UNIVERSITY OF BRITISH COLUMBIA SUSTAINABLE BUILDING SCIENCES PROGRAM

Impacts of Green Walls on Indoor Environmental Quality

CIVL592A

Helen Brennek and Leon Yuen, in association with Perkins + Will Architects

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Executive Summary

This project was taken on as part of the Sustainable Building Sciences Program and UBC. Indoor environmental quality impacts of green walls are a relatively new area of study, and data detailing their effects in Vancouver's climate are scarce or nonexistent. Therefore, Perkins and Will Architects suggested a study be completed on the green wall in the firm's Vancouver office.

This project investigated the impacts green walls have on indoor environmental quality in Vancouver's moderate and humid climate. In particular, Perkins and Will would like to be able to reference this study when providing council to clients who are interested in green wall installations. Having scientific data specific to Vancouver will add further confidence to recommendations made by the firm, and enable them to draw on specific observations made within their own office. Indoor air quality is influenced by a variety of factors. This study examined the following aspects of indoor air quality:

1. Temperature gradient up the wall, compared with the temperature gradient outside the wall at similar heights.
2. Humidity gradient between the wall and other office locations
3. VOC levels at the wall and near common VOC sources
4. Carbon dioxide gradients between the wall and other office locations

Positive impacts could not be confirmed due to project constraints, but no detrimental effects on the office appear to be resulting from the green wall. All parameters measured indicated a healthy and comfortable indoor environment, meeting the relevant standards.

Future studies would be most effective if focused on active green walls functioning as bio-filters, or static green walls in locations upstream of human occupancy or in spaces where air is recirculating. Such studies should also investigate potential increases in endotoxins, and should include measurements before the installation of the wall in order to allow quantifiable impacts to be determined.

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Introduction

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Objective and Scope

This project investigated the impacts green walls have on indoor environmental quality in Vancouver's moderate and humid climate. In particular, Perkins and Will would like to be able to reference this study when providing council to clients who are interested in green wall installations. Having scientific data specific to Vancouver will add further confidence to recommendations made by the firm, and enable them to draw on specific observations made within their own office.

Green walls may impact indoor environmental quality in a variety of ways. In determining scope for this project, the following areas of impact were considered:

- Psychology
- Acoustics
- Air quality

Psychological impacts of the green wall could have considered aspects such as employee satisfaction and productivity. This area of research was ruled out due to time constraints and expertise areas of the project team. It was also determined that without the ability to run tests prior to the green wall being installed, acoustics would be exceedingly difficult to study. The client expressed the greatest interest in air quality and the team was best equipped to address this interest. Therefore, the final scope included only measurements related to indoor air quality as opposed to the entire indoor environment.

Indoor air quality is influenced by a variety of factors. The factors chosen for this study include the following.

- Temperature
- Humidity
- Volatile organic compound concentration
- Carbon dioxide concentration

Project Description

The Wall

This study will examine the impacts in air quality in the Perkins and Will Vancouver office as a result of a static green wall mounted on the back wall of the atrium. The wall is 30 feet and 6 inches high and 8 feet wide. It contains over 1000 individual plants composed of over 45 species. The wall was designed and installed by Green over Grey, a company which uses a patented anchoring system for the plants. The wall is irrigated at all times and requires monthly maintenance (Green over Grey, 2012).

Parameters of Interest

This study examined the following aspects of indoor air quality:

1. Temperature gradient up the wall, comparing it with the temperature gradient outside the wall at similar heights.
2. Humidity gradient between the wall and other office locations
3. VOC levels at the wall and near common VOC sources
4. Carbon dioxide gradients between the wall and other office locations

Background

Temperature

While building temperature alone does not directly impact Sick Building Syndrome or human health directly, pathogens may replicate faster and humidity can be increased at higher temperatures. Therefore, as temperature increases, likelihoods of propagating molds, fungi, and other irritants also increase.

Temperature is also a concern as it is a major contributor to thermal comfort of building occupants. For HVAC design in future buildings which will employ green walls, it will be useful to know how building temperature is impacted by the presence of such a wall so designs can be adapted accordingly. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) recommends that building temperature remain between 20 and 28 degrees Celsius, with considerations for humidity (ASHRAE, 2004).

Humidity

Humidity can have significant impacts on human health and comfort indoors. Where Sick Building Syndrome is concerned, high levels of humidity may increase off-gassing of air pollutant particulate from building furnishings and finishes (Baugman & Arens, 1996).

The spread and growth of pathogens as a result of excessive humidity is also a major concern. It is possible that installation of a 244 square foot irrigated wall may increase indoor humidity such that recommended limits are exceeded and condensate forms on surfaces, increasing bacteria, molds, and fungi growth which can make people ill and cause allergic reactions. ASHRAE recommends that the humidity ratio never exceed 0.012 indoors (ASHRAE, 2004). At a dry bulb temperature of 20 degrees Celsius, for example, this amounts to approximately 82% relative humidity. Studies have shown that humidity impacts human health and pathogen growth in the following ways:

- <40% RH
    - Exhaled pathogens dry up quickly in the air and become easily airborne, allowing them to be inhaled by others and spreading illness
    - No lower limit actually exists so this range is within standards
- 40%RH – 70%RH

    - Exhaled pathogens are weighed down by moisture in the air, discouraging inhalation by others. This is the recommended range.
- >70%RH
    - High moisture content in the air collects on surfaces as condensate, encouraging mold, fungi, and bacterial growth (Bartlett, 2013)
    - Leads to illness, respiratory issues such as asthma, allergic reactions (Arundel, Sterling, Biggin, & Sterling, 1986).

Results will, therefore, be compared to these ranges and benchmarks.

Volatile Organic Compounds

Volatile organic compounds (VOC)s are a form of air pollutant commonly found in the indoor environment. Building materials such a manufactured wood, carpeting and paint emit VOCs. Photocopiers, printers, electronics, pesticides and cleaning agents are some examples of VOC sources from building occupants. Indoor VOC concentration is a measure of health risks inside buildings and high concentration level is directly linked to sick building syndrome (EPA, 1991) (Andersson, et al., 1997) (Norback, Michel, & Widstrom, Indoor air quality and personal factors related to sick building syndrome, 1990) Some of the short term health effects includes:

- eye, nose and throat irritation
- headaches
- loss of coordination
- nausea
- damage to liver, kidney and central nervous system (EPA, 2012)

Exposure to formaldehyde also has carcinogenic effect on humans (Rugina, Lupu, Neamtiu, Neagu, Dumitrascu, & Gurzau, 2011). Although VOCs have been proven to have adverse impacts on humans, no regulatory limits or precise guidance have been set for indoor VOC concentration levels with the exception of formaldehyde which has a ceiling limit of 1 ppm and a 8-hour work shift average of 0.3 ppm. However, low VOC concentration is often a characteristic of sustainable buildings. LEED awards credits under the category of indoor environment quality if the selected building materials pass the emission chamber tests conducted in laboratory for low VOC emission (Oppl & Augustin, 2012). Other sustainable building codes such as BREEAM also encourage the use of low emitting products.

Based on studies done by Dr. Darlington at the University of Guelph, active bio-filtration green walls have been shown to reduce the concentration of total VOC and formaldehyde (Darlington, Chan, Malloch, Pilger, & Dixon, 2000) (Darlington, Dat, & Dixon, 2001). VOC concentration is also reduced in the presence of a small scale bio-wall according to a UBC study (Curtis, Mckeown, & Stuart, 2012). On the other hand, plants are also known to produce VOCs and emit micro-spores into the environment. The influence of passive green wall on VOC is less understood. Since plants known to remove VOCs have been selected for the green wall at Perkins and Will office, the effects may be quantified through studies such as this one.

Carbon Dioxide

The recommended safety limit of CO_2 concentration in the workplace is 5000 ppm, much higher than the typical indoor concentration level (Prill, 2000). While CO_2 does not have a serious health effect on humans, exposure to high concentration level can cause headaches, tiredness and drowsiness (Norback, Nordstrom, & Zhao, 2013). CO_2 concentration is mainly used as an indicator of ventilation system effectiveness - high CO_2 concentration implies that the ventilation rate is too low in the building. As a result, CO_2 concentration is often associated with health related issues and indoor air quality (Seppanen, Fisk, & Mendell, 1999). ASHRAE standard 62 recommends a ventilation rate of 20 cubic feet per minute per person which corresponds to a CO_2 concentration of 800 ppm (ASHRAE, 2001). The standard also suggests the indoor-outdoor differential to be kept below 600 ppm.

Plants consume CO_2 and produce oxygen in the photosynthesis process. Previous study of a passive green wall at UBC has shown a 13% reduction in CO_2 concentration (Curtis, Mckeown, & Stuart, 2012). This study measured CO_2 concentrations throughout the office to characterize the ventilation system, which is mainly driven naturally by the stack effect in the atrium.

Method

Instrumentation and Calibration

The continuous temperature on the green wall was measured using 12 T-type thermocouples. The thermocouples were calibrated at the CIRS lab in UBC as part of a prior study. Each thermocouple is wired to a data acquisition device connected to a PC. The data is logged on the PC using the TracerDAQ software.

The Q-Trak Plus IAQ Monitor 8552 was used to measure the temperature, humidity and CO_2 concentration level within the office. The handheld instrument implements a non-dispersive infrared (NDIR) detection technique which correlates the intensity of IR light absorbed by CO_2 in the air to the CO_2 concentration. The detectable range of the instrument is 0 to 5000 ppm with an accuracy of 3% + 50 ppm (TSI, 2006). The device was calibrated by the manufacturer prior to the start of the project.

VOC concentration was measured with the handheld ppbRAE plus instrument, which was also recently calibrated by the manufacturer. The device uses a photo-ionization technique which ionizes the VOCs in sample air with a UV light source. The charge of the ionized air is measured with a detector which is a function of the VOC concentration. The ppbRAE plus has a limit has a detection limit for the device is 1 - 9999 ppb (Rae Systems, 2002).

Spot measurement and continuous measurement of VOC, CO_2, humidity and temperature were taken at various locations throughout the office. The location selection and instrument placement will be described in detail below.

Test Setup

Spatial Gradient

To measure the spatial distribution on the ground floor, spot measurements were made at approximate twelve foot intervals starting from the atrium and extending into the office space. The handheld instruments were placed on a rolling chair to maintain a constant height for all the test point. The integration time was set to one minute, and five minutes of data were collected and averaged for each spot measurement to minimize the effect of instantaneous office activity on the reading. The purpose of these measurements was to observe the spatial differences in temperature, humidity, VOC and CO_2 which can potentially be attributed to the presence of the green wall. Four gradient lines were established, labelled A, B, C and D in Figure 1. Gradient A and B extended into the office area where most of the employees' desks are located. Gradient C was directly perpendicular to the face of the wall and extended towards the washroom. Finally, gradient D extended towards the entrance of the office.

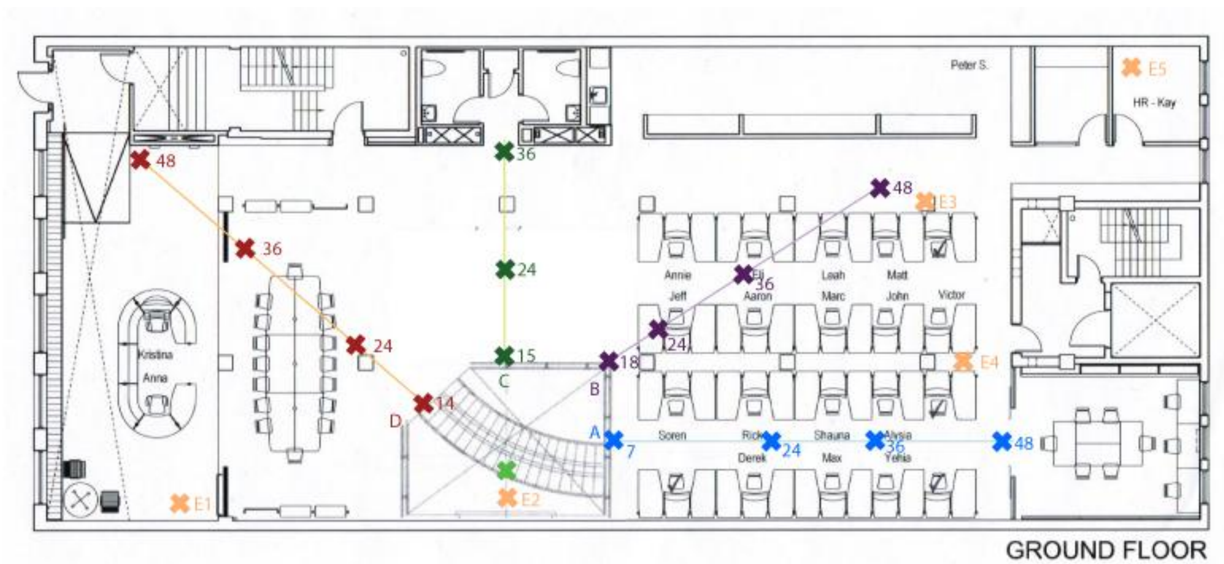

Figure 1. Floor plan for spatial gradient - Light orange: continuous measurements - Other colours: spot measurement

Twenty-four to 36 hours of continuous data were collected at various locations within the office indicated by the light orange 'X's in Figure 1. The main purpose of these tests was to determine the peaks and fluctuations of humidity, CO_2 and VOC levels on a typical workday at different regions of the office. Point E2 was directly in front of the green wall which has the potential to absorb VOC and CO_2 and contribute humidity. Point E3 and E4 were in the office area where CO_2 and VOC were expected to be generated. Comparing the continuous data between these locations was used to indicate the long term overall influence of the green wall. Point E1 was located near the reception desk, away from the office and the green wall. This was used as a secondary reference point. An extra set of data was collected in the Human Resources office upon request and is shown as point E5 in Figure 1. Staff in the HR office reported developing a cough after prolonged time in the office.

Vertical Gradient

The temperature gradient along the height of the green wall was recorded using data-logging thermocouples. The goal was to assess the thermal impact of the green wall on the office environment. Because the green wall was situated in a naturally ventilated atrium, the cooling effect of the wall was of interest. The thermocouples were hooked directly onto the plants of the green wall with sensing wires suspended in air. The first set was placed at one foot from the ground of the basement level. The rest of the thermocouples were placed approximately every three feet up to fifteen feet high. Figure 2 indicates the location of the thermocouples. The initial project plan was to install thermocouples along the full height of the wall with the support of the Green Over Grey maintenance crew to place the higher ones. However, a meeting with the Green Over Grey maintenance crew could not be scheduled within the timeline of this project so the thermocouples could only be placed within the reach of a ladder. A second set of thermocouples was placed on the concrete wall roughly four feet away from the green wall measurement points at the same height. The range of green wall cooling effect can be characterized by comparing the two sets of measurement data.

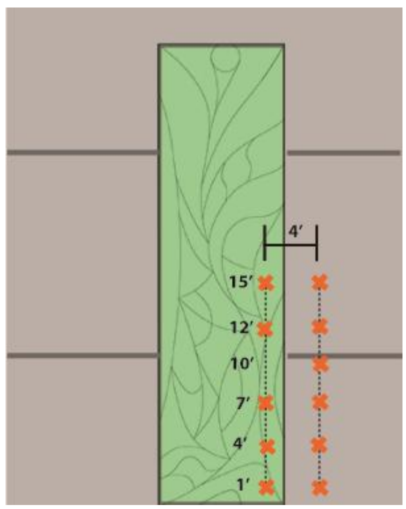

Figure 2. Front view of the green wall - the marks indicate the location of thermocouples

Results

Temperature

The temperature on the green wall was measured continuously for three days. The distribution of data shown in Figure 3 demonstrates a warming gradient up the wall. This is as expected, since heat rises, and demonstrates the effectiveness of the testing setup. Average temperatures at the different heights can be seen in Table 1.

Table 1. Temperature profiles at different heights up the green wall.

Height (ft)	Mean (°C)	Standard Deviation (°C)
15	20.96	1.07
12	20.44	1.02
7	20.18	1.20
4	19.79	0.98
1	19.01	0.78

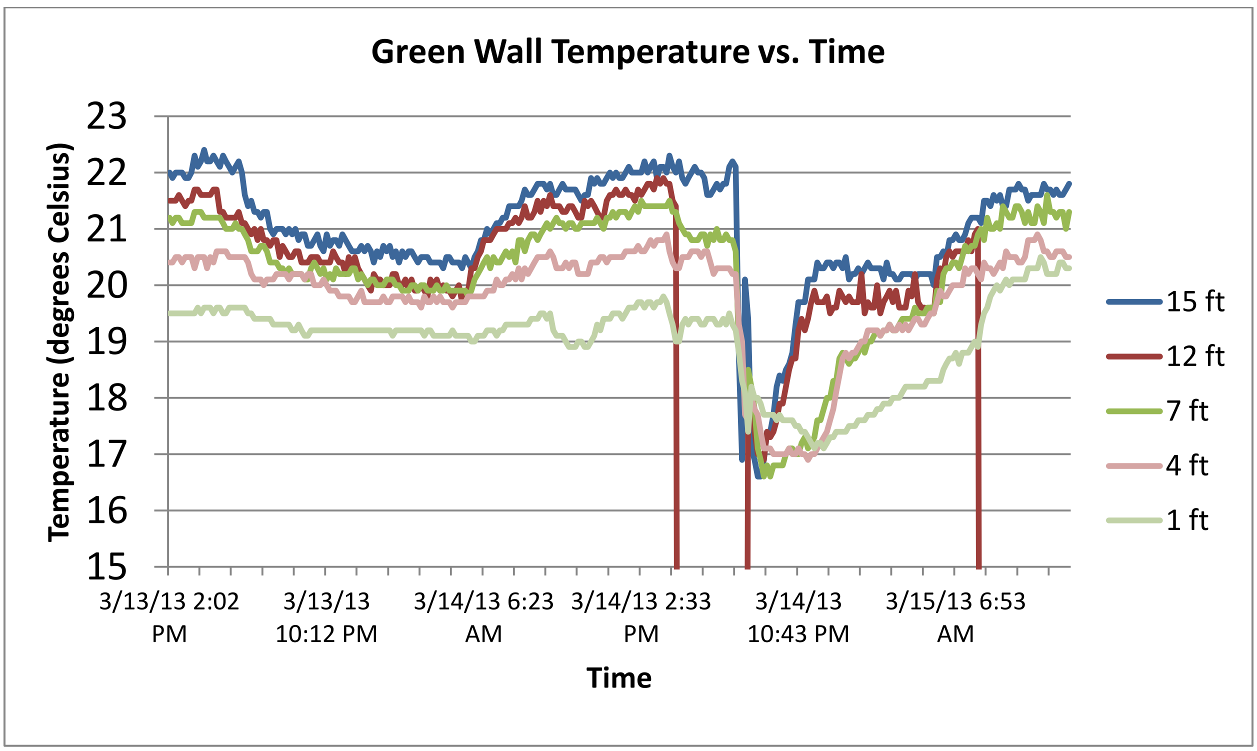

Figure 3. Green wall temperature as a function of time for approximately a three day period

While temperature was being measured on the wall, a control data set was also being measured a short distance away. Figure 4 shows the comparison between control and green wall temperatures. Green wall temperatures were approximately 1.2°C lower than the control temperatures. This implies that the green wall has a cooling effect, which is expected due to latent heat loss as a result of the irrigation system. However, the control system was a short distance away and, except for a short period during the second day of testing when it is believed that the green wall maintenance team watered the wall, temperatures in this location were within ASHRAE thermal comfort limits.

Table 2. Mean temperatures and average deviations for continuous measurement of the green wall and control gradients

	Mean (°C)	Standard Deviation (°C)
Green Wall	20.1	1.2
Control	21.2	0.67

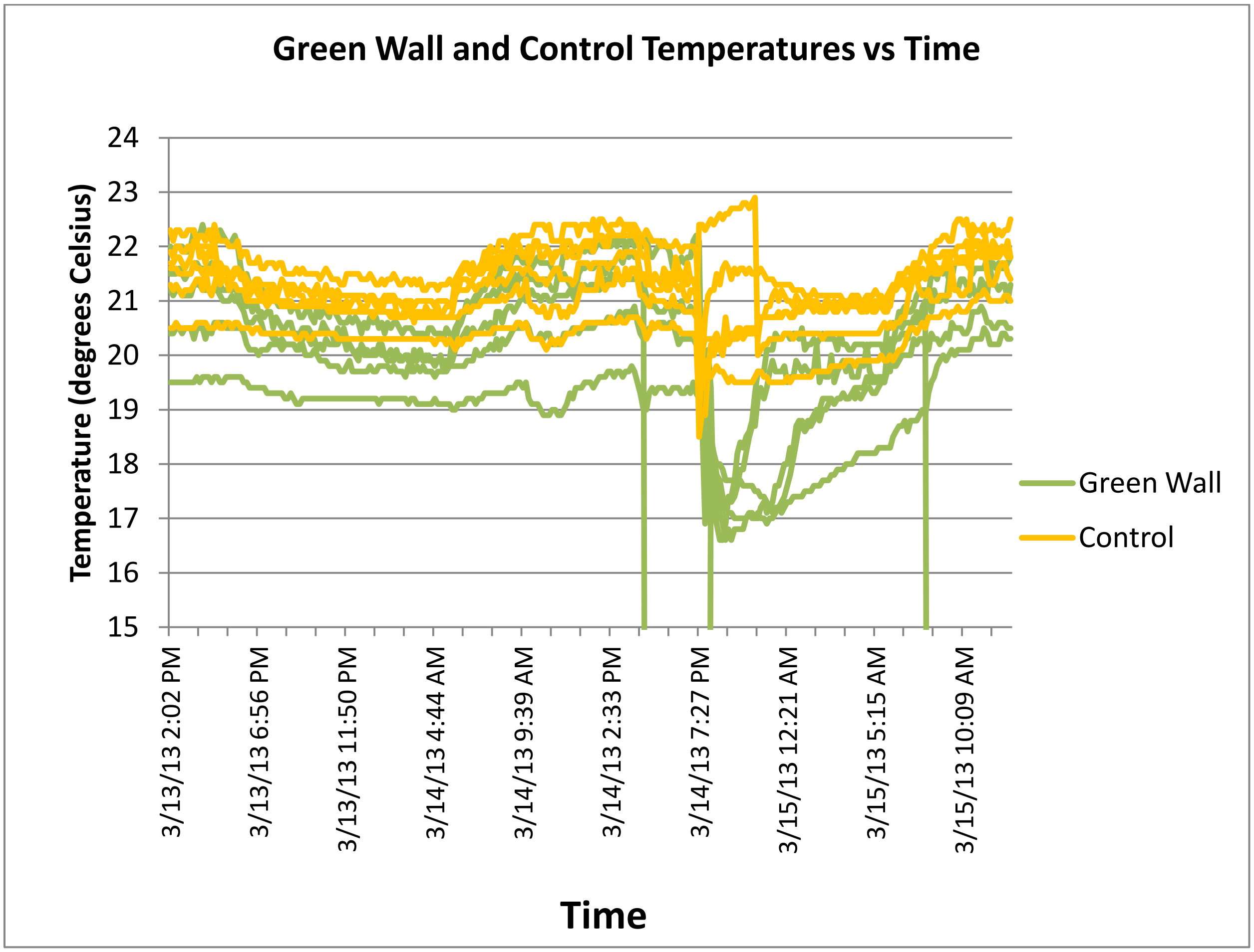

Figure 4. Green wall and control temperatures as a function of time

Humidity

The continuous humidity measurement for the Human Resources office is shown below in Figure 5. Relative humidity varies in an inversely proportional manner relative to temperature, as is expected if the level of moisture in the air is approximately constant but temperature is changing (for example, as a result of the room being occupied or electronics being turned on). The graph is relatively smooth until working hours begin around 8am, followed by peaks and valleys reflecting times when the door may have been closed or meetings held in the room. Around 6:00pm the temperature subsides and relative humidity increases as a result of the staff leaving.

Table 3. Statistics for continuous relative humidity and temperature measurements in the Human Resources office

	Mean	Standard Deviation	Minimum	Maximum
Temperature	21.3°C	1.8°C	19.4°C	26.0°C
Relative humidity %	43.2%	2.6%	36.3%	63.7%

The maximum humidity of 63.7% was well under the ASHRAE upper limit. Relative humidity did drop slightly below the target range of 40-70% during times when the temperature in the office was particularly high.

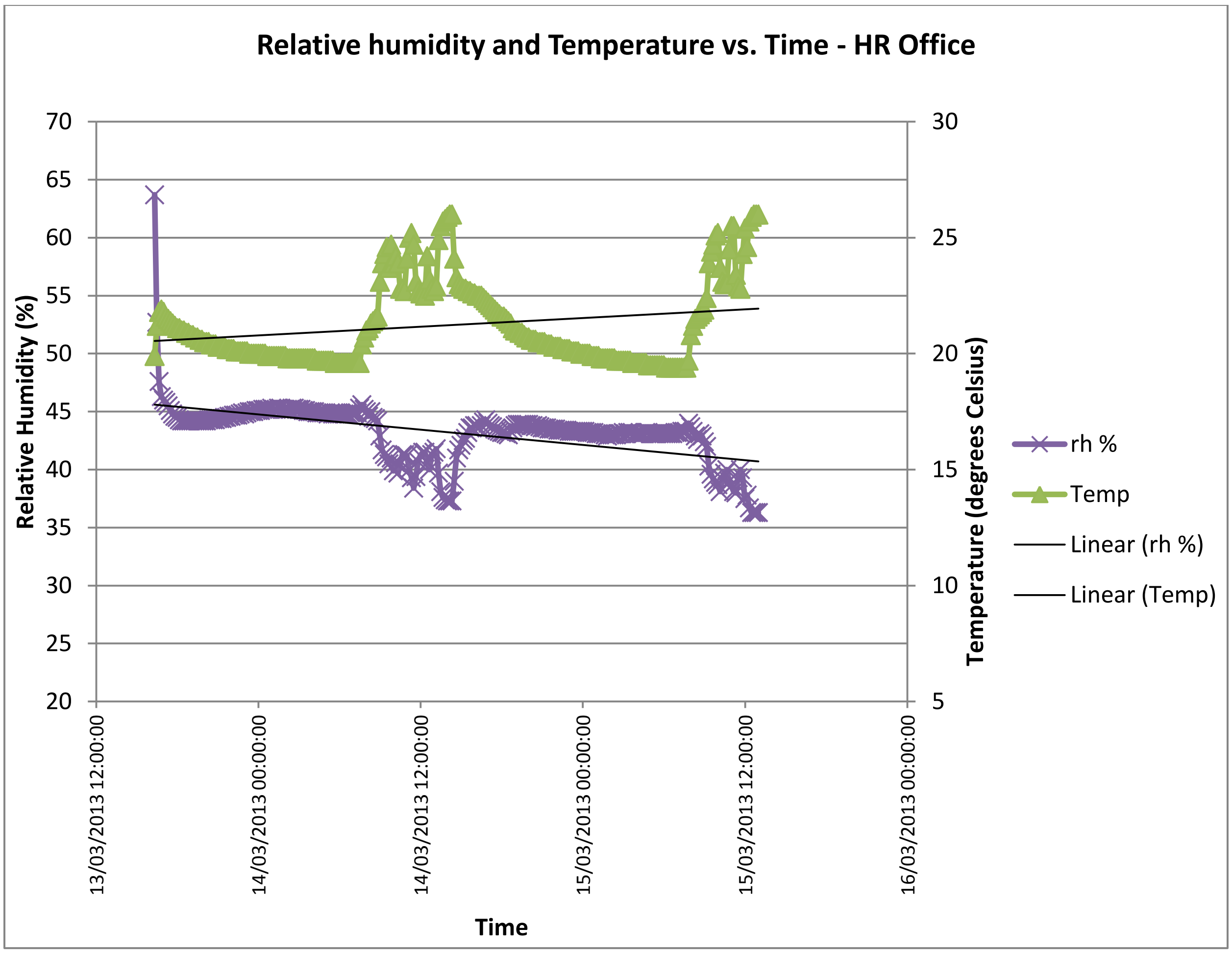

Figure 5. Relative humidity and temperature over a three day period, measured in the Human Resources office.

The continuous relative humidity measurement taken at the back office can be seen in Figure 6. This set of relative humidity data showed a very different pattern relative to temperature, though the overall trend in humidity was inversely proportional to temperature as in the previous data set. The humidity in this space stayed within the healthy range and ASHRAE thermal comfort standard throughout the test period, as is shown in Table 4.

Table 4. Statistics for continuous relative humidity and temperature measurements at the back of the main office area.

	Mean	Standard Deviation	Minimum	Maximum
Temperature	21.9°C	0.38°C	21.4°C	23.1°C
Relative humidity %	43.8%	1.6%	40.2%	46.8%

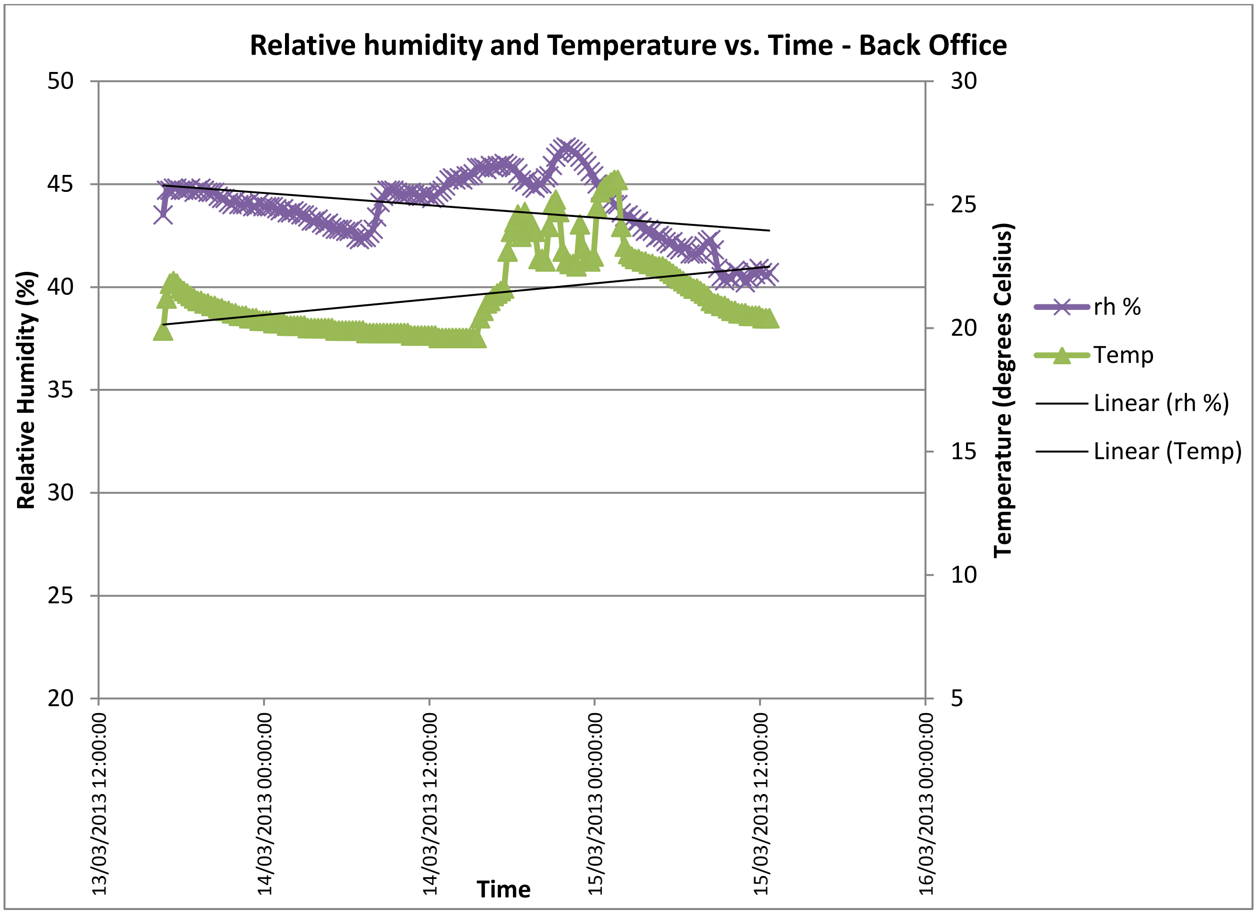

Figure 6. Relative humidity and temperature as a function of time over a three day period at the back of the main office area.

Lastly, instantaneous measurements were taken of the relative humidity and temperature along gradients A, B, C, and D. These measurements are shown in Figure 7. Gradient D showed relative humidity increasing along with distance from the green wall. This is counter to what may be expected if the irrigation system in the green wall were humidifying the space. Gradients A, B, and C showed very little change between the green wall and the end points, with a very slight increase in humidity at greater distances from the wall for the former two.

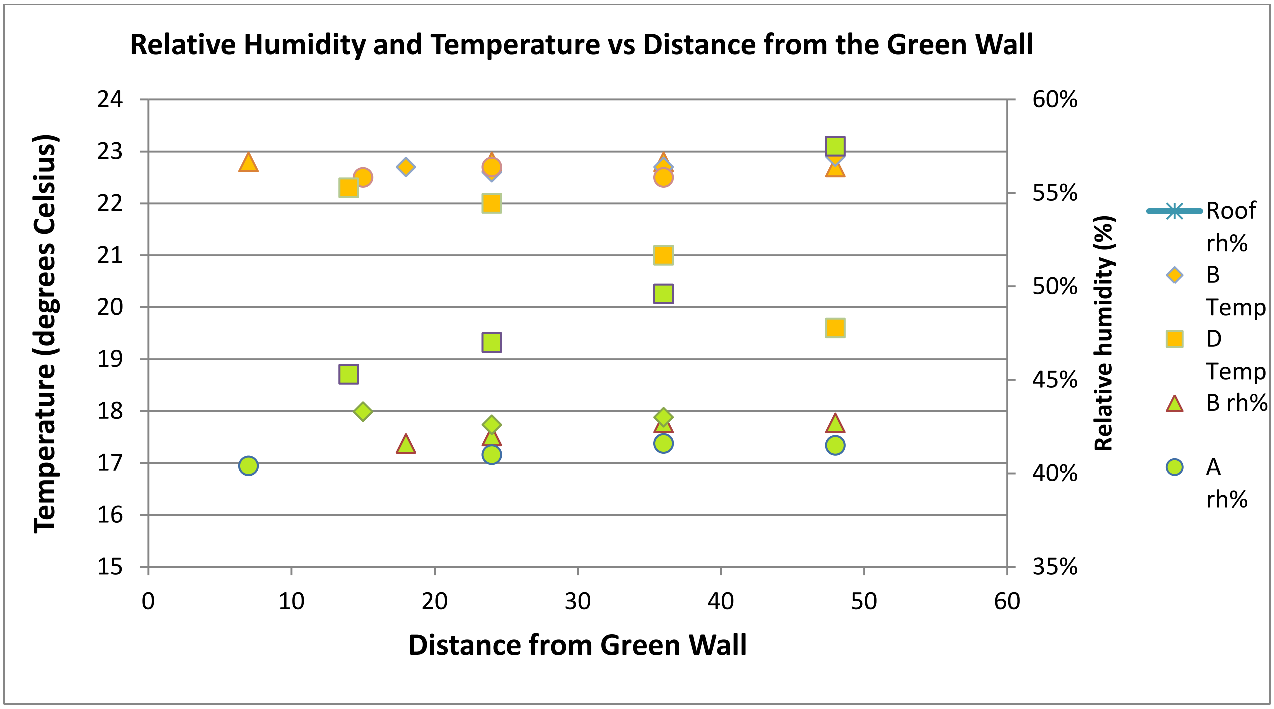

Figure 7. Relative humidity and temperature as a function of distance from the green wall.

Volatile Organic Compounds

Two ppbRAE were used for continuous and spot measurements. Neither of the instruments detected any level of VOC. Figure 8 is a sample test data from the ppbRAE. The VOC concentration in the Perkins and Will office was below the detectable threshold limit of 1 ppb. This agrees with the findings of the LEED IAQ pre-occupancy study in the office prior to the installation of the green wall (PHH ARC Environmental Ltd., 2012).

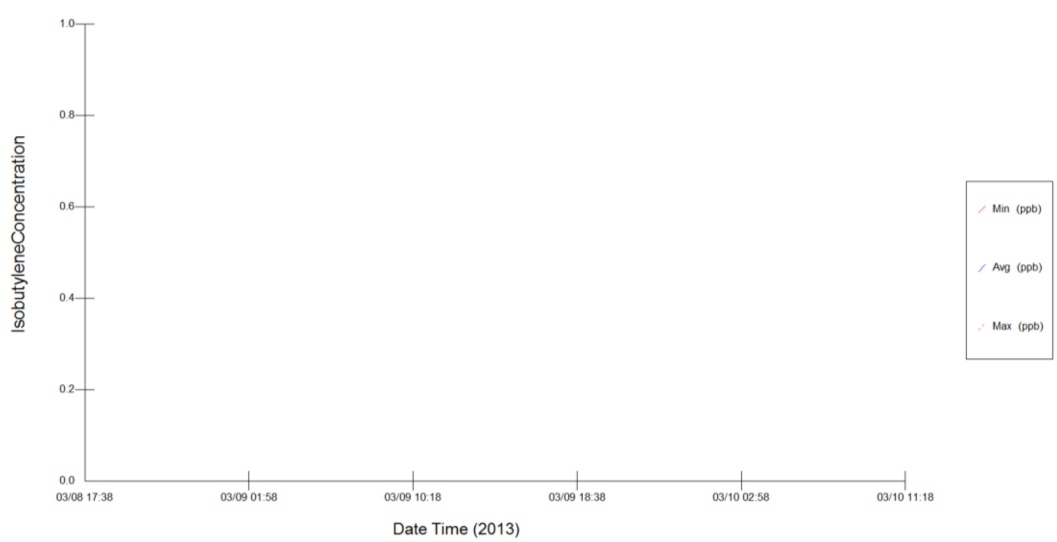

Figure 8 - Sample data downloaded from ppbRAE

Carbon Dioxide

The CO_2 concentrations from spot measurements on two different days are plotted against the distance from the wall in Figure 9 and in Figure 10. For day 1 shown in Figure 9, the lowest point for gradient A, B and C is closest to the atrium and the green wall. As the air in the office is ventilated out of the atrium, the result meets expectations. The CO_2 concentration along gradient D is roughly levelled. Because gradient D extends towards the entrance of the office away from the majority of occupants, the CO_2 concentrations should remain relatively low. The highest measured concentration level is the furthest point in gradient B which extends into the desk space. The trend of this data set shows that the desk spaces where most office occupants are situated act as CO_2 sources.

However, the same trend cannot be seen in the spot measurement data collected on day 2. As shown in Figure 10, the CO_2 concentration is highest for gradient A and C closest to the atrium. The gradient D data on day 2 shows a similar trend to day 1 data. Nonetheless, the concentration is about 50 ppm higher for day 2. The gradients extending into the desk space have the lower concentration for day 2. Based on observations, the number of occupants in the office was lower on day 2. There was also an ongoing meeting in the basement of the atrium when the measurements were recorded, creating a CO_2 source near the green wall. These factors are possible influences on the trend of the data.

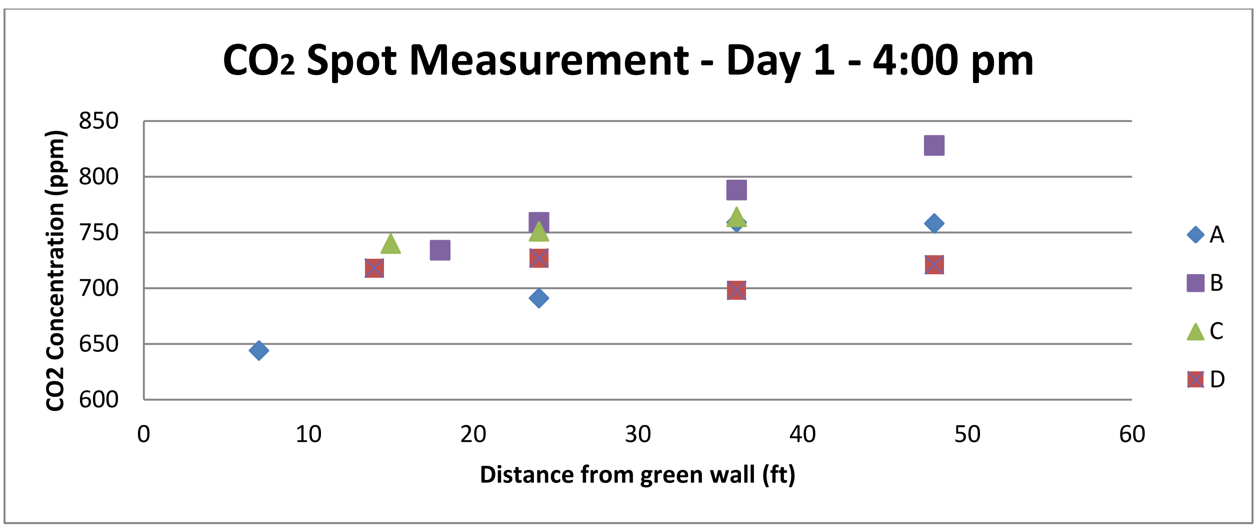

Figure 9 - Spot measurements spatial gradient - Wednesday - March 13, 2013

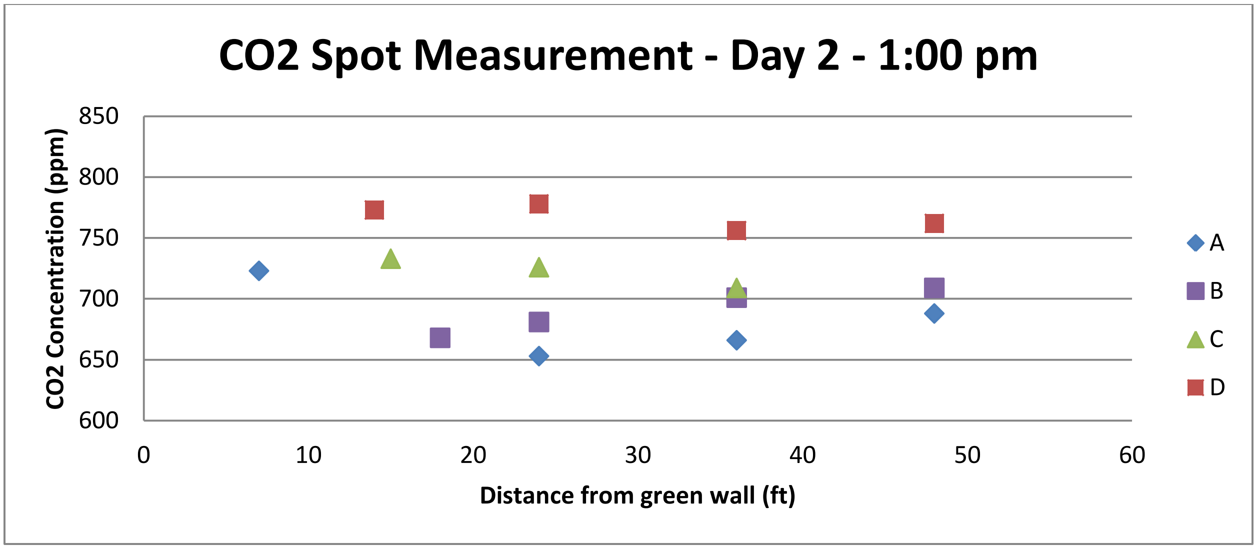

Figure 10 - Spot measurements spatial gradient - Friday - March 15, 2013

Figure 11 shows the 24 hours continuous data at the green wall, the office desk space and the reception area recorded on three different days overlapped onto the same plot. The CO_2 concentration on all three plots starts to increase around 9:00 am when occupants begin to enter the office. The concentration begins to plateau around 11:00 am. The plateau at the green wall remains around 780 ppm. The office data stays around 700 ppm in the morning but suddenly increases to 820 ppm after 2 pm. The measurements recorded around the reception area are considerably lower than the other two measurements at all times. This indicates that a significant amount of air likely enters from the entrance to maintain a low CO_2 concentration around the reception area.

The rise and drop off times of the green wall data cannot be directly compared to other data sets since they are taken on different days - the characteristics will change depending on the specific condition of that day such as the time occupants enter and leave the office. The fluctuation of the office data is quite significant as shown in Figure 12. The profile at the plateau of the curves changes on different days. Because of this variation likely caused by occupant activities, the influence of the green wall on CO_2 concentration cannot be conclusively determined based on the data.

Figure 13 includes the data set collected in the HR office. The CO_2 concentration occasionally exceeds the recommended level of 1000 ppm. Upon interviewing a staff member from one of the offices monitored, due to the confidential nature of her position, she often leaves the door to her office closed. Because the building is naturally ventilated and kept at a minimal level of circulation, this likely contributes to the high CO_2 concentration level observed in her office. The concentration drops quickly after around 6:00 pm.

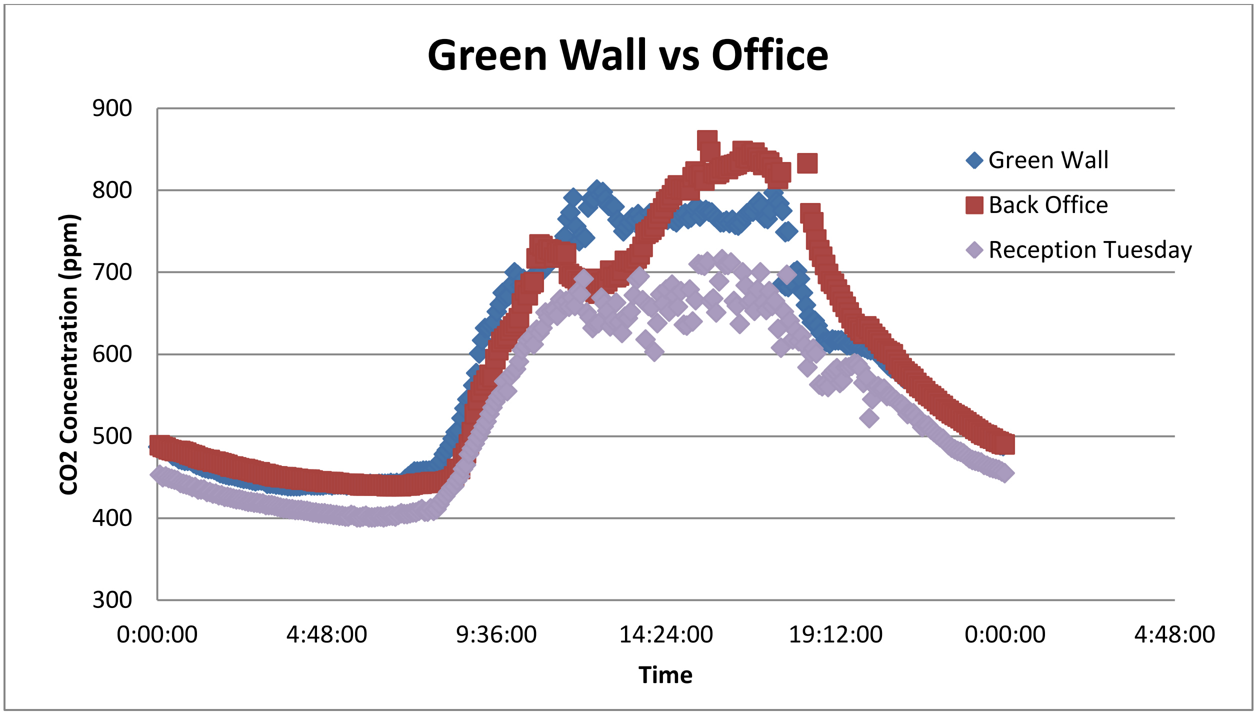

Figure 11 - 24 hour log of CO2 concentration - Green wall, office and reception area comparison - Measurements recorded on 3 different days

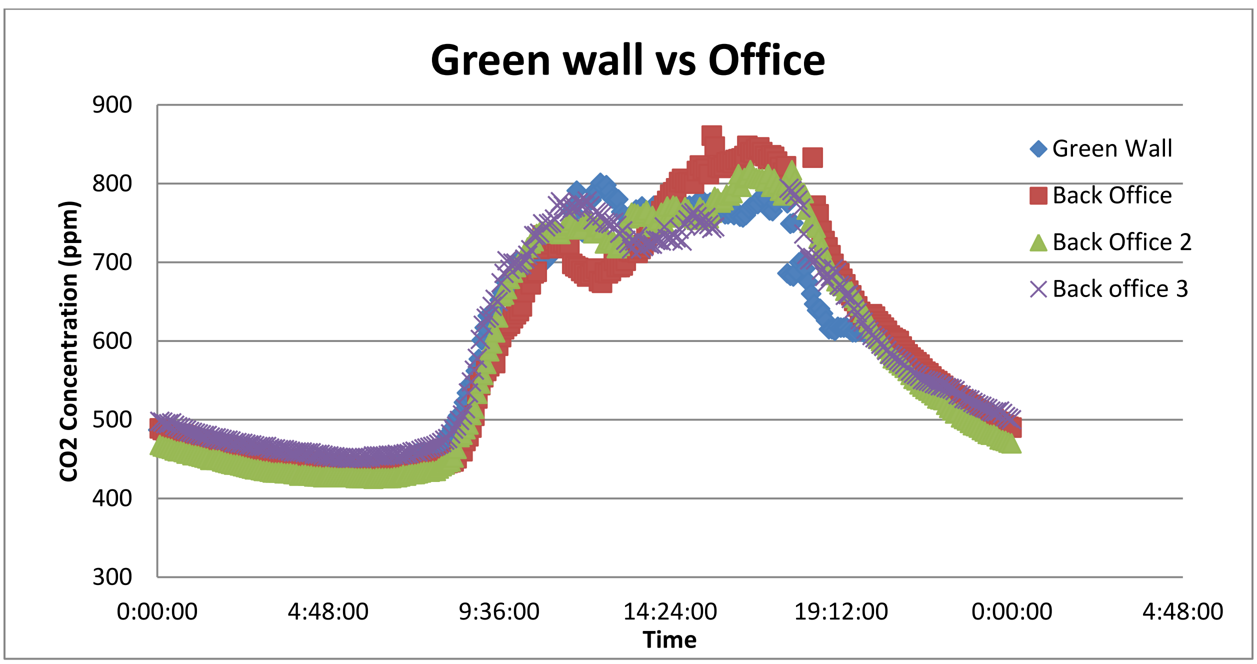

Figure 12 - 24 hour log of CO2 concentration - Variation within the office on different days - Measurements recorded on 3 different days

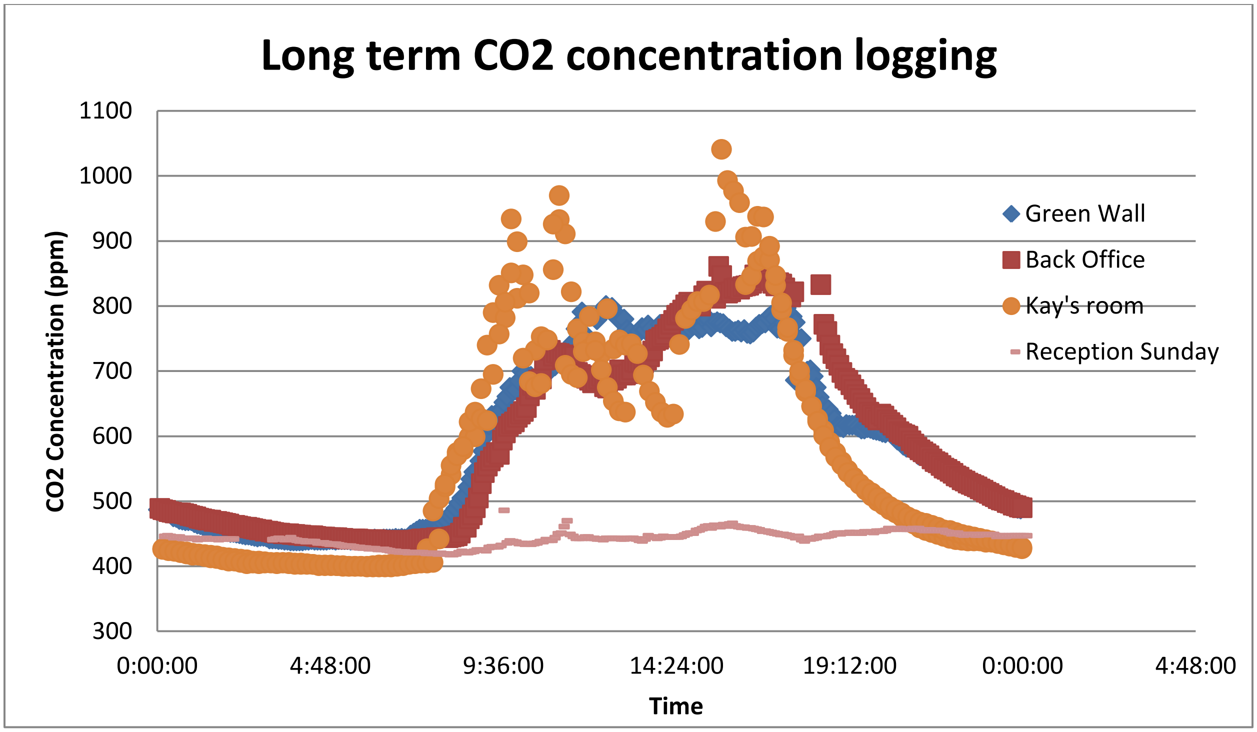

Figure 13 - 24 hour log of CO2 concentration - Green wall, office space, Kay's room and weekend data - Measurements recorded on 3 different days

Constraints

There were several constraints on this project which impacted the results and conclusions.

1. Because the wall was installed prior to the start of the project, and each office environment is unique, no control environment or baseline data set was available for comparison. This makes it difficult to draw conclusions as to the impact the green wall itself has when added to the existing office environment.
2. Similarly, while continuous measurements could be taken to show parameters during unoccupied office hours, instantaneous measurements were only possible during hours when the office was occupied. Because of changes in office activities, this has the potential to skew gradient results.
3. Because the project time span was relatively short, a limited number of measurements could be taken. The small sample size may accuracy of results.
4. For most of the project duration, only a single set of instrumentation was available (one Q-trak, one ppbRAE). Therefore, continuous measurements could not be taken simultaneously in more than one location and gradients are assumed to be consistent with regular office use.
5. The green wall is located downstream from the office space air flow. Therefore it is unlikely that impacts on the air as a result of the green wall would be experienced in upstream locations along the natural HVAC system path.

6. The VOC measurement instrumentation used has a minimum threshold of 1 ppb. The office was consistently below this threshold so no detailed VOC measurements could be recorded.

Conclusion and Recommendations

Conclusion

While temperatures on the green wall were cooler than ASHRAE standard temperatures for thermal comfort, the control gradient showed that this is not the case only four feet away. The control gradient, while close to the green wall, was far enough away for temperatures along it to be within thermal comfort standards. Therefore, it was assumed that the office space itself, which is much further from the wall, would not be negatively impacted, and no interactive effects with the HVAC system would be experienced.

Humidity did not increase near the wall, but actually was shown to increase at greater distances from the wall. This implies that despite the 244 square feet of green wall being irrigated continuously, no increase in humidity exists such that thermal comfort or health in the office is compromised.

The VOC concentration level was below the detection limit of the handheld instrument. This result is consistent with the pre-occupancy study conducted prior to the green wall installation. The VOC emission from the green wall was below the detectable amount of 1 ppb. Consequently, the green wall did not appear to have any adverse affect on VOC concentration. The VOC concentration reduction effect of the passive green wall could not be confirmed in this study.

The continuous CO_2 measurement data indicated that the ventilation system in the office works reasonably well. The concentration reaches a steady state equilibrium point which implies that the rate of CO_2 generated by occupants is balanced by the rate of ventilation. The steady state concentrations are lower than the ASHRAE recommended limit of 800 ppm for most of the measurements. Because the office is naturally ventilated with assistance from the air handling unit only as required, the ventilation rate is relatively low and occupant activities are clearly reflected in the readings. The CO_2 concentration spatial distribution changes throughout the day. The only ventilation concern is in the Human Resources office where the concentration level peaks to 1000 ppm at certain times when the door is closed for privacy. The HR staff who reported developing a cough is likely sensitive to this concentration peak, a sign of insufficient ventilation level. Because closing the door significantly cuts the HR office off from the general ventilation, additional measures to increase the air exchange rate in this space are required. In a low ventilation setting, occupants should remain conscious of how their action affect local air quality. Lastly, the influence of the passive green wall on CO_2 concentration could not be observed due to the wall location and the limitation of not being able to make simultaneous comparison between office area and green wall.

In conclusion, positive impacts could not be confirmed due to project constraints, but no detrimental effects on the office appear to be resulting from the green wall. All parameters measured indicated a healthy and comfortable indoor environment, meeting the relevant standards.

Recommendations

It is highly recommended that research continue in this area. However, future studies would be most effective for active green walls functioning as bio-filters, or for static green walls in locations upstream of human occupancy or in spaces where air is recirculating. Such studies should also investigate potential increases in endotoxins, and should include measurements before the installation of the wall in order to allow quantifiable impacts to be determined.

Additionally, more sensitive VOC detection equipment should be employed to obtain true readings of VOC levels.

Lastly, since fundamental air quality parameters do not appear affected by static green walls downstream of office spaces, future research should be undertaken to determine the potential acoustic and psychological effects of such installations (for example, impacts on employee satisfaction or productivity).

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