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Use of Carbon Dioxide (CO_2) Monitors to Assess Ventilation Effectiveness in Schools

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Abstract

The COVID-19 pandemic has highlighted the importance of good ventilation in mitigating the transmission of airborne virus particles. In many countries, CO_2 monitors have been mandated for use in indoor spaces to inform good ventilation practices. However, there is limited guidance on the use of CO_2 monitors to assess ventilation performance in large groups of buildings. In occupied classrooms, locating multiple monitors to collate reliable environmental data can be a difficult task because of the functions and usage of the space. This study used observations and physical measurements of CO_2 in three real-world naturally ventilated classrooms, in three primary schools to assess whether the use of a single CO_2 monitor, in one location could predict the room ventilation performance. The results indicate that for naturally ventilated classrooms, a single CO_2 monitor placed at head height (about 1.5 m) on a vertical wall, away from windows, doors, or air supply, and not directly under the breathing zone of occupants can be used to express the ventilation performance of classrooms. This study provides a systematic method for monitoring CO_2 to direct ventilation intervention programmes for large groups of school buildings.

Keywords: carbon dioxide, classrooms, mesurement locations, sensors, ventilation performance.

Introduction

Ventilation is one component of maintaining healthy indoor environments and it is an important COVID-19 mitigation measure for schools (Corsi et al., 2021; Gettings et al., 2021). Good ventilation simply means providing sufficient fresh air into indoor spaces and this is associated with removing air that contains virus particles and is essential in preventing the spread of COVID-19 (MoE, 2022B., CDC, 2021). Ventilation rate can be estimated from the concentration of CO_2 (Mahyuddin & Awbi, 2012; Aliboye, et al., 2006) and is generally expressed in air changes per hour or fresh air supply rate per person. CO_2 is in exhaled breath and monitoring CO_2 concentrations is the most common approach used to measure ventilation performance in schools, given that it is often used as a surrogate of the rate of outside air supply per occupant (Ackley et al., 2022; Daisey et al., 2003).

Studies (Daisey et al., 2003; Kruisselbrink et al., 2016; Milton et al., 2000) have shown that CO_2 levels exceeding 800 parts per million (ppm) are frequently associated with lack of fresh air in a building. At levels normally measured in buildings, CO_2 is not considered a contaminant. However, given that certain levels of indoor CO_2 correspond to various ventilation rates, it is widely recognised as an indicator of the ventilation rates inside a building (Persily, 1997). For example, "CO_2 levels of 800 ppm, 1250 ppm, and 2000 ppm corresponds to approximately the air exchange rates of 6, 3, and 2 ACH, or the fresh air supply rates of 10, 6, and 4 L/s/person in a typical classroom - depending on occupancy and volume" (Chen et al., 2022). Outdoor CO_2 levels are currently about 410 ppm. Com-

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plaints of headaches, drowsiness, lethargy, tiredness, eye, nose and throat irritation maybe more prevalent at CO_2 concentrations that are three or four times higher than the outdoor levels (Daisey et al., 2003; OSHA, 2017). In schools, CO_2 levels exceeding 1000 ppm can indicate a potential fresh air/ventilation problem (Fisk et al., 2013; Rosbach et al., 2013; Satish, Mendell, Shekhar, Hotchi, Sullivan, et al., 2012), and studies (Cartieaux et al., 2011; Dorizas et al., 2015; Ferreira & Cardoso, 2014; Salthammer et al., 2016) have associated the prevalence of allergic and respiratory diseases among school children with poor ventilation in classrooms.

"Carbon dioxide is a colourless and odourless gaseous element which, on itself is not a problem, but when at high concentration level, with a concentration of body smells (bioeffluents) and other unwanted pollutants, it has a very sharp, acidic odour that is irritating to humans" (Persily, 1997). A CO_2 level higher than the outdoor level can be used as a tracer gas to study ventilation performance within a space and many school related studies (Aliboye et al., 2006; Rosbach et al., 2013; Satish et al., 2012) have widely used CO_2 measurements because of the advantage of requiring relatively simple equipments. However, these studies do not provide guidance on representative placement of CO_2 monitors (sensors), as there is inconsistency between the different measurement strategies used by researchers in selecting representative locations and the number of CO_2 sampling sensors needed in a space. Mahyuddin & Awbi, (2012) stated that the location of sensors largely depended on researchers' personal experiences.

Researchers suggest that the best position to locate CO_2 sensors was at seated head height (Jones & Kirby, 2012; Mumovic et al., 2009), and the breathing zone (Priyadarsini et al., 2022; Gao et al., 2014;) in a classroom. Commonly used measurement heights were, 0.6 m (Dias Pereira et al., 2014), 1.1 m (Bennett et al., 2019b; Bakó-Biró et al., 2012; Zeiler & Boxem, 2009; Mumovic et al., 2009;), 1.2 m (Priyadarsini et al., 2022; Mahyuddin, Awbi, & Alshitawi, 2014; Godwin & Batterman, 2007), 1.5 m (Priyadarsini et al., 2022; Rosbach et al., 2013; Geelen et al., 2008; Norbäck & Nordström, 2008; Lawrence & Braun, 2007; Katsoulas, 2002; Shendell et al., 2004; Chung & Hsu, 2001), and 1.8 m (Coley & Beisteiner, 2016; Mahyuddin, Awbi, & Alshitawi, 2014; Gao et al., 2014; Coley & Beisteiner, 2002) respectively.

Many of these authors suggest that CO_2 sensors should be located to avoid exposure to heat sources such as the sun and heating systems and away from windows which could influence the data values due to direct airflow, and measured CO_2 using a single sensor in one location. Though measurement heights of 1.1 m and 1.5 m at the center of the space were largely used in previous studies, a few studies such as Mahyuddin, Awbi, & Alshitawi, (2014) used 12 sensors, Zeiler & Boxem, (2009) used 14 sensors, and Godwin & Batterman, (2007) used 6 sensors. The most obvious reason for using multiple sensors is the differences in the objectives of these studies. Additionally, some researchers did not state the number of sensors used in their measurement protocol (Mi et al., 2006; Chung & Hsu, 2001; Mysen et al., 2005) and though a few others stated that their sensors were located centrally, they did not state the specific height of the sensors (Ferreira & Cardoso, 2014; Bartlett et al., 2004; Jones & Kirby, 2012; Grimsrud et al., 2006; Sekhar et al., 2003).

Majority of these studies were carried out in mechanically ventilated classrooms with limited information about CO_2 measurement protocols in naturally ventilated classrooms, and did not examine whether the use of a single sensor is representative of the CO_2 levels across a classroom. The variance in the number of sensors used in these previous studies and the different placement height (such as 1.1 m and 1.5 m) of the sensors within the space illustrates the challenges of establishing the most appropriate approach towards field measurement of CO_2 concentration, especially in occupied classrooms.

In reposne to improving ventilation to mitigate the transmission of COVID-19, many countries such as the United Kingdom, New Zealand, Ireland, Belgium, and the United States of America have rolled out CO_2 sensors in schools and public spaces. This is as a response to the application of CO_2 monitoring, which has been widely suggested during the pandemic to support active management of ventilation, aimed at minimizing infection risk.

In New Zealand, the Minitsry of Education (MoE) has rolled out CO_2 sensors to all schools as part of a ventilation self-assessment toolkit (Henry, 2021). The MoE is continuing to take a phased approach to deploying a one-point (single) multi-variable internal environmental monitoring device (also called data logger and sensors) to measure CO_2 levels, temperature, light, and relative humidity and sound levels in schools (MoE, 2022a). The later is aimed at developing a method for routine measurement of the environmental conditions of New Zealand's school building portfolio to collect hard data to inform investment decisions (MoE, 2022a).

To make sense of the readings from the CO_2 sensors, several countries have made recommendations on CO_2 concentration levels that translate to effective ventilation. In some cases, these are lower values than recommended in national building codes and some countries have also used highly visual display screens in some public spaces. However, there has not yet been any evaluation of the best place to locate these sensors in occupied spaces to be representative of the space, especially in school buildings which could be impacted by many factors, including occupancy and usage. Also, appropriate information and support that is specifically tailored to the group of users who will intervene in response to the CO_2 measurements is lacking.

Table 1 presents a high level summary of the CO_2 guidance in different countries in response to COVID-19, and shows that there is a common agreement across a range of countries that CO_2 levels under 800 ppm would translate to good ventilation.

Table 1

CO_2 guidance in different countries in response to COVID-19

Authors	Country/Organization	CO_2 Guidance
(DQLS, 2022; MoE, 2022b)	New Zealand	<800 ppm
(HPSC, 2021)	Ireland	800 ppm
(AIST, 2020)	Japan	<1500 ppm
(HCSP, 2022)	France	800 ppm
(IRK, 2020)	Germany	1000 ppm
(WHO, 2020, 2021)	World Health Organization	800 ppm
(CDC, 2021)	USA	800 ppm
(REHVA, 2022)	European Union	800 ppm
(ECDC, 2020)	European Union	800 - 1000 ppm

Though CO_2 monitoring is technically straightforward, it requires clear guidance to enable sensors to be used effectively by users to sustain better ventilation. In any occupied classroom, the number of CO_2 sensors, the placement of the sensors, and their calibration and maintenance are very important to obtaining reliable data. For example, the CO_2 concentration measured by a single sensor fixed on a wall may not be a true representation of the actual concentrations in the occupied space, if airflow from air conditioning systems, or drafts from windows flows directly over the sensor location, the measurements recorded will be artificially low. Hence, this study aims to investigate whether a one-point CO_2 sensor can predict the concentration across a classroom and where might be the best location for a one-point sensor.

This paper is an extended experiment that builds on an earlier work by (Ackley, 2021a; Ackley et al., 2020, 2021b, 2018), which investigated if a one-point sensor measurement could reveal the distribution of lighting and thermal performance across a space. While the previous studies focused only on the lighting and thermal variable, the specific objectives of this study are:

- To explore the adequacy of using a one-point CO_2 sensor to assess the ventilation performance of classrooms.
- To provide guidance on how to use a one-point CO_2 sensor to better express the room ventilation performance for large groups of school buildings.

Methodology

Prior to the COVID-19 pandemic, three typical classrooms in three schools with different environmental conditions and orientations were selected from the New Zealand Ministry of Education's (MoE) building portfolio for the case study. As reported in Ackley et al (2020 and 2021), the classrooms were naturally ventilated, with windows on two opposite walls and are typical building designs that are commonly found in many New Zealand schools. Using the MoE 'Smooth Sensor' monitors, all five environmental variables (lighting, temperature, humidity, sound and CO_2) were measured, but only the CO_2 result is reported in this paper. As shown in the case study classroom floor plans in Fig. 1, the goal was to compare the spatial relationship between the multiple horizontal measuring planes sensors (A1-3) positioned at a height of 0.8 m looking upwards with that of the vertical one-point sensors on each of the 4 walls (B1-4) positioned at a height of 1.5 m above the ground. A single external sensor was also placed at a height of 1.5 m in the outside covered corridor.

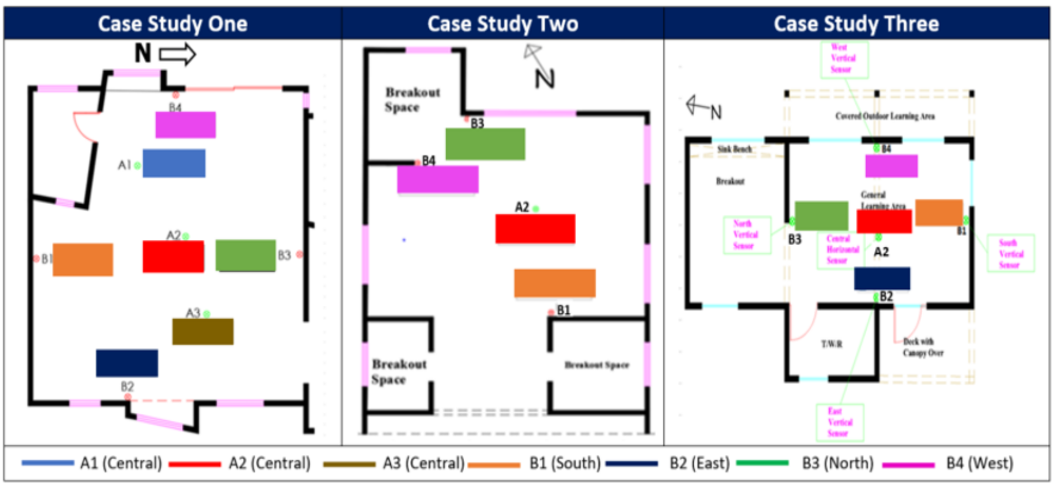


Fig. 1

Plan of case study classrooms showing orientation (A sensors horizontal, on the working plane; B sensors vertical, on adjacent wall) and colour annotation of the sensors

Line graphs, sparklines, ratio analysis and averages were used to analyse four days of data collected in each season (summer - case study one, autumn - case study one and two, and spring seasons - case study three). Line graphs were used to visually assess trends and patterns in the data, while sparklines (tiny graphical trend lines) were displayed on the floor plans of the spaces to enable a comparison of the spatial differences in data trends. Averages were used to assess the extent of variation between horizontal and vertical sensors and a ratio analysis (quantitative method) was carried out to measure how much a variable has changed between two measurements. Observations for one school day in each of the three case study classrooms were carried out using a pre-designed template to understand how the spaces were used by the occupants (the template included observations such as occupant's action to open and close windows, the number of occupants, break periods and the type of learning activities). The measurement interval was 10 seconds and data was analysed from 8 am to 3 pm for the school days. A three-step calibration procedure was used; (1) in-depth calibration of the sensors at the Building Research Association of New Zealand's (BRANZ) laboratory, (2) calibration of sensors in a systematic grid (sensors were placed in a horizontal surface and data compared with that of a research grade reference sensor), and (3) as shown in Fig. 2, sensors were paired and spot measurement calibration (comparing readings to that of the reference sensor) was carried out at the case study classrooms immediately after the sensors were deployed and before they were removed. The CO_2 measurement range was 300 to 5000 ppm (±0.2°C accuracy), temperature range was -40 to 125°C (±0.2°C accuracy) and humidity range was 0-100% (accuracy: ±3.0% of reading or ±50 ppm - whichever is greater).

Fig. 2
Image of horizontal (red rectangle) A sensors on the working plane and vertical (red rectangle) B sensors on the walls in case study one classroom

Results

School Days CO_2 Analysis

In Fig. 3, the school days were analysed to explore the relationship between horizontal measuring plane sensors and vertical wall sensors. CO_2 concentrations appear to rise and fall at different periods in a typical school day and follow a similar pattern in all three case studies and seasons. The CO_2 level rises from a base of about 410 ppm (external atmospheric CO_2 concentrations) to a peak of about 2,300 ppm. During the one day observation, a reference handheld CO_2 sensor was used to

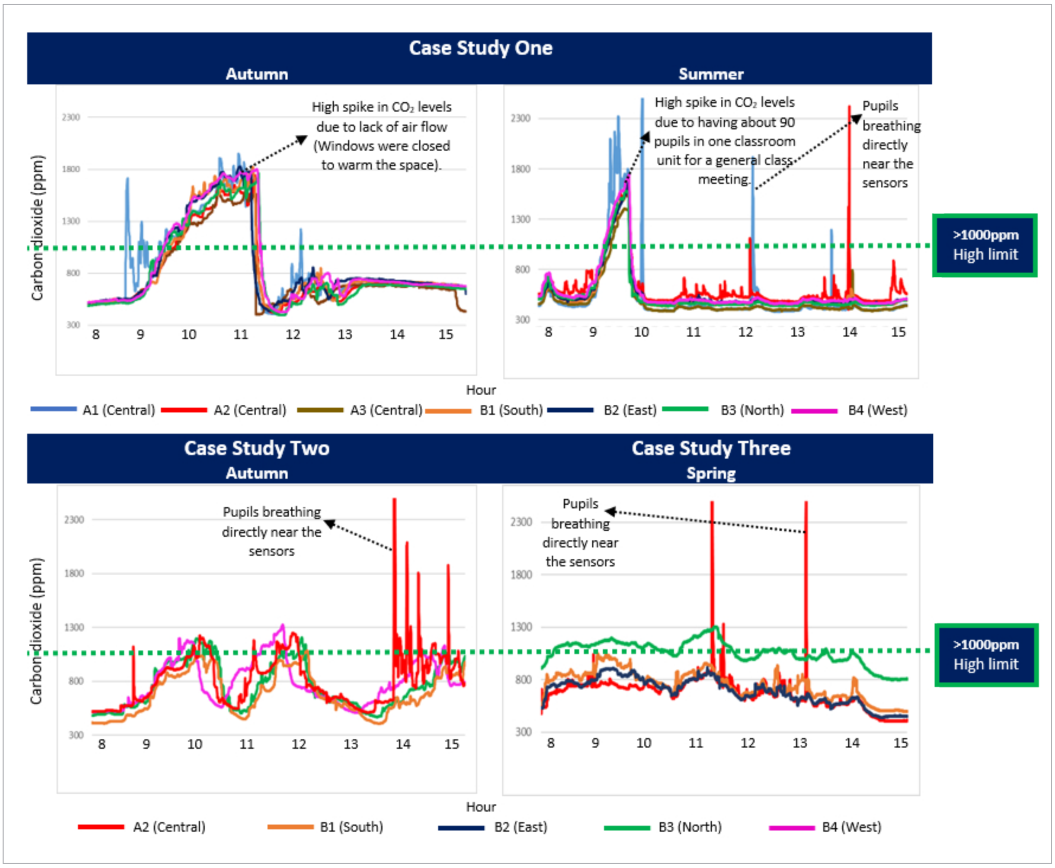


Fig. 3
Line graphs showing CO_2 trends between 8 am – 3 pm during school days (A sensors horizontal, on the working plane; B sensors vertical, on adjacent wall)

carry out spot measurements at different times of the school day. It was observed that the fluctuations in CO_2 levels was due to occupancy and the occupants' actions to opening and closing of doors and windows. As shown in case study one, the spikes in sensors A1 and A2 was due to the location of these sensors at the central area of the classroom and from the observation of space usage, students like to converge around the central area. These two sensors had the highest CO_2 levels at some point in time. For example, the summer line graph in case study one shows sudden spikes of high and low CO_2 levels at a point in time, while the autumn graph shows high levels of CO_2 in the morning hours which remained constant for a longer period. This illustrates that instances of window opening during the summer potentially reduced the CO_2 levels while the windows were closed for a longer period during autumn where heaters were used to warm up the space.

Though the line graph patterns show a relatively consistent rise and fall of CO_2 levels across sensor points, the trend indicates that there is a variation in CO_2 levels between horizontal measuring plane sensors and vertical wall sensors. There were periods of a sudden spike in CO_2 levels in sensors that were closer to occupants. For example, during spring in case study three, when central horizontal measuring plane sensor A2 recorded about 2300 ppm, vertical wall sensor (North) B3 recorded <1300 pm. Given that the rapid increase of CO_2 concentration was due to CO_2 generation (as a result of people breathing) and the rapid decreases are removal of those sources (probably opening windows and doors), these patterns indicate that under the influence of CO_2 sources there was a more obvious variation in CO_2 levels. The decrese in CO_2 levels when windows and doors were open for airflow affirms that CO_2 monitoring is a good indicator for assessing ventilation performance in classrooms.

In Fig. 4, the sparkline pattern also shows variations in CO_2 concentration across sensor points. For example, the horizontal plane sensors (A1-3) showed a spatial variation with the vertical wall

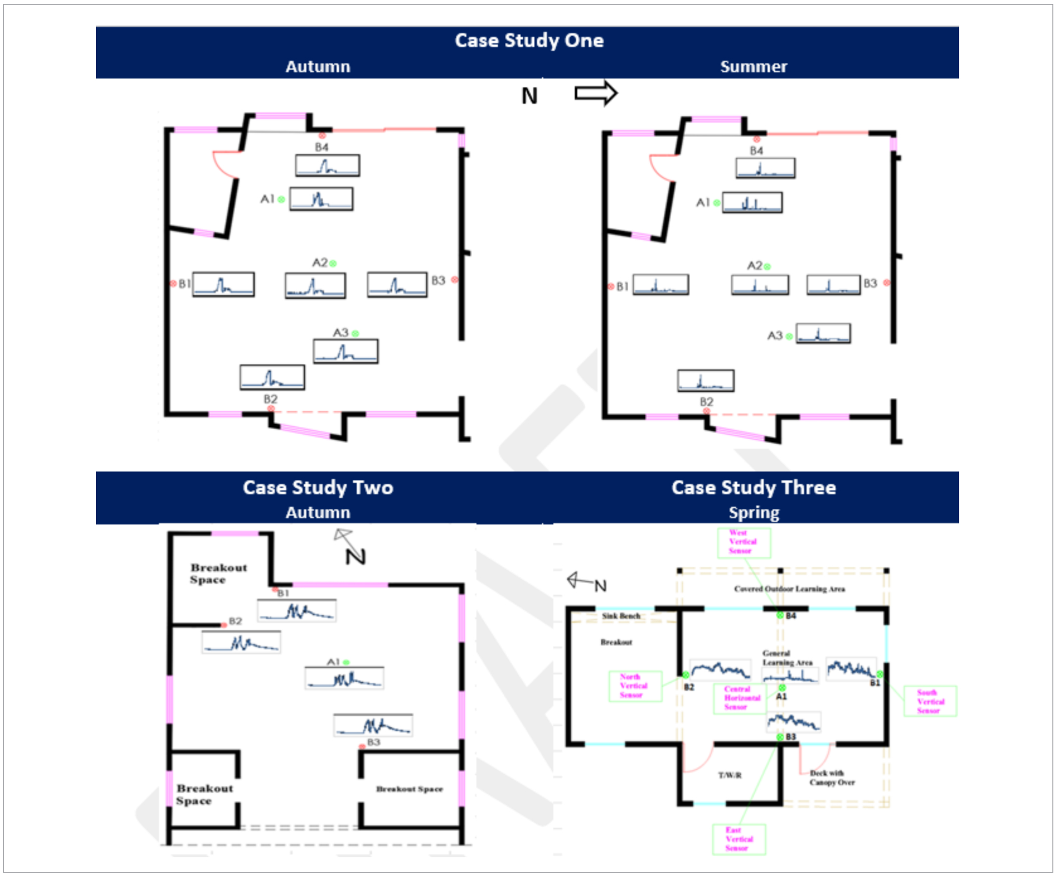


Fig. 4

Sparklines showing CO_2 visual patterns comparison between horizontal measuring plane (A) and vertical wall (B) sensors - 8 am to 3 pm in the school days sensors (B1-B4). This was more obvious during the summer in case study one and during spring in case study three. It was observed that some windows were usually opened during the teaching period and students tend to open and close windows when they feel warm or cold. Hence, it is indicative that the occupancy pattern and airflow within the space resulted in the temporal variance in CO_2 concentration across the space.

Carbon dioxide Comparative Ratio Analysis

In **Tables 2** to **4** and **Fig. 5** to **7** below, the values recorded on the central horizontal sensor A2 was divided by the values on the vertical wall sensors B1-B4 during school days. The frequency of the data was categorised into four bins depending on the ratio of change between the two compared variables and percentages were used to describe the fold change. The relationship between the horizontal plane and vertical wall sensors was for 80% of the time largely consistent around a ratio of 1.0 – 1.5, which indicated that a vertical wall sensor can reliably predict the CO_2 levels at the centre of a classroom. However, as reported above, during instances of higher CO_2 levels the ratio increased to 1.5 and could be higher at a point in time, which indicates an obvious variation in CO_2 at higher levels, compared to lower levels.

CO_2 levels spiked at some point in time, which is most likely due to occupancy and space usage, but the overall trends didn't compromise the large consistency in the ratio between the vertical and horizontal plane sensors. These trends suggest that provided the factors of CO_2 variability are taken into account, a vertical wall sensor can predict CO_2 levels at the centre of a space and can assist with the diagnosis of patterns when measuring CO_2 levels in many school buildings. The application of these findings in assessing ventilation performance is discussed further below.

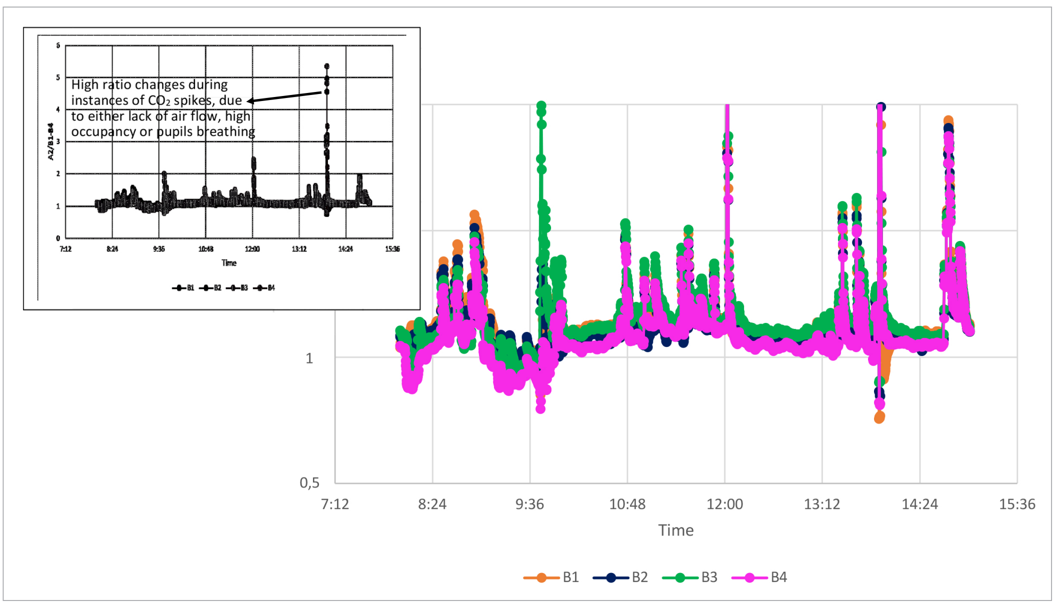
Table 2

Ratio Analysis comparing the relationship between CO_2 levels at the central horizontal sensor A2 with vertical wall sensors B1-4 respectively

Case Study One - Summer								
Bin	A2(Central)/B1(South)		A2(Central) /B2(East)		A2(Central) /B3(North)		A2(Central)/B4(West)	
	Frequency	Percentages	Frequency	Percentages	Frequency	Percentages	Frequency	Percentages
0.5 – 0.99	6	0%	0	0%	0	0%	50	2%
1.0 – 1.19	130	5%	87	3%	188	7%	319	13%
1.2 – 1.5	2334	93%	2399	95%	2278	90%	2121	84%
>1.5	53	2%	37	1%	57	2%	33	1%

Fig. 5

Comparison of ratio between horizontal and vertical sensors



Case Study Two - Autumn								
Bin	A2(Central)/B1(South)		A2(Central) /B2(East)		A2(Central) /B3(North)		A2(Central)/B4(West)	
	Frequency	Percentages	Frequency	Percentages	Frequency	Percentages	Frequency	Percentages
0.5 – 0.99	1743	74%	1959	83%	905	38%	1899	80%
1.0 – 1.19	612	26%	360	15%	1450	62%	456	19%
1.2 – 1.5	0	0%	27	1%	0	0%	0	0%
>1.5	0	0%	9	0%	0	0%	0	0%

Table 3

Ratio Analysis comparing the relationship between CO_2 levels at the central horizontal sensor A2 with vertical wall sensors B1-4 respectively

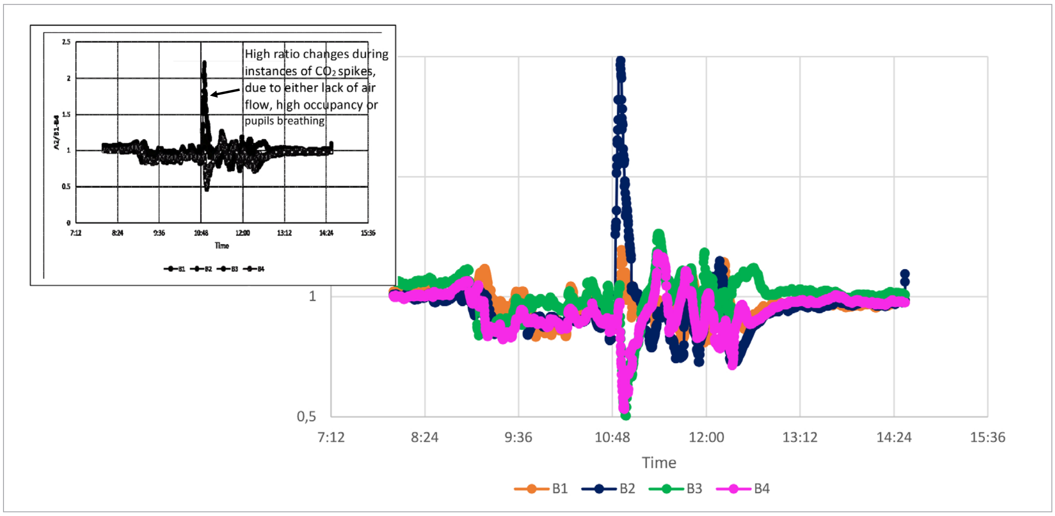


Fig. 6

Comparison of ratio between horizontal and vertical sensors

Case Study Three - Spring						
Bin	A2(Central)/B1(South)		A2(Central) /B2(East)		A2(Central) /B3(North)	
	Frequency	Percentages	Frequency	Percentages	Frequency	Percentages
0.5 – 0.99	1812	72%	1	0%	2490	99%
1.0 – 1.19	436	17%	1863	74%	13	1%
1.2 – 1.5	263	10%	645	26%	10	0%
>1.5	7	0%	7	0%	8	0%
More	3	0%	5	0%	0	0%

Table 4

Ratio Analysis comparing the relationship between CO_2 levels at the central horizontal sensor A2 with vertical wall sensors B1-4 respectively

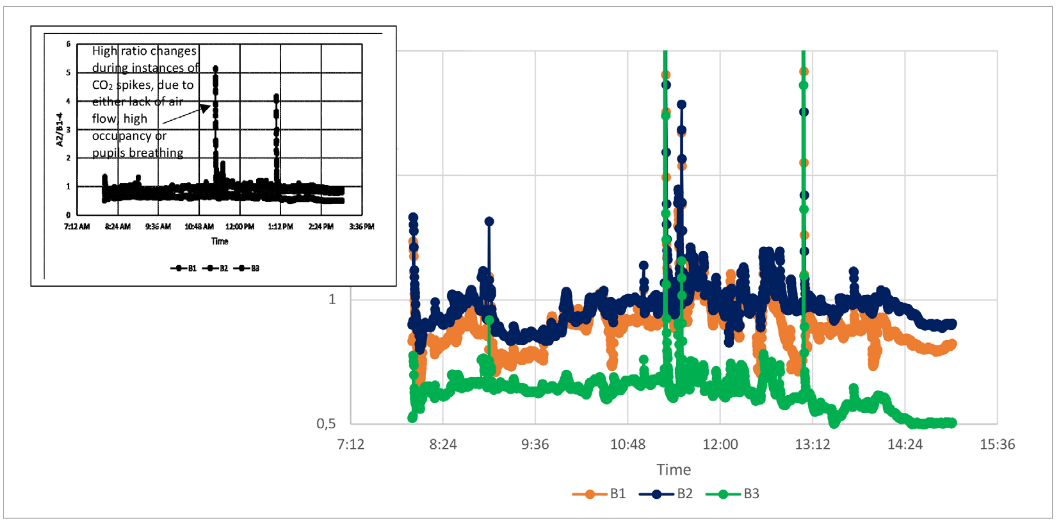


Fig. 7

Comparison of ratio between horizontal and vertical sensors

Comparison between Horizontal and Vertical Sensors Average CO_2 Levels

Table 5 shows the result for the school hours (8 am to 3 pm) in case study one. The goal of analysing the averages was to identify the possible range of variation between CO_2 concentrations across the various sensor points. Sensors A1-3 where the spatial horizontal measuring plane sensors while sensors B1-4 where the vertical wall sensors respectively, while sensor C1 was the external sensor located outside the building. The column annotated as "Diff" represented the calculation of the difference between sensor A2 (Central) and the vertical wall sensor that showed the least relationship to ascertain the level of variation between the sensor points.

The data generally shows that CO_2 variation between the horizontal measuring plane sensors and the vertical wall sensors were largely <100 ppm, which is relatively close to the instruments' accuracy of +/- 50 ppm. During the cold autumn season, there were variations in the levels of CO_2 when the classroom windows were closed to warm up the space. However, the difference becomes less pronounced during the summer (warmer) when the windows and doors in the classrooms were opened for cross ventilation. This illustrates that the sensors had more identical values, unless under the influence of CO_2 sources (someone breathing at the sensors) and actions of occupants to close and open their windows. Furthermore, CO_2 variations were also evident among different locations with same heights. For example, in case study one – autumn, and at 10 am, the average CO_2 concentration measured at sensor A1 was 1634 ppm, while that of sensors A2 and A3 were 1520 and 1452 ppm respectively. This indicates an uneven distribution of CO_2 even within the same horizontal measuring height.

Table 5

Average CO_2 levels in the school days from 8 am-3 pm

Case Study One - Autumn

The grey column is the difference between sensor (A2) and the vertical sensor with the least correlation in the ratio analysis

Hour	Central A1 (ppm)	Central A2 (ppm)	Central A3 (ppm)	South B1 (ppm)	East B2 (ppm)	North B3 (ppm)	West B4 (ppm)	Diff (ppm)	External C1 (ppm)
8 am	682	554	543	542	555	520	546	-1	533
9 am	1140	1025	1011	1064	1133	1107	1148	-108	530
10 am	1634	1520	1452	1633	1674	1549	1682	-154	528
11 am	673	722	704	755	666	825	849	56	534
12 pm	680	605	614	646	693	588	669	-88	533
1 pm	692	693	682	722	738	672	725	-45	523
2 pm	676	677	630	700	696	672	690	-19	523
3 pm	452	478	423	478	508	480	516	-30	536

Case Study One - Summer

The grey column is the difference between sensor (A2) and the vertical sensor with the least correlation in the ratio analysis

Hour	Central A1 (ppm)	Central A2 (ppm)	Central A3 (ppm)	South B1 (ppm)	East B2 (ppm)	North B3 (ppm)	West B4 (ppm)	Diff (ppm)	External C1 (ppm)
8 am	473	618	486	526	538	555	582	80	440
9 am	1180	1031	886	1001	995	984	1092	36	443
10 am	412	515	405	456	469	453	482	46	401
11 am	416	546	409	464	479	454	477	67	402
12 pm	449	511	407	461	460	448	475	51	401
1 pm	436	545	424	475	476	457	492	69	401
2 pm	410	536	408	463	471	460	475	65	402
3 pm	453	588	453	533	543	504	518	45	400

Summariliy, the results of all three case studies and across all seasons indicated that under the influence of CO_2 sources there is non-uniformity of CO_2 concentration between horizontal measuring plane sensors and the vertical wall sensors. The analysis showed that the variability of CO_2 concentration between horizontal measuring plane sensors located at the center of the classroom and vertical wall sensors was largely <100 ppm. This variation was observed to be due to the proximity of groups of CO_2 sources (such as students) and lack of air movement in relation to the sensors' position. These findings are consistent with a study by Mahyuddin & Awbi, (2010) which found that "in the spatial distribution of CO_2, the difference between the maximum and the minimum concentration was in the range of 76-123ppm". ASTM, (2009) suggested that when measuring multiple CO_2 points, the monitored points should differ by less than 10% of the average CO_2 concentration in the building.

In the literature, researchers mostly preferred measurement heights of 1.1 m and 1.5 m at the middle of a zone and having one sampling point in a room at a representative location. However, when CO_2 concentration is non-uniform as evident from the analysis above, there will be deviations from the average expected CO_2 levels across a space. The results of this study showed that higher levels of CO_2 concentration were also found on the wall mounted sensors (1.5 m), which were not within the students breathing zone. The horizontal plane sensors, which were within the students breathing zone also showed a variance in CO_2 concentration at some point in time (and even among different locations with the same height). Mahyuddin et al., (2014) experiment on the spatial distribution of CO_2 levels across different heights indicated that even at higher levels in a room above 1.0 m and 1.2 m, there were higher CO_2 concentration values. They suggested that deviations from the average measured values could become large when there is a significant variation in CO_2 concentration levels.

Therefore, it can be inferred that when measuring CO_2 concentration at scale in buildings to assess ventilation performance, a ±100 ppm temporal non-uniform variation of CO_2 concentration is not so large, given that it might be within the acceptable CO_2 concentration limit and is highly unlikely to constitute a risk to health in the range of values found in this paper. When measuring CO_2 levels at scale in buildings to identify good and poorly ventilated spaces, **Fig. 8** uses a typical simple form classroom typology to illustrate and provide guidance on how to use a one-point sensor to measure CO_2 levels in a large property portfolio.

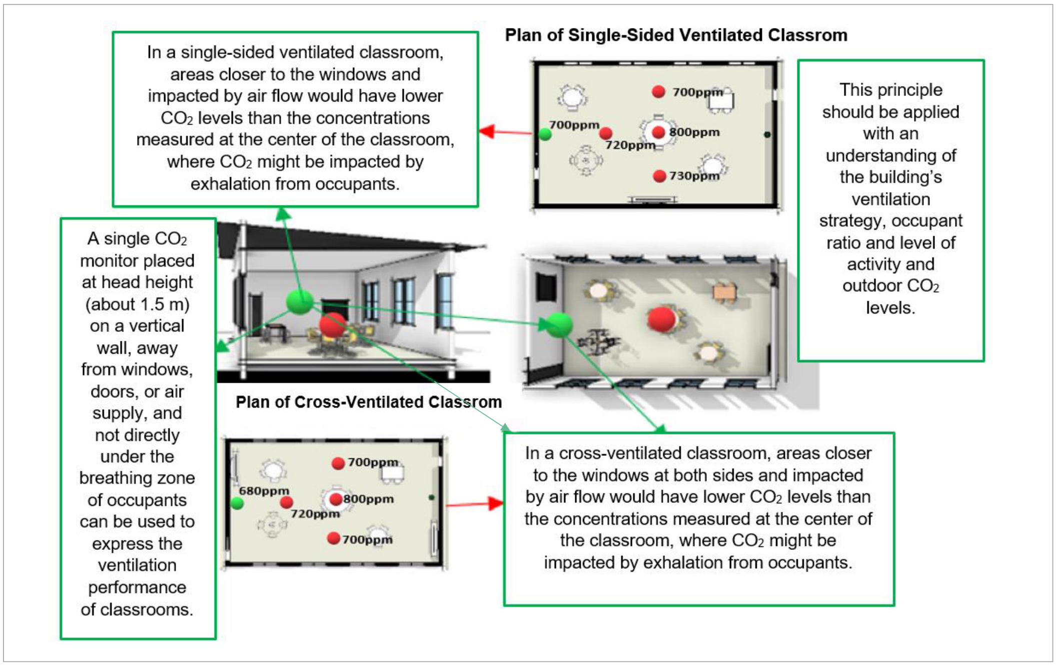


Fig. 8
Illustration on how to use a one-point sensor to measure CO_2 at scale in many buildings

Conclusion

This study has showed that due to non-uniform air-flow, occupancy ratio and exhalation, activity levels (breathing near horizontal sensors placed on tables showed instances of a high spike in CO_2 levels) and external conditions such as outdoor CO_2 levels, there were varying levels of CO_2 concentration from location to location in the case study classrooms. The extent of variation was about ±100 ppm, and this value could vary from one part of a space to another especially during the cold days/season when the windows are closed to keep temperature within acceptable levels for teaching. The variation becomes less pronounced during the warm summer season when occupants in the naturally ventilated classrooms frequently opened their windows for air flow.

In any occupied real-world classroom, it can be practically impossible to measure reliable CO_2 concentration on the working plane or at the central occupied zone without the occupants effect and obstruction of the functions of the space. Also, it might not be cost effective (in a large property portfolio) and could be practically difficult to deploy multiple CO_2 sensors in each space, due to the nature of the day to day activities carried out in the classroom. Hence, the use of a one-point sensor will suffice.

To explore the adequacy of using a one-point sensor to better express the ventilation performance in classrooms, this study used observations and physical measurements of CO_2 in three typical New Zealand classrooms and the main conclusions are that:

- Measuring CO_2 using a one-point sensor at a wall height of about 1.5 m and not relatively close to people (avoid the occupant's effects) can be useful in assessing ventilation performance. This measurement should be carried out in conjunction with the understanding of the sources of CO_2 and their distribution.
- However, using more than one sensor to measure CO_2 in an occupied space could significantly improve the accuracy of determining the average CO_2 concentration that is representative of the space.
- Given that many factors affect the effectiveness of natural ventilation (such as being dependent on human behaviour and ambient conditions), it can be inferred that the one-point CO_2 measurement protocol above could be applicable to mechanically ventilated classrooms that have a more consistent and controlled ventilation performance.

Additionally, in respect to making sense of CO_2 readings, the following is recommended:

- To understand the readings, a consistent CO_2 value less than 800 ppm is an indication that an indoor space is well ventilated and readings consistently higher than 1500 ppm are likely to indicate overcrowding or poor ventilation and requires actions to be taken to lower the levels.
- Continuous CO_2 monitoring is valuable because it can help asset managers to easily identify ventilation issues and occupants to actively manage existing ventilation including balancing the need for good ventilation alongside thermal comfort, moisture, energy use and noise control.

Due to the limited evidence-base on the effectiveness of monitoring CO_2 and other indoor air quality elements, further research and assessment in practice is required. But this study will assist architects, engineers, policy makers, and building scientist to understand how they might use limited number of sensors for routine prediction of ventilation performance in classrooms. The same process could be used, possibly with some modifications in any large property portfolio to prioritise ventilation remediation works.

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