to below 30% of peak

527 concentration, typically for 10-40 minutes. Using this approach, one person is able to test 8-12
528 rooms per day, with repeat measurements. We have measured rooms up to 1500 ft², with the
529 primary limitation being the ability to keep room air well mixed.

530
531 Test results for two research labs are shown in Figure 7, plotted as a function of elapsed time with
532 a logarithmic concentration axis. When exponential tracer decay is plotted in this log-linear space,
533 transient changes in ventilation rate can be visually identified as breaks in the slope. The results
534 for Lab 1 are typical for a room with isolated HVAC supply and no recirculated air. Lab 2 exhibited
535 an unexpectedly rapid drop in tracer at the beginning of the test, which we can interpret as
536 resulting from dilution of the tracer into an adjacent space that shares ventilation with Lab 2.
537 Occupants of the two rooms would not be effectively isolated from each other. This demonstrates
538 the utility of high-performance measurements in finding unexpected (and perhaps undocumented)
539 aberrations in HVAC system construction or operation.

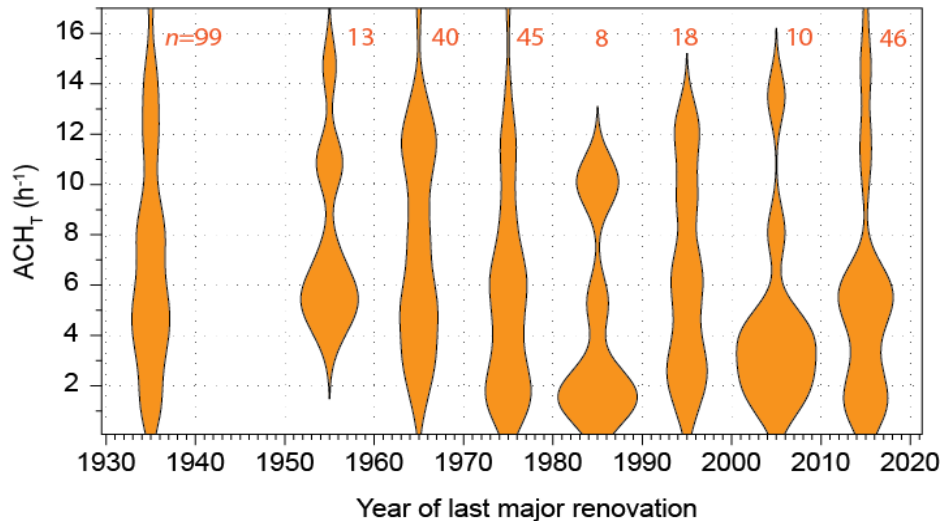
540



541
542 **Figure 7.** Ventilation test results using CH₄ tracer and a Picarro GasScouter sensor for two
543 different labs at Southern California University. Lab 1 is typical for spaces with isolated ventilation,
544 but in Lab 2 we observed rapid dilution of the tracer (red line) into an adjacent room before
545 stabilizing into a normal decay. Note that each test lasted <30 minutes total.

546
547
548 After a period of initial method development and optimization, the methane test equipment has
549 been deployed by the University's Facilities & Operations staff, and is being used in support of
550 reoccupation planning. Figure 8 summarizes the data collected thus far. Fresh-air exchange rates
551 varied from room to room, and building to building, over a very large range. Low values were

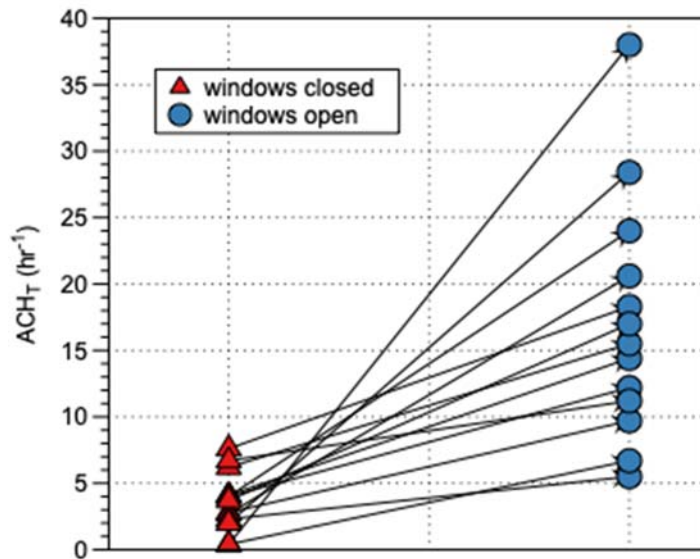
552 typically encountered in offices and restrooms, and the highest values ($>10 \text{ h}^{-1} \text{ ACH}_T$) almost all
 553 represent laboratory spaces. These ranges highlight the inherent difficulty of measuring a few
 554 spaces and extrapolating to others in the building. Note that many higher education laboratories
 555 are operated with 100% outside air ventilation. Also visible is a decline in the average air-
 556 exchange rates from the oldest buildings through those built in the 1980's, a result of historically
 557 increasing prioritization of energy efficiency, recirculation, and air-tight building construction.
 558
 559



560
 561
 562 **Figure 8.** Violin plot of ACH_T calculated from CH_4 tracer measurements in 279 rooms from 21
 563 buildings across the Southern California University campus, binned by decade of last HVAC
 564 system replacement. Each vertical symbol represents the probability distribution function (PDF)
 565 of ACH values among rooms from buildings of that age class. Number of rooms in each age class
 566 is given at the top in red.

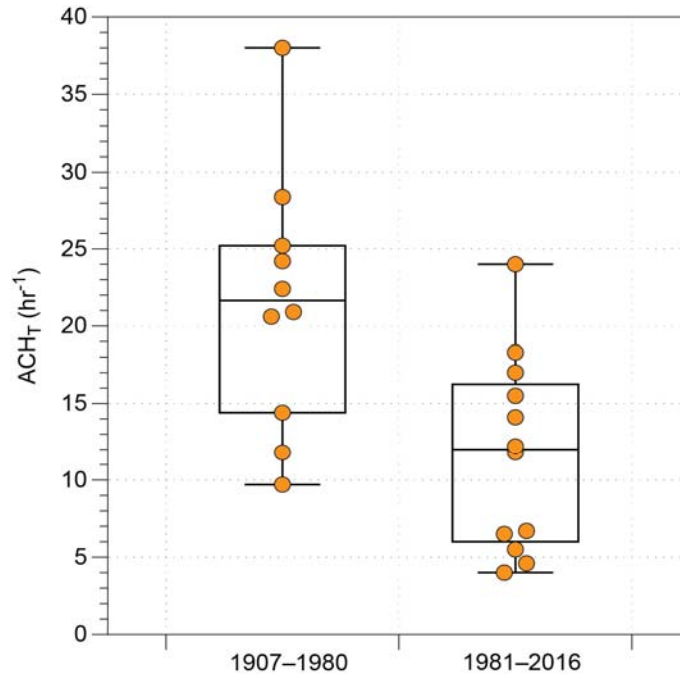
567
 568
 569 **3.4 Southern California Secondary School.** The same methane tracer and Picarro GasScouter
 570 technique described in the previous section was also employed at a nearby secondary school
 571 during October 2020. The school comprises a campus of multiple buildings constructed over the
 572 past century, with a range of construction types from cottages and small (4-6 room) single-story
 573 buildings to larger, multistory monolithic buildings with >30 rooms. Given the moderate climate,
 574 similar to the California Coastal schools, many of the older buildings were originally built without
 575 forced-air heating or air conditioning, and were instead designed with large banks of windows on
 576 opposing walls to maximize natural ventilation. The tested rooms included classrooms, offices,
 577 and other specific-use spaces (dining, choir, theater) across a representative cross-section of
 578 buildings. Since leaving windows open all winter is a realistic option for this school, our initial
 579 interest was to compare ventilation rates with windows sealed and HVAC systems continually
 580 running, versus with windows open. Consistent with the Coastal California School study,
 581 comparison of 11 classrooms and offices demonstrated the clear benefit of opening windows,
 582 with ventilation in every space at least doubling, and increasing 3-fold or more in many rooms
 583 (Figure 9). This led quickly to a decision that all windows would remain open when the school was

584 occupied, regardless of outside temperature. In our experience, this ability to test scenarios and
585 provide immediate, quantitative data to support policy decisions is one of the key benefits of the
586 trace-gas testing methodology.
587



588
589 **Figure 9.** Comparison of measured outside-air ventilation rates for 11 classrooms and offices in
590 the Southern California Secondary School with windows closed, HVAC on (triangles) versus
591 with windows open (circles).
592
593

594 With the decision to keep windows open, all subsequent testing was done as such. Results are
595 summarized in Figure 10, which bins buildings by age of construction. This comparison
596 emphasizes the contrast between older, smaller buildings with many windows, versus newer,
597 larger buildings that rely on mechanical ventilation. Nevertheless, even the newest buildings all
598 achieved $\geq 4 \text{ h}^{-1} \text{ ACH}_T$. In the older buildings, rooms with windows open achieved a stunning 21.3
599 $\text{h}^{-1} \text{ ACH}_T$ on average, levels that are more than 3 times the WHO guidelines even for healthcare
600 settings (6 ACH). These encouraging results provide a counterpoint to our findings in North East
601 University A and B, that older buildings in cold climates, which were designed for heat retention,
602 often have poor natural ventilation.
603
604
605



606
607

Figure 10. Summary of ventilation test results for 22 classrooms and offices of the Southern California Secondary School, binned by year of construction. All spaces were tested with windows open using the CH₄ controlled-release method.

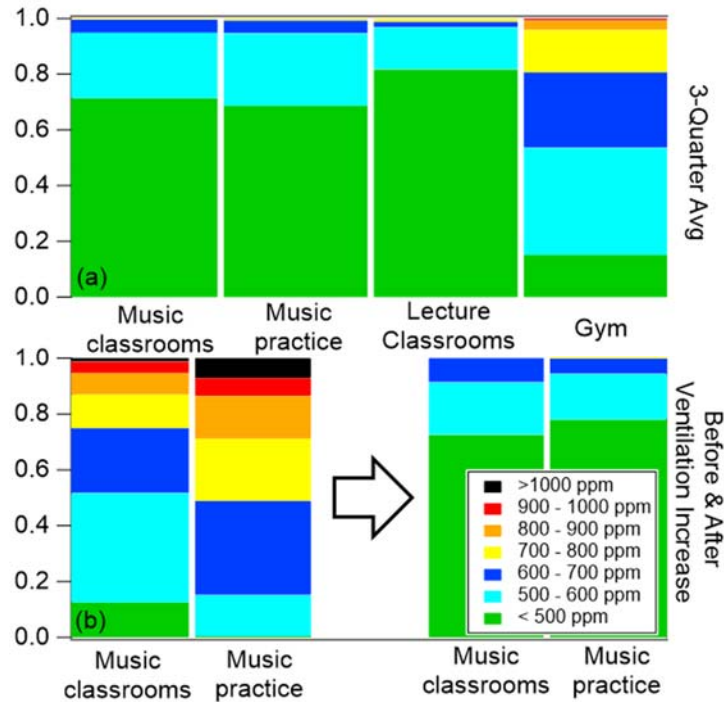
611
612

3.5 Mountain West University. Twelve NDIR CO₂ sensors (Aranet4, Aranet) were installed in mechanically ventilated rooms in buildings across the campus from September 2020 through April 2021 for passive in situ monitoring, with the goals of gaining insight into room usage and ventilation. Building construction dates spanned from 1985 (lecture classrooms) to 1999 (gym complex) and 2002 (music building). Information was shared with the campus facility managers to allow for optimization of ventilation. The rooms included four large ensemble music classrooms, two individual music practice rooms, two standard lecture classrooms, one science laboratory classroom, and three rooms in the campus gym facility. In all cases, ventilation is provided via forced air through centrally regulated HVAC units.

622

The sensors recorded CO₂ levels every 2 minutes. Data was averaged during typical main usage hours (08:00 – 22:00 for music classrooms and practice rooms; 09:00 – 15:00 for lecture classrooms; 15:00 – 21:00 for the gym), over non-holiday weekday (Monday-Friday) periods during the academic term between September and April. Figure 11a shows that during typical hours of operation, most rooms with sensors showed CO₂ levels <500 ppm for 70-80% of measurements. The average of the three gym sensors showed higher average readings, though these measurements show that 95% of measurements were still <800 ppm. These CO₂ levels are within a range that would indicate satisfactory ventilation during full occupancy of the space, but

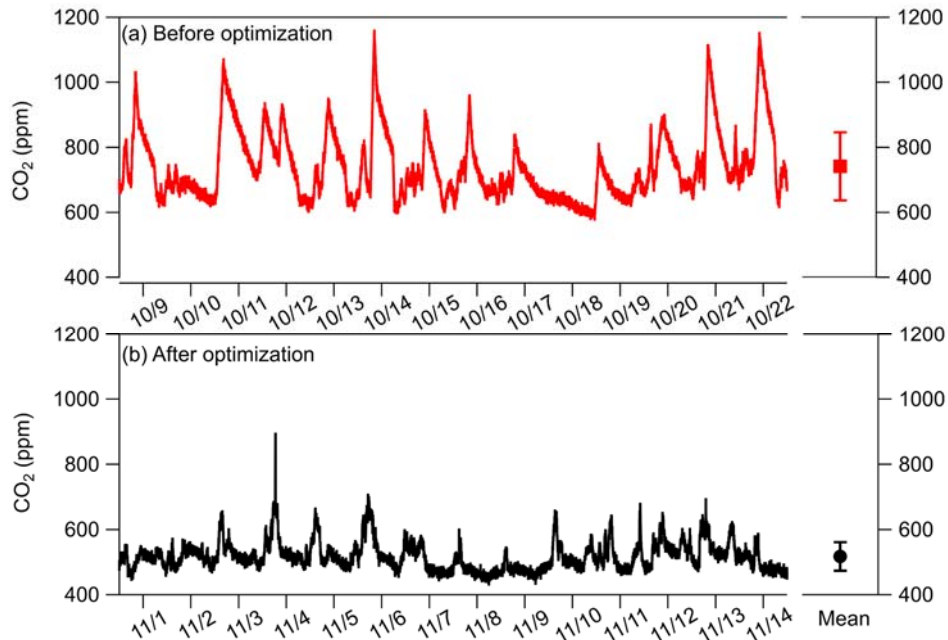
631
632



633
 634 **Figure 11:** Passive CO₂ measurements showing relative fraction of time observed in each
 635 concentration range from the Mountain West University. (a) Data reported for four different types
 636 of classrooms, averaged over in-use periods during three academic terms of observation. (b)
 637 Nighttime data for music classrooms and practice rooms for Fall academic term comparing before
 638 (left columns) and after (right columns) building ventilation was optimized to run at night and on
 639 weekends. See the text for additional details of the averaging periods.

640
 641
 642 we note that there was reduced occupancy during the time of these measurements due to COVID-
 643 19-related restrictions.

644
 645 As an example of actionable information that was obtained, overnight (10:00 PM - 2:00 AM) CO₂
 646 buildup was observed in classrooms and practice rooms in the music building when the rooms
 647 were used informally as practice spaces after hours (Figure 11b). The ventilation operation for
 648 that building was initially set up based on anticipated classroom usage to run only from 5:30 AM
 649 until 6:00 PM and was off at nights and on weekends. Figure 12a shows data from one music
 650 classroom over a two-week period as an example of the high CO₂ concentrations, overnight
 651 buildup in CO₂, and slow decay rates frequently observed. After the data was shared with the
 652 facilities managers, the HVAC schedule was updated to include ventilation after hours. This is
 653 important if the space is being occupied after hours. CO₂ levels at night fell dramatically to where
 654 only <10% of measurements were >600 ppm (Fig 12b), and variability in CO₂ concentration
 655 decreased. A time-series of CO₂ concentration following schedule optimization shows the
 656 average CO₂ concentration dropped from 741 ± 105 ppm to 517 ± 43 ppm.
 657



658
 659 **Figure 12:** CO₂ concentrations shown for a single ensemble music classroom at the Mountain
 660 West University before (a) and after (b) ventilation schedule optimized to run also at nights and
 661 on weekends. Mean value shown for two-week window displayed in each case, where bars
 662 show standard deviation of measurements.

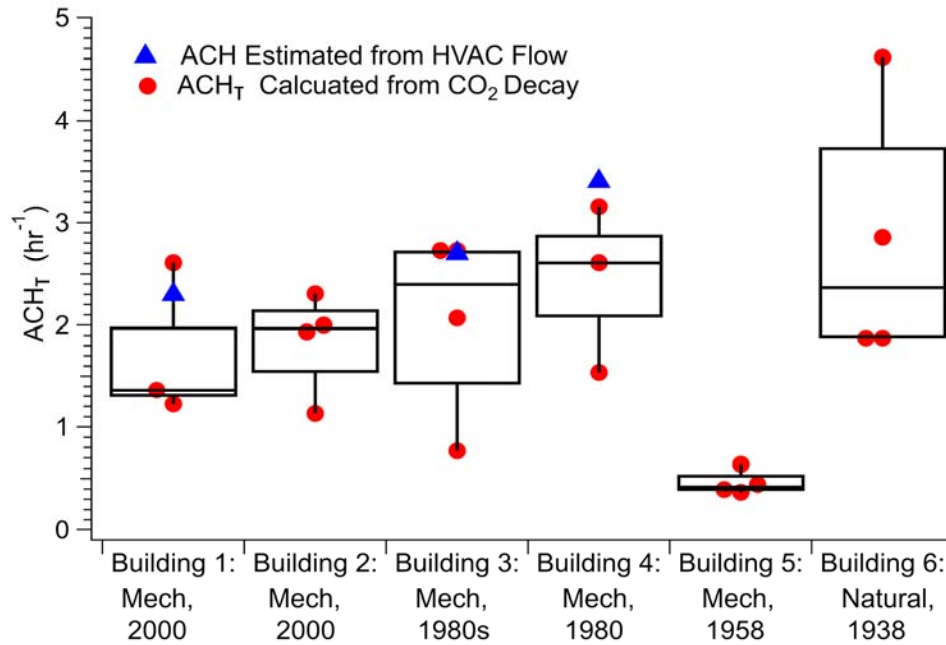
663
 664
 665 As the above example illustrates, the usage of passive CO₂ devices provides a relatively simple,
 666 inexpensive, and low-maintenance way to monitor ventilation or changes in space usage, that
 667 allows facility managers to make critical updates to ventilation schedules based on real usage
 668 data. Observations in the gym complex provided (Figure S1) a complementary example to the
 669 music building scenario, in which passive CO₂ monitoring revealed trends in space usage and
 670 confirmed the suitability of the ventilation schedule for that facility. See Supporting Information for
 671 more details.

672 A single PM sensor (QuantAQ MODULAIR-PM) was also continuously operated to passively
 673 monitor particulate concentrations in one private music practice room where a CO₂ device was
 674 also installed for passive monitoring. Over a six-month measurement period of November – April,
 675 CO₂ and PM₁ concentrations were compared on an hourly basis and are shown in Supplemental
 676 Figure S2. The time series of CO₂ and PM₁ values (Fig. S2a) show only mild and inconsistent
 677 similarity, and a direct correlation plot (Fig. S2b) shows an extremely low R² value of <0.1.
 678 Correlations with PM_{2.5} and PM₁₀ are similarly poor, but are not shown. As expected, these two
 679 pollutants are not related as there are many other sources of particulate matter indoors that do
 680 not also emit CO₂. In some cases CO₂ concentrations are high and PM is relatively lower, and in
 681 other cases the opposite is true. These data illustrate that in situ PM monitoring alone, or in
 682 combination with CO₂ monitoring, cannot easily provide information about the risk of transmission
 683 of airborne pathogens in an indoor space, due to the low contribution of respiratory-generated
 684 particles or aerosol-borne pathogens to the overall aerosol burden.

685 **3.6 South East University.** Professional grade low-cost sensors (QuantAQ MODULAIR-PM and
686 MODULAIR) with the capability to detect carbon dioxide (CO₂) and particulate matter (PM) were
687 deployed to monitor these species and characterize ventilation rate in various classrooms and
688 indoor spaces at a university in the urban Southeast U.S. from August 2020 through March 2021.
689 The MODULAIR-PM sensor measures PM through a combination of an optical particle counter
690 (OPC) and nephelometer. Similar to Mountain West University, poor correlation was observed
691 between simultaneous in situ CO₂ and PM measurements. Buildings studied were built from 1920-
692 2020 and have mechanical or natural ventilation systems. Portable HEPA filter-based air cleaners
693 were added as a mitigation to rooms with older mechanical ventilation systems (prior to 1960s).
694 As discussed in the Methodology section, we took advantage of in-person classes and fogging
695 events that occurred when a room was disinfected with a cleaning aerosol spray to calculate
696 ACH_T. In-person classes led to a buildup of CO₂ in the room, while fogging released PM. It was
697 ensured that fogging was conducted when no one was in the classroom, and that the personnel
698 performing the fogging were wearing appropriate personal protective gear. In our calculations, it
699 is assumed that the room is well mixed, the only sources of CO₂ during classroom occupancy are
700 the occupants, and the only source of PM during the fogging event is the fogging spray. When
701 using PM data to estimate ventilation rate, it is assumed that the effects of aerosol deposition and
702 gravitational settling on aerosol decay rate are negligible. Thus, the calculated ventilation rate
703 based on PM decay analysis may be an overestimation.

704 Data from two selected classrooms were presented in Figure 2 of the Methodology section as
705 examples of the technique. Room A is a large lecture hall that is equipped with an HVAC system
706 recirculating indoor air and new outdoor air. The mixture of recirculated and outdoor air is filtered
707 by a MERV 13 filter. Room B is a smaller 20-person classroom that is equipped with an older
708 HVAC system and has a mix of recirculated and outdoor air that is filtered by a MERV 8 filter.
709 Room B also has an added portable air cleaner with a HEPA filter. In these two rooms,
710 background indoor CO₂ levels ranged from 350 to 450 ppm, and CO₂ levels during in-person
711 classes averaged from 430 to 600 ppm, occasionally reaching 1000 ppm. Background PM_{2.5}
712 levels ranged from 1 to 10 µg m⁻³ in general, with occasional levels up to 20 µg m⁻³, while fogging
713 events resulted in PM_{2.5} levels of 40-80 µg m⁻³. The primary filtration of air in Room B is due to
714 the portable air cleaner, which can provide an ACH of up to 4 h⁻¹ at the maximum setting. Using
715 the decay of PM_{2.5}, the ACH for was estimated to be 2.8 h⁻¹. This indicates that the unit was likely
716 not running at the maximum setting during the fogging event.

717 Figure 13 shows a summary of ACH_T calculated from CO₂ decay data in six different classrooms
718 in six buildings across campus over a 2-week period in March 2021. Data are also shown for ACH
719 calculated from the HVAC air supply rates that were available. It is important to note that the ACH
720 values estimated from HVAC flow rates are based on total air flow to the room, which is a mixture
721 of outdoor air (“clean” air) and air recirculated from other rooms (that may contain higher levels of
722 CO₂ from occupancy.) Although during the sampling period there were low building occupancy
723 levels due to COVID-19 restrictions, the ACH estimated from HVAC supply flow could be an
724 overestimate of clean air changes. ACH calculated using the air supply was similar to the
725 measured ACH_T in each case, suggesting that there is no significant interference from recirculated
726 CO₂. Overall, the absolute ACH values found across all buildings were on a similar order of



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Figure 13. Samples collected from 6 rooms in 6 different buildings with either mechanical (Mech) or natural ventilation over the same 2 week period. Red dots are calculated from in situ CO₂ data during different classes in the same room. Blue triangles are from recorded HVAC air supply rates.

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magnitude, regardless of building age or type of ventilation (mechanical vs natural). The one exception is the room in building 5, which saw significantly lower ACH values. This observation was in agreement with building 5 having one of the older HVAC systems on campus, and for these reasons that classroom was equipped with an additional portable HEPA filter air cleaner prior to the beginning of the semester. Unlike the observation by North East University A, the ACH_T for the naturally ventilated classroom was on the higher end of the range of mechanically ventilated room ACH_T values, despite being much older than the other buildings investigated. Similar to what Southern California Secondary School noted, this can be attributed to the fact that building 6 is a small classroom with multiple windows. In contrast, buildings 1-5 have no windows, appear more tightly sealed, and run with mechanical ventilation systems. This is common in both the Southeast U.S. (due to high humidity and heat) and in large university buildings in order to combat high energy expenditures.

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In addition to structure and ventilation design, the rooms studied in buildings 1-5 are centrally located in the building layout. These factors, combined with the fact that buildings 3-5 have older ventilation systems, could partly explain why observed ACH values were lower than those reported by some of the other universities. It should also be noted that during the sample period, ventilation rates were not at their maximum levels. The rooms in buildings 1 and 2 have CO₂

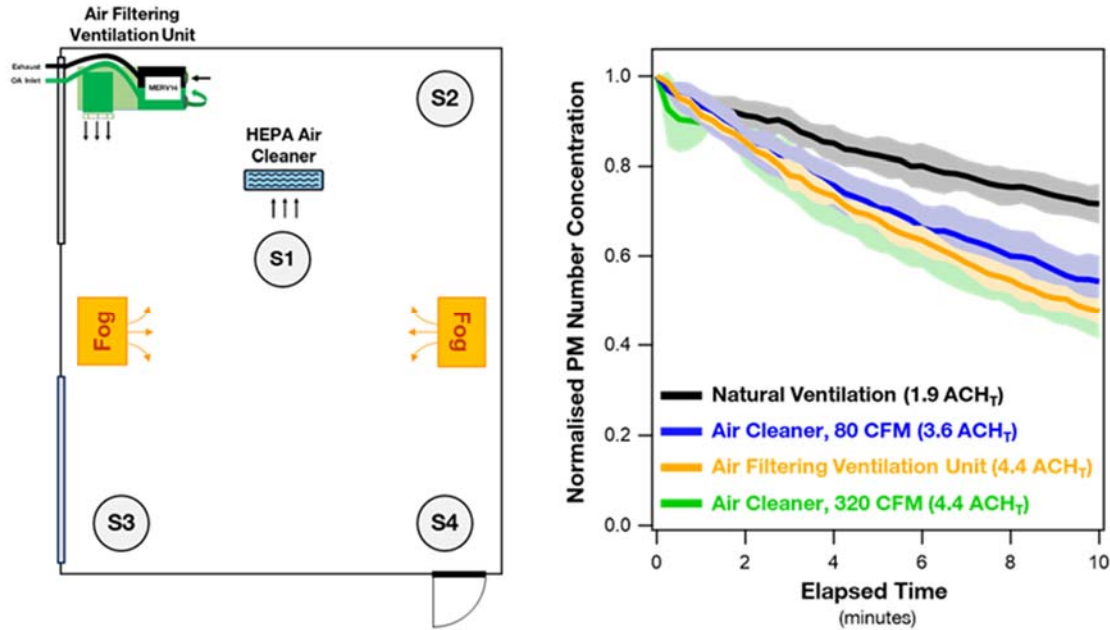
751 demand-controlled ventilation, meaning that once CO₂ levels reach a certain value (often 800-
752 1000 ppm) the HVAC system will automatically increase air flow rates. During the time period that
753 these samples were collected, classroom occupancy was limited due to COVID-19 precautions
754 and CO₂ levels did not exceed 750 ppm in either room. It is possible that higher CO₂ levels would
755 result in higher ACH_T values.

756 **3.7 North East University B.** Similar to North East University A, North East University B is
757 situated in an urban area, and comprises buildings with a range of ages and ventilation types. To
758 address the challenges of increasing ventilation and filtration in campus spaces without
759 mechanical ventilation or limited supply, we explored the impact of two portable air cleaner
760 devices on air change rate, and the spatial variation in PM concentrations in a naturally ventilated
761 space, via controlled release of particulate matter. The two air cleaner devices were: (a) a
762 commercially available HEPA recirculating air cleaner (Model HPA 304, Honeywell, Charlotte,
763 NC) as well as (b) an in-house designed and fabricated unit known as the Air Filtering Ventilation
764 Unit (AFVU), which brings in some outdoor air, tempers with a return, and includes MERV 14
765 filtration, effectively simulating a typical mechanical ventilation system (Figure S3, see Supporting
766 Information for more details).

767 A library space on campus with no mechanical ventilation, was used for testing as it was
768 representative of other classroom spaces and common rooms on campus. Additional details of
769 the testing space are given in the Supplemental Information. The room was pre-cleaned by HEPA
770 filtered vacuuming and damp wiping of hard surfaces, and a sticky mat was placed at the room
771 entryway. Radiator blower fans were turned “off” during testing. In addition, all windows,
772 fireplaces, passive air transfer grilles, built-in wall bookcases, radiator covers, and floor rugs were
773 covered with polyethylene sheeting and taped shut. As testing was conducted in January 2021
774 with lower humidity levels (19-22%), all polyethylene sheets used in the space were electrically
775 grounded by bonding with aluminum metal tape and copper wire to metal outlet covers to help
776 reduce static electricity. The commercial air cleaner was operated in two modes (80 CFM and
777 320 CFM) and was positioned in the center of the room, 0.6 m away from one of the 4 sampling
778 locations (S1, Figure 14). Details of the AFVU placement and operation can be found in the
779 Supporting Information.

780 Test PM was generated using fog generators (Model C Breeze, Degree Controls, Inc., Milford,
781 NH) with long-duration fog liquid. Paraffin candles (“Glimma”, Ikea Systems, BV, Sweden) were
782 also used to generate test PM. PM levels (0.02-1.0 μm) were monitored in real-time using a P-
783 Trak monitor (Model 8525, TSI, Shoreview, MN). Four P-Trak monitors were positioned at
784 different locations across the testing space and operated in parallel. Temperature and humidity
785 (Model EVM, 3M, Oconomowoc, WI) was also continuously monitored at the approximate room
786 center.

787 In the first set of experiments, we used the controlled release of PM to evaluate the air change
788 rate provided by each of the portable air cleaner devices. This procedure was modified from one
789 developed by the Association of Home Appliance Manufacturers (AHAM) for testing portable air
790 cleaning devices inside a sealed laboratory chamber, but here we use a real-life space with less



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793 **Figure 14.** Comparison of PM tracer decay using different filtration/ventilation approaches in a
 794 naturally ventilated library test space in North East University B. *Left:* The plan view indicates the
 795 location of two fog generators, the PM sampling locations (S1-S4), and the two supplemental
 796 filtration/ventilation devices that were individually evaluated: an air filtering ventilation unit and a
 797 commercially-available air cleaner. *Right:* Ventilation test results for various scenarios are shown
 798 with the measured ACH_T .
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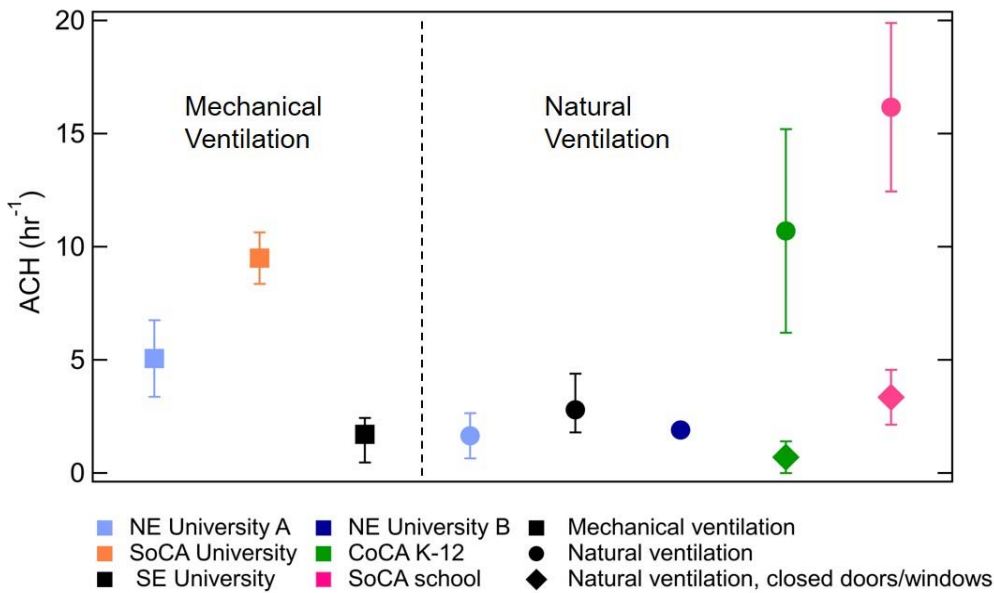
800 controlled conditions and a different PM source. In this set of experiments we released PM from
 801 two foggers, which were oriented facing the center of the room, positioned 1 m from opposite
 802 walls, and 1 m above the ground (Figure 14). The generated PM was dispersed in the room using
 803 two box fans (Model 9723, AirKing, Inc., West Chester, PA) for 1 minute. These box fans were
 804 positioned under the fogger devices. The foggers were then shut off, room air mixing continued
 805 for one additional minute with the box fans, and particle concentrations monitored for 10 minutes,
 806 at which time four recirculating HEPA-filtered blowers (Model Defendair HEPA 500, Sylvane, Inc.,
 807 Roswell, GA) were turned on to clean room air in preparation for the next test. Natural particle
 808 removal (decay) rates were measured this way under static room conditions without any
 809 ventilation or air cleaning equipment running. The effectiveness of the AFVU and the
 810 commercially available HEPA air cleaner were assessed individually by turning each unit on once
 811 the fog release and air mixing were completed, and the rate of aerosol removal was compared to
 812 the natural decay rate. PM decay was assessed at each of the four sampling locations; the mean
 813 and associated standard deviation are shown Figure 14. The AFVU and the commercially
 814 available portable air cleaner both enhanced ACH_T compared to natural ventilation in the test
 815 space (1.9 per hour). Operation of the commercial filtration unit at the low fan speed (80 CFM)
 816 provided 3.6 ACH_T . Increasing the flow of this unit to 320 CFM achieved a similar ACH_T as the
 817 AFVU 4.4 per hour.

818 We also evaluated the spatial distribution of aerosol across the test space using the two
 819 supplemental filtration/ventilation approaches (see Supporting Information). When a continuous
 820 PM source was provided via burning candles in the center of the test space, use of the commercial
 821 HEPA recirculating filter resulted in more spatial heterogeneity than the AFVU, with high stable
 822 PM concentrations found over the entire test period at sampling locations S1 and S3 (Figure S4).
 823 This was attributable to the poor mixing of vertical discharge under dynamic continuous PM
 824 generation for the ventilation conditions of the room and lower airflow rate compared to the AFVU.
 825 Details may be found in the Supporting Information.

826 Overall, the mid-sized recirculating HEPA-filtered air cleaner improved ACH_T in the naturally
 827 ventilated library. The highest fan speed of the commercial device achieved an equivalent total
 828 ACH as the AFVU that provides 20% outdoor air. The AFVU, however, provided improved PM
 829 removal rates across the test space compared to the commercial unit when tested against
 830 continuously generated PM that might occur in an occupied room. We concluded based on these
 831 studies that deployment of the two tested portable air cleaners in spaces without mechanical
 832 ventilation on campus could be used to improve indoor air quality, aligning spaces with applicable
 833 ventilation guidelines and support increases in room occupancy rates.

834
 835 **4. Discussion**

836 Figure 15 summarizes the ACH measurements made at the different institutions in this study.
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 840 **Figure 15.** Summary of ventilation measurements reported here. NE: North East, SE: South East,
 841 CoCA: Coastal California, SoCA: Southern California.

842
 843 The naturally ventilated buildings on the West Coast studied here were designed for cross-
 844 ventilation and had relatively high ACH, particularly when windows and exterior doors were
 845 opened, consistent with previous findings (Howard-Reed et al., 2002). In each case, cross-

846 ventilation with open windows and/or doors led to higher ventilation rates than sealing the room
847 and using HVAC. For the buildings studied in Southern California, older construction
848 corresponded to better ventilation.

849
850 Older buildings in the Northeast U.S. without mechanical ventilation, designed to keep heat in
851 during cold winters, often have insufficient air exchange. Many buildings in the Northeast were
852 designed in the wake of the 1918 influenza pandemic for windows to be open year-round, even
853 while a steam radiator was in operation during winter (Sisson, 2020). This practice has fallen out
854 of favor over the past century as energy efficiency became a priority. Given the relatively low cost
855 of portable filter-based air cleaners, their installation in buildings of this type may be justified even
856 when ventilation data are not available for these spaces, or measurements are not practical.

857
858 We note that, for both naturally and mechanically ventilated systems, ventilation parameters and
859 airflow patterns vary with occupancy and ambient weather conditions or season. Measurements
860 should ideally be made for a variety of conditions to get a more comprehensive picture of
861 ventilation for a particular space.

862
863 The controlled-release experiments described here were effective for characterizing ventilation in
864 a mixture of building types encountered in U.S. universities and K-12 schools in a repeatable
865 manner. While all the approaches discussed here yielded valuable insights, those employing low
866 cost, reliable, easy-to-use sensors are best suited to general use. Other approaches employed
867 costly equipment or required specialized technical expertise to perform the experiments or
868 interpret the data.

869
870 At North East University B, controlled-release PM experiments allowed estimation of air change
871 rates and revealed spatial variation in flow patterns in naturally ventilated rooms. Those results,
872 along with the observations of delayed clearance in sections of some irregularly shaped
873 classrooms in the Coastal California K-12 School District (Figure 6), highlight that a room-level
874 evaluation of ventilation may mask heterogeneity in flow fields and potentially problematic
875 microenvironments within an otherwise well-ventilated room. The effectiveness of this approach
876 relies on the use of very fine particles that have minimal additional removal process such as
877 deposition to surfaces. In situ monitoring of absolute PM concentrations is fundamentally limited
878 as an indicator of aerosol pathogen risk, however, because the concentration of PM associated
879 with respiratory emissions of infected individuals will generally be small compared to background
880 aerosol.

881
882 CO₂ controlled-release experiments, such as were performed at North East University A and
883 Coastal California K-12 School District, are most effective for naturally ventilated buildings or
884 during periods of low occupancy in mechanically ventilated buildings, due to the risk of
885 interference from recirculated CO₂. For the studies presented here, which were conducted in
886 Summer-Fall 2020 and early 2021, low occupancy was the norm due to COVID-19 related
887 occupancy restrictions, but similar conditions may be encountered after hours or during holidays.

888

889 In situ monitoring is an accessible approach for observing air quality trends while a space is being
890 actively used, allowing quick response once problems are identified, in the form of schedule
891 changes or engineering interventions. Setup and maintenance of low-cost sensors for CO₂ or PM
892 requires relatively little technical expertise.

893

894 **5. Conclusion**

895 Ventilation and filtration are key components of a layered approach towards risk reduction for the
896 transmission of airborne infectious diseases. Such an approach also includes vaccines, masking,
897 physical distancing and other controls on occupancy, and testing. Adequate ventilation and air
898 cleaning is also critical for maintaining healthy indoor air quality.

899

900 We have presented a number of practical approaches for gathering room-level ventilation data
901 for educational spaces, and anecdotal examples of their application in a range of building and
902 room types, and climates across the U.S. In particular, approaches using reliable low-cost air
903 quality sensors show promise for use by nonspecialists. Room-level ventilation data allows
904 consideration of indoor air quality and transmission of respiratory disease in decision making with
905 regards to occupancy and ventilation strategies. As we have demonstrated, it can also be critical
906 in identifying areas for mitigation (i.e. with filtration devices) and providing clues into building
907 occupancy patterns which must be accounted for in the ventilation strategy.

908

909 Ventilation data can also be useful for communicating and building trust with faculty, staff,
910 students, and the rest of the community. Knowing that ventilation is satisfactory, problem areas
911 have been identified, and mitigation measures have been put into place can ease anxieties and
912 build confidence about return to campus or increased occupancy, and improve confidence in the
913 future indoor air quality. Broad participation in the process of data collection, made possible by
914 the use of more accessible approaches such as in situ CO₂ monitoring with low cost sensors, can
915 provide an additional sense of agency (Schaefer et al. 2020).

916 **Author contributions**

917 VFM, JAH, DYM, NLN, KJGP, RS, AS, TS, and SW designed experiments, analyzed and
918 interpreted data. JAH, DYM, NLN, KJGP, RS, AS, TS, and SW collected data. All authors
919 participated in writing the manuscript and the development of Table 1.

920 **Declaration of competing interest**

921 The authors declare that they have no known competing financial interests or personal
922 relationships that could influence the work reported in this paper.

923 **Acknowledgements**

924 The authors thank Prof. Bill Nazaroff and Prof. Atila Novoselac for helpful discussions. VFM and
925 DYM acknowledge Columbia University School of Engineering and Applied Sciences and the
926 Alfred P. Sloan Foundation Chemistry of Indoor Environments program for financial support, and
927 Columbia Facilities. TMS and RAS gratefully acknowledge the Santa Barbara Unified School
928 District and Goleta Union School District for their cooperation and help with measurements. ALS

929 acknowledges Caltech and the Divisions of Geological & Planetary Sciences and Chemistry and
930 Chemical Engineering for financial support, Caltech Facilities for testing and data collection, and
931 Nathan Dalleska, John Crouse, and Paul Wennberg for contributions to method development
932 and deployment. SW and NLN acknowledge support from Georgia Tech COVID-19 Rapid
933 Response fund, and helpful discussions with Philip Johnston, Richard Chew, and Gregory Spiro
934 from Georgia Tech Facilities. JAH acknowledges the University of Denver COVID-19 Response
935 team, Department of Facilities Management, Lamont School of Music, and Planning, and Office
936 of the Provost for funding and support. CK, RK, ML, and KJGP acknowledge the support of Julie
937 Paquette, Anthony Kosior, and JP Fernandez with method development and deployment. PJO
938 acknowledges support from the Johns Hopkins Center for Health Security and the Open
939 Philanthropy Project.

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941 **References**

942

943 ASHRAE Standard Project Committee 170, ANSI/ASHRAE Standard 111-2008 (RA 2017),
944 Measurement, Testing, Adjusting, And Balancing Of Building HVAC Systems (2017)

945

946 ASHRAE Standing Standard Project Committee 62.1, ANSI/ASHRAE Standard 62.1-2019,
947 Ventilation for Acceptable Indoor Air Quality (2019)

948

949 ASHRAE Epidemic Task Force, Core Recommendations for Reducing Airborne Infections
950 Aerosol Exposure [https://www.ashrae.org/file%20library/technical%20resources/covid-19/core-](https://www.ashrae.org/file%20library/technical%20resources/covid-19/core-recommendations-for-reducing-airborne-infectious-aerosol-exposure.pdf)
951 [recommenda-](https://www.ashrae.org/file%20library/technical%20resources/covid-19/core-recommendations-for-reducing-airborne-infectious-aerosol-exposure.pdf)
952 [tions-for-reducing-airborne-infectious-aerosol-exposure.pdf](https://www.ashrae.org/file%20library/technical%20resources/covid-19/core-recommendations-for-reducing-airborne-infectious-aerosol-exposure.pdf) January 2021

952

953 Batterman, S. Review and Extension of CO₂-based Methods to Determine Ventilation Rates
954 with Application to School Classrooms. *Int. J. Environ. Res. Public Health* 14(2), 145 (2017)

955

956 Bhangar, S., Huffman, J.A., Nazaroff, W.M., Size-resolved fluorescent biological aerosol particle
957 concentrations and occupant emissions in a university classroom. *Indoor Air* 24(6) 604-617
958 doi:10.1111/ina.12111 (2014)

959

960 Centers for Disease Control and Prevention, National Center for Immunization and Respiratory
961 Diseases, FLUVIEW: A Weekly Influenza Surveillance Report Prepared by the Influenza
962 Division <https://www.cdc.gov/flu/weekly/weeklyarchives2020-2021/ILI22.html> Accessed August
963 2021

964

965 Charlesworth, P.S., Air Exchange Rate and Airtightness Measurement Techniques - An
966 Applications Guide. International Energy Agency: Air Infiltration and Ventilation Centre, St
967 Albans: Oscar Faber. August 1988

968

969 Corsi, R., Miller, S.L., VanRy, M.G., Marr, L.C., Cadet, L.R., Pollock, N.R., Michaels, D., Jones,
970 E.R., Levinson, M., Li, Y., Morawska, L., Macomber, J., Allen, J.G. Designing infectious disease
971 resilience into school buildings through improvements to ventilation and air cleaning. Report of

972 the Lancet COVID-19 Commission Task Force on Safe Work, Safe School, and Safe Travel
973 <https://covid19commission.org/safe-work-travel> April 2021
974
975 Fisk, W.J., The Ventilation Problem in Schools: Literature Review. *Indoor Air* 27(6)1039-1051
976 (2017)
977
978 Gettings, J., Czarnik, M., Morris, E., Haller, E., Thompson-Paul, A.M., Rasberry, C., Lanzieri,
979 T.M., Smith-Grant, J., Aholou, T.M., Thomas, E., Dreznek, C., KacKellar, D. Mask Use and
980 Ventilation Improvements to Reduce COVID-19 Incidence in Elementary Schools — Georgia,
981 November 16–December 11, 2020. *MMWR Morb Mortal Wkly Rep* 70:779–784. DOI:
982 10.15585/mmwr.mm7021e1 (2021).
983
984 Greenhalgh, T., Jimenez, J.L., Prather, K.A., Tufekci, Z., Fisman, D., Schooley, R. Ten scientific
985 reasons in support of airborne transmission of SARS-CoV-2. *Lancet* 397(10285) 1603-1605
986 doi:10.1016/S0140-6736(21)00869-2 (2021)
987
988 Howard-Reed, C., Wallace, L.A., & Ott, W.R. The Effect of Opening Windows on Air Change
989 Rates in Two Homes, *J. Air Waste Management Assoc.*, 52:2, 147-159, DOI:
990 [10.1080/10473289.2002.10470775](https://doi.org/10.1080/10473289.2002.10470775) (2002)
991
992 Jones, E., Young, A., Clevenger, K., Salimifard, P., Wu, E., Lahaie Luna, M., Lahvis, M., Lang,
993 J., Bliss, M., Azimi, P., Cedeno-Laurent, J., Wilson, C., Segule, M.N., Keshavarz, Z., Chin, W.,
994 Dedesko, S., Parikh, S., Vallarino, J., Allen, J. Healthy Schools: Risk Reduction Strategies for
995 Reopening Schools. Harvard T.H. Chan School of Public Health Healthy Buildings program.
996 November, 2020.
997
998 Korsavi S.S., Montazami A., Mumovic D., Ventilation rates in naturally ventilated primary
999 schools in the UK; Contextual, Occupant and Building-related (COB) factors,
1000 *Building and Environment*, 181, 107061 (2020)
1001
1002 Lednicky, J.A., Lauzardo, M., Fan, Z.H., Jutla, A., Tilly, T.B., Gangwar, M., Usmani, M.,
1003 Shankar, S.N., Mohamed, K., Eiguren-Fernandez, A., Stephenson, C.J., Alam, M.M., Elbadry,
1004 M.A., Loeb, J.C., Subramaniam, K., Waltzek, T.B., Cherabuddi, K., Morris, J.G., and Wu, C.-Y.
1005 Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. *Int. J. Infectious*
1006 *Diseases*, 100, 476-482, doi:10.1016/j.ijid.2020.09.025 (2020)
1007
1008 Levinson, M., Geller, A.C., Allen, J.G., The Lancet COVID-19 Commission Task Force on Safe
1009 Work, Safe School, and Safe Travel. Health Equity, Schooling Hesitancy, and the Social
1010 Determinants of Learning, *Lancet Reg. Health - Americas*, 2, 100032, DOI:
1011 [10.1016/j.lana.2021.100032](https://doi.org/10.1016/j.lana.2021.100032) (2021)
1012
1013 Li Y., Leung, G.M., Tang, J.W., Yang, X., Chao, C.Y., Lin, J.Z., Lu, J.W., Nielsen, P.V., Niu, J.,
1014 Qian, H., Sleigh, A.C., Su, H.J., Sundell, J., Wong, T.W., Yuen, P.L. Role of ventilation in

1015 airborne transmission of infectious agents in the built environment - a multidisciplinary
1016 systematic review. *Indoor air*. 17(1):2-18. DOI: 10.1111/j.1600-0668.2006.00445.x (2007)
1017
1018 Liddament, M.W. and Orme, M. Energy and Ventilation. *Applied Thermal Eng.* 18(11) 1101-
1019 1109 (1998) doi:10.1016/S1359-4311(98)00040-4
1020
1021 Miller, S.L., Nazaroff, W.M., Jimenez, J.L., Boerstra, A., Buonanno, G., Dancer, S.J., Kurnitski,
1022 J., Marr, L.C., Morawska, L., Noakes, C. Transmission of SARS-CoV-2 by inhalation of
1023 respiratory aerosol in the Skagit Valley Chorale superspreading event. *Indoor Air* 31(2),314-323
1024 doi:10.1111/ina.12751 (2021)
1025
1026 NOAA Global Monitoring Laboratory, Trends in Atmospheric Carbon Dioxide,
1027 <https://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html> Accessed August 2021
1028
1029 Persily, A., Tracer gas techniques for studying building air exchange. United States National
1030 Bureau of Standards NBSIR 88-3708, February 1988.
1031
1032 Persily, A.K., Field measurement of ventilation rates. *Indoor Air*, 26: 97-111.
1033 <https://doi.org/10.1111/ina.12193> (2016)
1034
1035 Peng, Z. and Jimenez, J.L. Exhaled CO₂ as a COVID-19 Infection Risk Proxy for Different
1036 Indoor Environments and Activities. *Environ Sci Technol Lett* 8(5) 392-397
1037 doi:10.1021/acs.estlett.1c00183 (2021)
1038
1039 Rudnick, S.N. and Milton, D.K. Risk of indoor airborne infection transmission estimated from
1040 carbon dioxide concentration. *Indoor Air* 13(3) 237-245 doi:10.1034/j.1600-0668.2003.00189.x
1041 (2003)
1042
1043 Schaefer, T., Kieslinger, B. and Fabian, C.M., 2020. Citizen-Based Air Quality Monitoring: The
1044 Impact on Individual Citizen Scientists and How to Leverage the Benefits to Affect Whole
1045 Regions. *Citizen Science: Theory and Practice*, 5(1) 6 DOI:10.5334/cstp.245 (2020)
1046
1047 Singer, BC, Delp, WW. Response of consumer and research grade indoor air quality monitors to
1048 residential sources of fine particles. *Indoor Air* 28 624– 639. doi:10.1111/ina.12463 (2018)
1049
1050 Sisson, P. “Your Old Radiator is a Pandemic-Fighting Weapon,” Bloomberg CityLab, Aug 5 2020
1051 [https://www.bloomberg.com/news/articles/2020-08-05/the-curious-history-of-steam-heat-and-](https://www.bloomberg.com/news/articles/2020-08-05/the-curious-history-of-steam-heat-and-pandemics)
1052 [pandemics](https://www.bloomberg.com/news/articles/2020-08-05/the-curious-history-of-steam-heat-and-pandemics)
1053
1054 Tang, M., Zhu, N., Kinney, K., and Novoselac, A. Transport of indoor aerosols to hidden interior
1055 spaces, *Aerosol Science and Technology*, 54:1, 94-110, DOI:10.1080/02786826.2019.1677854
1056 (2020)
1057

1058 Turner, W.J.N., Sherman, M.H., Walker, I.S. Infiltration as ventilation: Weather-induced dilution,
1059 *HVAC&R Research*, 18:6, 1122-1135, DOI: [10.1080/10789669.2012.704836](https://doi.org/10.1080/10789669.2012.704836) (2012)
1060
1061 U.S. Green Buildings Council. LEED BD +C: New Construction v4 Minimum Indoor Air Quality
1062 Performance <https://www.usgbc.org/credits/new-construction/v4-draft/eqp1> (2019)
1063
1064 Wargocki P, Porras-Salazar JA, Contreras-Espinoza S, Bahnfleth W. The relationships between
1065 classroom air quality and children's performance in school. *Build Environ*. 173:106749.
1066 doi:10.1016/j.buildenv.2020.106749 (2020)
1067
1068