Title	New directions : potential climate and productivity benefits from CO2 capture in commercial buildings(Main article)
Author(s)	Gall, Elliott Tyler; Nazaroff, William W.
Citation	Gall, E. T., & Nazaroff, W. W. (2015). New directions : potential climate and productivity benefits from CO2 capture in commercial buildings. Atmospheric environment, 103, 378-380.
Date	2015
URL	http://hdl.handle.net/10220/26372
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New Directions: Potential Climate and Productivity Benefits from CO_2 Capture in Commercial Buildings

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Primarily because of humanity's heavy reliance on fossil fuels, ambient CO_2 levels have risen from 280 ppm in preindustrial times to 400 ppm today, and levels continue to rise by a few ppm per year (Tans and Keeling, 2014). Progress toward stabilizing atmospheric CO_2 levels can be achieved not only through reducing emissions but also through the engineering of new or enhanced sinks of atmospheric CO_2. Research and private sector initiatives on removing CO_2 from ambient air (Boot-Handford et al., 2014) lead us to consider this challenge in the context of a well-known indoor air quality concern: elevated CO_2 concentrations in occupied buildings.

Considerable energy is consumed in operating commercial buildings. In the United States, commercial buildings consume 19% of the total energy use (US DOE, 2012) causing approximately 1000 Tg CO_2 y^{-1} of fossil carbon dioxide release to the atmosphere, which is 18% of the US and 3% of the global anthropogenic emission rate (Boden et al., 2011; U.S. EIA, 2011). Reducing the carbon footprint of buildings is a strategic priority for offsetting future anthropogenic carbon emissions (Ochsendorf, 2012).

In addition to CO_2 release associated with fossil energy use, carbon footprints of buildings include CO_2 generated from the metabolism of human occupants that is transported outdoors via indoor-outdoor air exchange. Elevated concentrations that occur indoors from human metabolism might be an attractive target for air capture technologies. Although the carbon in metabolic CO_2 is of contemporary rather than fossil origin, removing metabolic CO_2 would contribute in the same way as removing fossil CO_2 from air in pursuing climate-stabilization goals.

Metabolic CO_2 has long been used as an indicator of indoor air quality. As a proxy for the adequacy of ventilation, guidelines call for indoor CO_2 not to exceed 700 ppm above outdoor levels (ANSI/ASHRAE, 2013). High occupant densities in inadequately ventilated spaces can generate indoor CO_2 levels that exceed this limit. For example, Seppänen et al. (1999) document indoor CO_2 levels as high as 3700 ppm in offices and 2800 ppm in schools. On the other hand, a survey of US commercial buildings found lower values, with the median increment of indoor CO_2 being 140 ppm above the outdoor value (interquartile range: 100-220 ppm) (Apte et al., 2000). Human exposure to indoor CO_2 is expected to increase as a result of climate change, due to (a) higher ambient CO_2 concentrations and (b) energy-efficient building practices that reduce ventilation (Committee on the Effect of Climate Change on Indoor Air Quality and Public Health, 2011).

In addition to offsetting anthropogenic carbon emissions to the atmosphere, removing CO_2 either from recirculating airstreams or utilizing portable air cleaners indoors would decrease indoor CO_2 concentrations. Evidence suggests that exposure to CO_2 may degrade decision-making performance (Satish et al., 2012). In schools and offices, such effects might contribute to decrements in learning or in workplace productivity. Controlling CO_2 in offices and schools by means of active CO_2 removal therefore might confer multiple benefits: strengthening capture processes by treating indoor air with elevated CO_2 levels because of metabolic emissions, contributing to the attainment of carbon neutrality goals for buildings, and improving indoor air quality by reducing the CO_2 exposure of building occupants.

In the following paragraphs, we briefly explore the opportunity scale for reducing the carbon footprint of buildings through CO_2 capture in buildings. Schools and offices are used as specific examples for several reasons: the importance of productivity in these environments, the evidence of elevated indoor CO_2 concentrations from metabolic emissions, and their large number and high occupancy.

Considering the total building stock of the United States, the scale of indoor human metabolic CO_2 emissions can be estimated using a bottom-up approach:

$$E_{tot} = P \times E_m \times f_{in} \times 24\tfrac{h}{d} \times 365\tfrac{d}{y} \qquad (1)$$

where E_{tot} is the emission rate of human metabolic CO_2 emitted to all indoor microenvironments in the United States (g CO_2 y^{-1}), P is the US population (persons), E_m is the human metabolic emission rate (g CO_2 $person^{-1}$ h^{-1}), and f_{in} is the average fraction of time a person spends indoors, For a US scaling estimate, P is 3.2×10^8 persons, E_m is 34 g CO_2 $person^{-1}$ h^{-1} (Smith, 1988), and f_{in} is 0.87 (Klepeis et al., 2001). Thus, the overall human metabolic CO_2 emissions into US built environments is E_{tot} ~ 83 Tg CO_2 y^{-1}. An activity survey of Californians (Jenkins et al., 1992) indicates that the average proportion of time spent in schools (0.67 h/d per person) and offices (1.2 h/d per person) sum to 9% of the total time spent indoors, so the corresponding total emissions into these two microenvironment categories would be about 7.4 Tg CO_2 y^{-1}.

In addition to removing metabolic CO_2 emitted, indoor air capture can remove CO_2 supplied with outdoor ventilation air. The total quantity of CO_2 of outdoor origin that flows through US classrooms and offices can be estimated by combining 10 L/s per person as a typical outdoor-air ventilation rate (Apte et al. 2000), 400 ppm CO_2 in outdoor air, 320 million people, and 1.9 h/d as the average per-person occupancy of these indoor environments. The result is 5.8 Tg CO_2 per year. So, summing the metabolic emissions and the ventilation supply from outdoor air, we estimate that about 13 Tg CO_2 per year pass through offices and classrooms in the United States.

If CO_2 control were applied in these microenvironments and achieved a net capture efficiency of 75%, then the total carbon footprint of could be reduced by 10 Tg CO_2 y^{-1}. This reduction is similar in magnitude to that projected for energy efficiency efforts in buildings; it exceeds CO_2 reductions resulting from energy performance contracting in the US; and it is roughly half of the anticipated CO_2 reductions from appliance efficiency standards (IPCC, 2014).

Several key challenges must be overcome before office buildings or schools could become an effective point-of-control for active CO_2 removal. To realize the joint benefits of reducing CO_2 exposure and capturing CO_2 from air with higher than ambient levels, the CO_2 removal infrastructure must be located either in the building air recirculation system or in stand-alone indoor-air treatment units. Large commercial office spaces are often designed with recirculating airflow systems; however, classrooms commonly rely on simple package ventilators or on operable windows to provide outdoor air, which would present a different set of logistic challenges and opportunities.

The scaling analysis shows that a moderate efficacy is necessary to substantially reduce the carbon footprint of commercial buildings through active CO_2 capture. For dilute CO_2 levels, adsorption technologies appear to be the most promising approach (Lackner et al., 2012). Zhang et al. (2014) have demonstrated a polyethyleneimine-silica adsorbent that removes CO_2 with nearly 100% capture at relatively short (7.5 s) media-air contact times. He et al. (2012) have shown that removal of 80 mg CO_2 per gram of sorbent is possible at 400 ppm CO_2 and that the media can be regenerated at low temperatures with little effect on sorbent capacity. However, even assuming regeneration as frequent as weekly, substantial masses of sorbent media would be required to capture CO_2 from offices and schools. Distributing control technology to buildings would confer the benefit of capturing from higher CO_2 concentrations; however, it would also create the need to manage the collection and transport of the sorbent media to processing and disposal facilities. Development of collection and regeneration infrastructure, investigation of long-term regeneration efficiencies, and creation of reliable carbon storage are all foreseeable research needs that require solutions for carbon capture from buildings to become a practical reality. In addition, sorbents for direct air capture in indoor spaces must not produce harmful byproducts, as placement of sorbent media in recirculation ducts or in stand-alone indoor air cleaners could commonly result in human exposure to air treated by sorbent media.

Estimates of the total cost for air capture of CO_2 are disputed, in part because technologies for CO_2 air capture are still being developed (Lackner et al., 2012). Holmes and Keith (2012) have estimated the cost of air contacting (regeneration costs not included) at $60 per tonne of CO_2 for a functional prototype (Holmes et al., 2013). Cost estimates that include regeneration range broadly, from ~$20 to $1000 per tonne of CO_2 (Goeppert et al., 2012). To remove 10 Tg CO_2 y^{-1} at this range of costs, the corresponding expense would amount to $0.2-10 billion per year.

Workplace productivity and performance is found to decrease when indoor air quality is poor, in part a result of sick building syndrome (SBS) symptoms (Wyon, 2004). Low ventilation rates are significantly associated with degraded indoor air quality, increases in SBS symptoms, and decreased performance in simulated office tasks (Seppanen et al., 1999; Wargocki et al., 2000). Indoor CO_2 concentrations are elevated in occupied buildings with low per-person ventilation rates. While the specific role of CO_2 as an indoor pollutant requires further investigation, studies have documented statistically significant associations between CO_2 and

SBS symptoms (Apte et al., 2000; Tsai et al., 2012). The costs of sick building syndrome, likely dominated by accompanying decreases in worker productivity, are estimated to be $17-26 billion per year for US offices alone (Fisk, 2000; Fisk et al., 2011), higher than the estimated cost associated with capturing CO_2 in US offices and schools. Therefore, it is feasible that the cost of CO_2 capture in commercial buildings could be justified economically if it is demonstrated that doing so improves workplace productivity because of lower CO_2 levels in offices.

Indoor environments will evolve with the changing climate, and such an evolution may be consequential for a wide range of indoor pollutants (Nazaroff, 2013). The substantial energy demand of commercial buildings and the climate impacts of elevated outdoor CO_2 concentrations suggest a need to consider indoor CO_2 not only as a pollutant to be managed through dilution, but also to be captured and sequestered. While the technology and infrastructure to effectively do so remains to be developed, CO_2 removal in commercial buildings warrants attention in discussions of carbon sequestration as a potential win-win opportunity: increasing productivity in offices and schools and developing carbon-neutral buildings.

Acknowledgment

This research was funded by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. BEARS has been established by the University of California, Berkeley as a center for intellectual excellence in research and education in Singapore.

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