



The greenhouse gas emissions of indoor cannabis production in the United States

Hailey M. Summers , Evan Sproul and Jason C. Quinn

The legalization of cannabis has caused a substantial increase in commercial production, yet the magnitude of the industry's environmental impact has not been fully quantified. A considerable amount of legal cannabis is cultivated indoors primarily for quality control and security. In this study we analysed the energy and materials required to grow cannabis indoors and quantified the corresponding greenhouse gas (GHG) emissions using life cycle assessment methodology for a cradle-to-gate system boundary. The analysis was performed across the United States, accounting for geographic variations in meteorological and electrical grid emissions data. The resulting life cycle GHG emissions range, based on location, from 2,283 to 5,184 kg CO₂-equivalent per kg of dried flower. The life cycle GHG emissions are largely attributed to electricity production and natural gas consumption from indoor environmental controls, high-intensity grow lights and the supply of carbon dioxide for accelerated plant growth. The discussion focuses on the technological solutions and policy adaptation that can improve the environmental impact of commercial indoor cannabis production.

Understanding the greenhouse gas (GHG) emissions of commercial cannabis production is essential for consumers, the general public and policy makers to improve decision making to mitigate the effects of climate change. Since recreational legalization was pioneered in Colorado in 2012, the US legal cannabis industry has rapidly grown from a US\$3.5 billion industry to US\$13.6 billion in annual sales, with states like Colorado selling more than 530 tonnes of legally grown cannabis product every year^{1,2}. Additionally, with 48% of adults in the United States having tried cannabis at some point in their life and 13% of adults having consumed in the last year, substantial demand exists at the consumer level³. Despite its rapid growth and widespread use, there is minimal quantitative understanding of the GHG emissions from legal indoor cannabis cultivation.

The initial amendment legalizing recreational cannabis in Colorado required the majority of cannabis product to be sold at a collocated retail location⁴. This restriction led to cultivation practices occurring within the city limits of Denver, CO. This, along with security, theft and quality concerns, consequently led to the cultivation of cannabis indoors. Although data concerning the exact amount of cannabis by cultivation method are not currently publicly available for the United States, a recent survey of producers in North America showed that 41% of respondents indicated that their grow operations occur solely indoors⁵. It is well known that indoor cannabis cultivation requires significant energy input, reflected in high utility bills and industry reports^{4,6–9}. However, many of these large energy loads, along with other material inputs required to cultivate indoor cannabis, have not yet been equated to GHG emissions.

Previously, rudimentary quantifications of GHG emissions from indoor cannabis have been performed by equating emissions with electricity use from monthly bills^{6,7}. However, this approach omits additional GHG emissions from other energy sources, such as natural gas, upstream GHG emissions from the production and use of material inputs, and downstream GHG emissions from the handling of waste. The most thorough report quantifying GHG emissions from indoor cannabis is from Mills¹⁰, which states that growing 1 kg of cannabis indoors releases 4,600 kg of carbon dioxide

equivalent (CO₂e). However, the scope of the work was intended to be a central estimate, representing a singular US location case study for the industry's general practices. Furthermore, Mills¹⁰ conducted this study prior to legalization and only used data from small-scale experimental systems, thus lacking validation of full-scale commercial grow operations. Since Mills' work¹⁰, minimal research has been carried out to improve GHG emissions quantification or to investigate the geographic effects of growing indoor cannabis. To fill this knowledge gap, we have quantified the GHG emissions of commercial indoor cannabis production using life cycle assessment (LCA) methodology and expanded the scope to include geographic effects across the United States. The results of our investigation are presented in this article.

An indoor cannabis cultivation model was developed to track the necessary energy and materials required to grow cannabis year-round in an indoor, warehouse-like environment. This environment maintains climate conditions as required for the cannabis plants, yielding a consistent product regardless of weather conditions. The model calculates the necessary energy to maintain these indoor climate conditions by using a year's worth of hourly weather data from more than 1,000 locations in the United States¹¹. The analysed locations are independent of current legal status and represent hypothetical grow facilities in all 50 US states. The model then converts the required energy, supplied from electricity and natural gas, into GHG emissions through electrical grid emissions data from 26 regions in the United States¹² and life cycle inventory (LCI) data^{13,14}. Additionally, the model accounts for the upstream, or cradle-to-gate, GHG emissions from the production and transportation of material inputs such as water, fertilizers, fungicides and bottled carbon dioxide (CO₂) supplied for increased plant growth as well as the downstream process of waste handled in a landfill. The resulting cumulative GHG emissions for annual indoor cannabis cultivation across the United States, represented as kilogram CO₂e per kilogram of dried cannabis flower (kgCO₂e kg⁻¹), is presented in Fig. 1a.

The results presented in Fig. 1a are a combination of modelled natural gas consumption (Fig. 1b), electricity consumption (Fig. 1c)

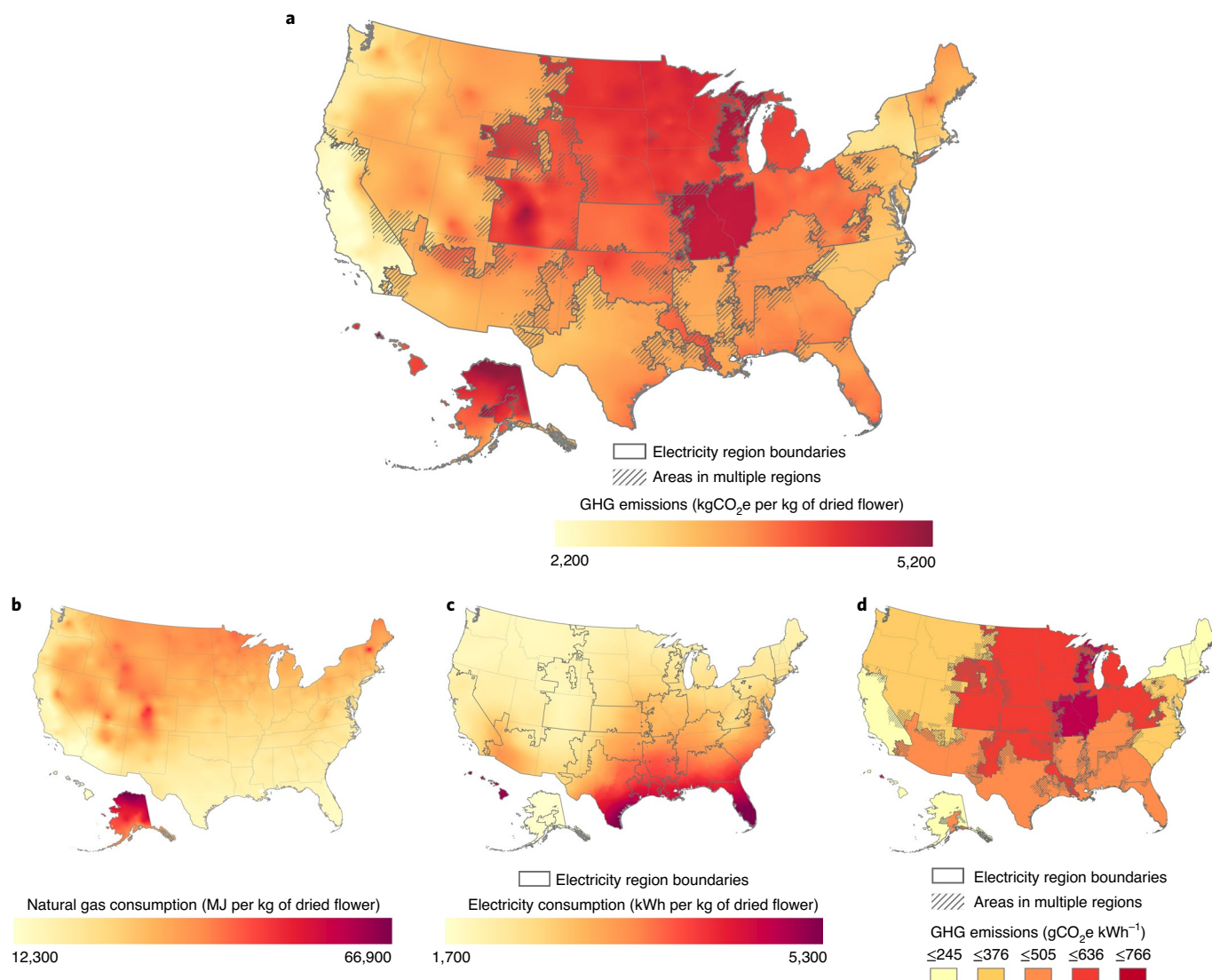


Fig. 1 | Life cycle GHG emissions and energy intensities from indoor cannabis cultivation modelled across the United States. **a**, Cumulative GHG emissions from cultivating cannabis indoors interpolated within eGRID electricity region boundaries. eGRID, Emissions and Generation Resource Integrated Database. **b**, Natural gas required to maintain indoor environmental conditions. **c**, Electricity required to maintain indoor environmental conditions and high-intensity grow lights. **d**, GHG emissions for the US electricity regions modelled. Full resolution figures are provided in Supplementary Figs. 1–4.

combined with geographically resolved GHG emissions for electric grid mix (Fig. 1d), and upstream and downstream GHG emissions. The resulting GHG emissions range from 2,283 to 5,184 kgCO₂e kg⁻¹, observed in Long Beach, CA and Kaneohe Bay, HI, respectively, with a median value for all locations analysed of 3,658 kgCO₂e kg⁻¹. As these results are independent of current legal status within individual states, these findings should not be interpreted as representing the current reality of the industry. Rather, the results represent GHG emissions if the cultivation method in each location were selected to be indoors.

The results in Fig. 1 show that a wide variation in GHG emissions from indoor cannabis cultivation exists across the United States. Regional trends show that areas such as the Mountain West and Midwestern United States are especially intensive for growing cannabis indoors. To better understand the factors that lead to variations in GHG emissions across the United States, Fig. 2 illustrates the contributions to the total GHG emissions in ten geographically and meteorologically diverse locations. The locations shown in Fig. 2 capture the full range of GHG emissions

results, from the minimum of Long Beach, CA to the maximum of Kaneohe Bay, HI, with a single location selected from the regions of Pacific Northwest, Pacific Southwest, Desert Southwest, Northeast, Southeast, Mountain West, East North Central, West North Central, Alaska and Hawaii. In addition, these ten locations represent large populations within US states that have legalized cannabis sales (either medical, recreational or both) and are in unique electricity regions. The results are shown on the basis of per kg of dried flower as total production quantities and cultivation method data are not publicly available. For each location, GHG emissions were divided into process categories to understand the largest contributors. Despite geographic variations, certain variables were shown to be consistently large contributors to the overall GHG emissions. These variables include indoor environmental controls by heating, ventilation and air conditioning (HVAC), required to maintain indoor temperature and humidity, as well as high-intensity grow lights and the supply of CO₂ for increased plant growth.

The HVAC systems are responsible for modifying air temperature and humidity to an allowable range before being supplied to

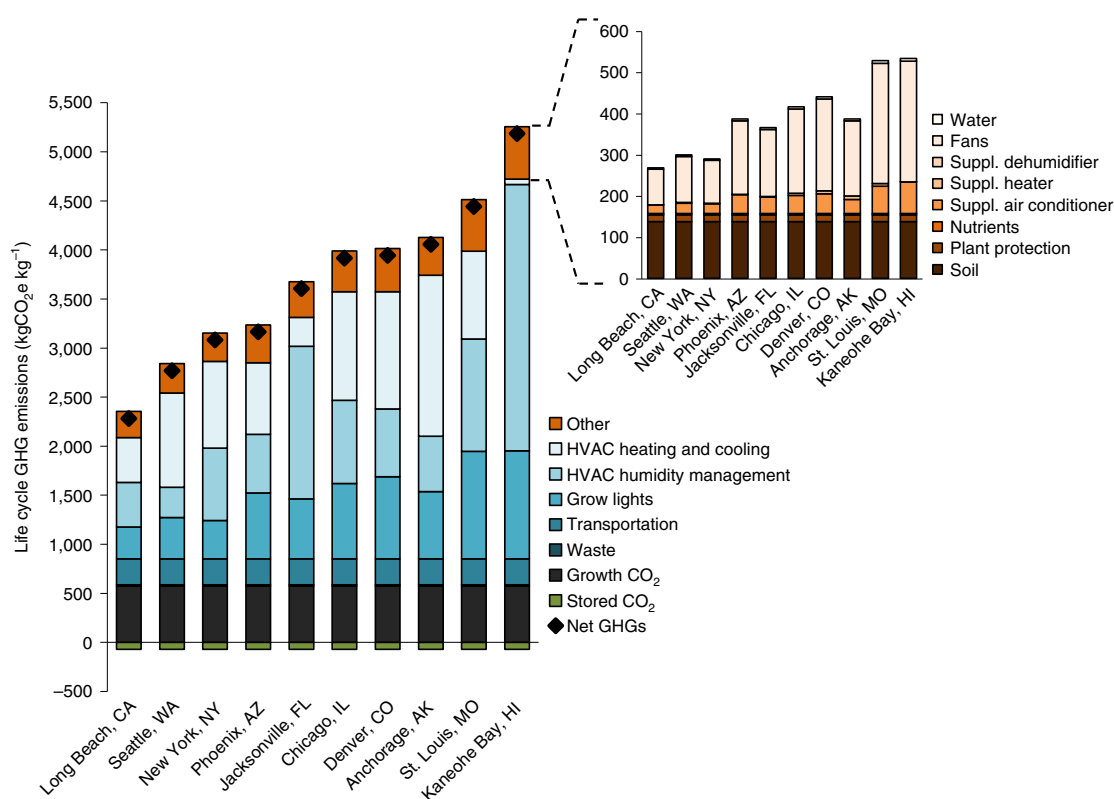


Fig. 2 | Breakdown of life cycle GHG emissions contributions from indoor cannabis cultivation. GHG emissions from indoor cannabis production at ten of the 1,011 locations modelled. The GHG emissions totals represent individual simulation results based on modelling input parameters specific to each location. The positive values represent released GHG emissions and the negative value represents stored GHG emissions based upon the model system boundary. The HVAC labels in the main figure refer to the major equipment used to manipulate outside air to meet inside condition criteria, whereas the indoor environmental controls in 'Other' are supplemental (suppl.) systems representing additional equipment located inside grow rooms that aid in maintaining environmental conditions.

the cannabis plants. This is critical to maintaining plant health as sudden changes in temperature and humidity can shock the plants and ultimately lead to crop damage and product loss. Additionally, cannabis plants require a regular supply of fresh air to help moderate humidity and oxygen levels. In this work, an air supply rate of 30 volumetric air changes per hour (ACH) was assumed. This value represents the average value from the literature, which reports values as high as 60 ACH and as low as 12 ACH (Supplementary Table 1). For comparison, the recommended ventilation for homes is 0.35 ACH and operating rooms in hospitals require a minimum of 15 ACH^{15,16}. Air condition modifications and supply by HVAC are cumulatively shown to be the largest contributor to overall GHG emissions regardless of location (see Supplementary Table 2 for all contributions). The contributions to GHG emissions from HVAC also infer that locations with lower GHG emissions are better suited meteorologically for indoor cannabis cultivation than locations with large GHG emissions as fewer modifications to the outside air conditions are required.

Categorized in Fig. 2 are HVAC processes that include modification to air humidity, labelled as HVAC humidity management (latent loads), and air temperature, labelled as HVAC heating and cooling (sensible loads). These processes represent annual energy demand for modifying air delivered to all stages of plant life cycle, including clone, vegetative, flowering and curing (also known as drying). HVAC humidity management largely depends on geographic variability, as in the case of Jacksonville, FL and Kaneohe Bay, HI, where dehumidifying the consistently hot and humid outside air to desired temperature and humidity ranges requires

significant energy through electric HVAC equipment. HVAC heating and cooling of air are shown to be major GHG emissions contributors in geographic locations where humidity ranges are acceptable, but average outside temperatures are consistently different from those of the desired indoor requirements for cannabis plants (15.6–29.4 °C). These conditions are observed most significantly in Denver, CO and Anchorage, AK. The results, as illustrated in Fig. 2, also indicate that at some locations, the supplied air conditions from HVAC at 30 ACH are sufficient to overcome the increased heat and humidity from lights and plants, respectively, while other locations require the use of additional supplemental equipment to keep inside conditions within tolerance. This categorization of supplemental environmental control equipment is shown in the breakdown of 'Other', as supplemental dehumidifiers, air conditioners and heaters. This equipment is turned on in the model when the HVAC equipment cannot maintain acceptable temperature and humidity ranges at the air supply rate of 30 ACH. All the supplemental systems were modelled as having an electric power supply and are cumulatively shown to have a minor contribution to the overall GHG emissions at the modelled air exchange rate. Specifically, for the ten locations shown in Fig. 2, the supplemental dehumidifiers were never operated because the frequency of ACH was able to maintain the required indoor humidity levels. Additionally, the supplemental heaters and air conditioners varied in use, but contributed less than 2% of the total GHG emissions in all locations.

The second most significant GHG emissions contributor observed universally is from high-intensity grow lights. Lighting

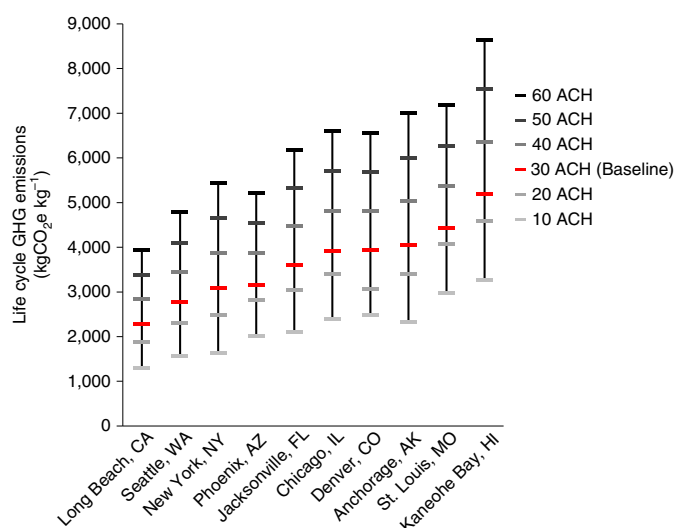


Fig. 3 | Sensitivity analysis of ACH. Impact of ACH on GHG emissions from indoor cannabis cultivation for the same ten locations displayed in Fig. 2. The baseline assumption for this study was 30 ACH, shown in red.

intensities for cannabis plants can be 50–200 times higher than a typical office setting and are run for 12, 18 or 24 hours, depending on the stage of the plant life cycle¹⁰. In all locations analysed, indoor lighting requirements were held constant and therefore the required annual kilowatt hours (kWh) of electricity are constant. However, the GHG emissions associated with electricity production vary more than sixfold as a result of geographically varying electric grid mixes, as shown in Fig. 1d. These variations in grid GHG emissions are most clearly observed in Fig. 2 between Kaneohe Bay, HI, where the grid mix is largely oil based (805 gCO₂e kWh⁻¹), and Long Beach, CA, where natural gas and solar power are much more prevalent (238 gCO₂e kWh⁻¹).

Lastly, supplemental CO₂ contributes significantly to overall GHG emissions and does so equally across all locations analysed as it is a fixed input that is independent of geography. CO₂ is introduced into the indoor grow environment to increase plant photosynthetic activity, therefore allowing plants to reach maturity sooner¹⁷. In these results, the contributing GHG emissions from the introduction of gaseous CO₂ is not from the CO₂ itself, but rather from the production processes associated with the compression of the gas into liquid form and subsequent storage within a cylinder. The sourced CO₂ gas itself is obtained free of environmental burden as it is typically received as a byproduct of another process, such as ammonia production¹³. It was also assumed that if the cannabis industry were not using the CO₂, it would be released into the atmosphere and therefore the physical CO₂ gas itself does not count as a penalty to the cannabis facility.

The results presented in Fig. 2 indicate that more than 80% of the GHG emissions for these locations are generated by practices that are non-traditional for agricultural products. Traditional agricultural cropping systems typically see the largest GHG emissions from practices associated with land preparation and management or fertilizer, but for indoor cannabis these values are on average less than 5% of the total¹⁸. This is not to say that values from these traditional practices are lower in indoor cannabis cultivation, but that the significant energy required to create an artificial climate for plants indoors causes cannabis to be extremely GHG emissions intensive.

Interpretation for improved decision making

The detailed results from this work enable specific recommendations on how the environmental burden of indoor cannabis cultivation can be reduced through engineering solutions as well as policy.

The results from the high-resolution, geographically resolved model identify specific aspects of indoor growth that lead to substantial GHG emissions. This insight can be applied to states with existing legal indoor practices and during policy and regulation development prior to individual state legalization.

For states that have already legalized medical and recreational cannabis, these results can be used to better understand what processes are the largest contributors to overall GHG emissions and therefore focus efforts toward modifying current practices to reduce GHG emissions. Namely, these findings can be used to develop best management practice guides similar to those of O'Hare et al.⁷, Massachusetts Department of Energy Resources¹⁹ and the Cannabis Sustainability Working Group²⁰. The results of this work can also help inform policies such as the recent California Statewide Codes and Standards Enhancement Program proposal²¹, which would require all indoor cultivation to switch to light-emitting diode lights by 2023, or House Bill 1438²² in Illinois, which limits lighting intensities and requires producers to commit to using high-efficiency HVAC equipment. With the quantitative GHG emissions results from this work, best management guides should include practices to specifically reduce GHG emissions from HVAC operations, high-intensity grow lights and supplemental CO₂ as these are the largest contributors in the majority of US locations.

In addition to holistic process changes, an uncertainty assessment through sensitivity analysis was performed to identify individual input parameters that result in large changes to GHG emissions in response to variation of an input value. The results indicate that the most sensitive variable is plant yield (kg of dried flower per plant), which was foreseeable as GHG emission results are presented on this basis (see Supplementary Fig. 5 for full results). Besides plant yield, ACH is the next most sensitive variable as this parameter is directly coupled with HVAC energy requirements and supplemental CO₂ amounts. In this work, 30 ACH was selected and held constant for all hours of operation within the indoor cannabis growth model on the basis of a literature survey, which is summarized in Supplementary Table 1. Further investigation into this high-impact variable indicates that varying ACH from 10 to 60 can result in a GHG emissions difference of more than 230%, depending on geographic location (Fig. 3 and Supplementary Table 11 for full results). It is also important to note that choosing the minimum ACH for each location may not necessarily be optimal as moisture needs to be removed from grow rooms to avoid mould and ultimately loss of product. Furthermore, the relationship between ACH and GHG emissions from indoor cannabis is non-linear in many locations due to varying equipment use and therefore energy demand. Specifically, the use of supplemental equipment declines on moving from 20 to 30 ACH because the indoor climate requirements are met by the increased supply of fresh air conditioned through HVAC equipment. Therefore, ACH warrants particular attention when developing best management practice guides for individual cultivation facilities or geographic regions. The results of the sensitivity analysis also identify temperature and humidity ranges, typically measured in facilities as vapour pressure deficit, and CO₂ concentrations as the next three most sensitive variables to overall GHG emissions. All three of these parameters are coupled with ACH, and although they would benefit from individual optimization, they reiterate the importance of optimizing ACH.

The results of this work also identify geographic regions within the United States and in individual states where indoor cannabis cultivation would have low GHG emissions. Federal restrictions limit the transport of cannabis across states and therefore a US-wide geographic optimization of growth locations is not feasible. However, in most US states, the intrastate transport of cannabis product is legal and therefore, if indoor cultivation is to remain within that state, this work highlights locations for indoor cannabis cultivation that would lead to lower GHG emissions.

These geographic variations are most noticeable in Colorado, where the mountainous locations of Leadville, Aspen, Gunnison and Alamosa lead to significantly more GHG emissions than locations on the plains of Pueblo, Trinidad or Denver. For example, the practice of growing cannabis in Leadville leads to 19% more GHG emissions than in Pueblo. The savings in GHG emissions from moving indoor cultivation to Pueblo and away from Leadville are likely to be much greater than the GHG emissions of transporting the final product to retail locations in Leadville. These results indicate that individual states can optimize their indoor cultivation locations to reduce GHG emissions. Laws may need to change for this geographic optimization to occur, such as the previously mentioned law in Colorado that stated cultivation and retail facilities be collocated. For states that have yet to legalize, flexibility with collocation requirements could improve the GHG emissions from the standpoint of intrastate geographic optimization.

Additional conclusions from this work can help inform policy for states where cannabis cultivation is not yet legal. For these states, developing policy to encourage greenhouse and outdoor cultivation can drastically reduce GHG emissions by avoiding the practice of indoor cannabis cultivation altogether. We acknowledge that shifting cannabis cultivation outdoors is not free of environmental burden as the literature has shown several concerns, including increased irrigation, excessive use of pesticides and nutrient run-off^{6,23}. Additionally, switching to greenhouse and outdoor practices requires appropriate regulation to avoid the potential encouragement of illicit practices that historically have led to additional environmental burden, such as illegal water diversion and deforestation^{8,23}. There are also concerns over greenhouse and outdoor cultivation associated with security, the inability to achieve multiple harvests per year and a lack of consistent product.

Although there are many hurdles associated with shifting cannabis growth to legal and well-regulated greenhouse and outdoor cultivation practices, preliminary investigations into the potential difference in GHG emissions when switching to greenhouse and outdoor cultivation practices indicated reductions of 42 and 96%, respectively^{6,7}. It is important to note that these reports are limited in scope and resolution as the GHG emissions are based primarily on electricity consumption through monthly bills. Therefore, the current state of the industry would benefit from understanding the true GHG emissions of greenhouse and outdoor cultivation at a similar resolution to the work presented here to allow real comparison between the three cultivation methods. The results of this study affirm that more than 80% of the GHG emissions from all indoor cannabis locations assessed are caused by practices directly linked to indoor cultivation methods, specifically indoor environmental control, high-intensity grow lights and the supply of CO₂ for increased plant growth. If indoor cannabis cultivation were to be fully converted to outdoor production, these preliminary estimates show that the state of Colorado, for example, would see a reduction of more than 1.3% in the state's annual GHG emissions (2.1 MtCO₂e)²⁴. These GHG emissions are on a par with entire sectors within the state, such as coal mining, waste management and industrial processes, which are responsible for 1.8, 4.2 and 4.5 MtCO₂e annually, respectively²⁴.

The conclusive results quantified in this study indicate that cultivating cannabis indoors leads to considerable GHG emissions regardless of where it is grown in the United States. These findings illustrate the need for change within the rapidly growing cannabis industry to reduce GHG emissions from indoor cultivation.

Methods

Model scope. Indoor cannabis cultivation facilities vary in the way they are built and operate, depending on existing building infrastructure, codes and permitting, and geographic considerations pertaining to HVAC equipment selection. Further variation is seen from the specific strain of cannabis being cultivated, leading to

different desired indoor cultivation climates. Modelled here is a representative facility of common indoor cannabis cultivation practices established through literature research and industry communication. The system boundary of the model represents a cradle-to-gate framework, encompassing operations associated with the warehouse-like facility to support indoor cannabis cultivation, including the necessary energy and material inputs as well as waste from the facility (Supplementary Fig. 6). Downstream activities, such as the transportation of the final product to point of sale, packaging, use and end of life, were not considered.

Model development and resolution. The modelled indoor cultivation facility operation includes the four primary cannabis stages of life, namely clone, vegetative, flower and curing, with permanent rooms established for each to house the necessary equipment and maintain the required growing environments. The operations are similar to an assembly line because established room environments are maintained constant while plants rotate through them, depending on the stage of life (Supplementary Fig. 7). The length of each plant stage was modelled using average durations from Colorado indoor growers, that is, 22, 50, 57 and 14 days for clone, vegetative, flower and cure, respectively¹. Because flowering is the longest stage, it creates a bottleneck effect. This effect was accommodated by determining when all other stages of life should start and end relative to flowering, resulting in an average of 6.2 harvests per year. Additionally, the maximum number of cannabis plants flowering in the allotted grow space was limited, representing a conservative GHG emissions estimate as the results are presented on the basis of yield (per kg of dried flower). Once the grow room timing was established, the model determined what climate modifications were needed to maintain a steady cultivation environment based on the required indoor air temperature, humidity and the outside conditions of the simulated location. Supplementary Fig. 8 illustrates a typical layout for a single grow room demonstrating the array of equipment necessary to perform these climate modifications.

The first series of model calculations quantified the necessary energy to modify outdoor air conditions, performed by HVAC, to meet the required temperature and humidity ranges of the grow room. Existing outdoor air conditions on an hourly resolution were obtained from typical meteorological year data sets from the National Renewable Energy Laboratory (NREL)¹¹. Each stage of plant life requires different indoor environmental conditions, and the desired temperature and humidity ranges that were modelled are listed in Supplementary Table 3. The HVAC energy calculations were based on the psychrometric principles of thermodynamics while accounting for the appropriate ambient pressure relative to location elevation. The air-exchange rate, modelled at a fixed rate of 30 ACH for all hours of grow operation, was obtained through a literature survey, with values ranging from 12 to 60 ACH (Supplementary Table 1). The resulting natural gas and electricity consumption were determined from the modelled HVAC energy requirements assuming a combustion heating efficiency of 80% (ref. ²⁵) and an electric cooling coefficient of performance of 3.25 (ref. ²⁶).

The model then calculated temperature and humidity values for the mixing of delivered HVAC air with existing inside growth conditions as well as operations occurring in the grow room. Operations occurring inside included added heat from high-intensity grow lights, heat loss or gain through the walls and added moisture from plant evapotranspiration²⁷ (Supplementary Table 4). Calculations of these events were based on inside heat transfer and the thermodynamic methodologies of greenhouse models found within the literature with appropriate modifications made to represent warehouse-like facilities^{27,28}. The model quantified the resulting temperature and humidity values inside the grow room, which were used to determine whether supplemental environmental control equipment, located inside grow rooms, was needed to keep the inside climate within the conditions listed in Supplementary Table 3. The supplemental equipment modelled was assumed to be electrical and included air conditioners, dehumidifiers and heaters. Further details of the energetic calculations for climate modification are provided in Supplementary Method 1 and Supplementary Fig. 9. Additional electric-based equipment was modelled, including high-intensity grow lights, circulating fans (which were assumed to be on anytime plants are in a grow room), water pumps and water heaters (Supplementary Table 5). The model determines, on an hourly resolution, the annual electricity and natural gas required to cultivate cannabis indoors at each location (Supplementary Table 12).

Beyond electricity and natural gas, material inputs, such as supplied CO₂, water, fertilizer, pesticides and fungicides, were also modelled. Supplied CO₂ was introduced into grow rooms when the high-intensity grow lights were on, and concentrations were held at the values listed in Supplementary Table 3 throughout air exchanges. Water was applied by drip irrigation at an average rate of 3.8 l per plant per day²⁹. Pumping power for water delivery was modelled at a rate of 0.99 Wh l⁻¹ (refs. ^{10,30}). Nutrients, in the form of nitrogen, phosphorus and potassium fertilizers, were supplied through the drip irrigation system in varying amounts and times (the amounts and schedule are provided in Supplementary Table 6)³¹. Cumulatively, the energy and material inventory derived from the indoor cannabis model serves as the foundation for the environmental assessment.

Environmental analysis. The indoor cannabis cultivation model accounts for all operational energy and materials needed to grow plants from infancy through to the dried retail-ready product in an indoor, warehouse-like setting. The required

energy primarily stems from HVAC equipment and lighting, and is provided through electricity or natural gas. The materials inventory consists of inputs such as water, fertilizers, pesticides, fungicides and supplemental CO₂. The energy and material inventory was translated into GHG emissions through attributional LCA methodologies^{32,33}, with the results presented for a cradle-to-gate, per kg of dried flower, system boundary (Supplementary Fig. 6). All GHG emissions were allocated to the dried flower assuming 6.2 harvests per year¹ and an assumed yield of 0.44 kg of dried flower per plant¹⁰.

From the indoor cannabis model, electricity was quantified for 1,011 US locations and the resulting annual kilowatt hours were cross-referenced with geographically specific GHG emissions data to appropriately capture variations in electrical grid mix (see Supplementary Fig. 10 for all US locations analysed). Geographically resolved GHG emissions data for electricity generation were obtained from the Environmental Protection Agency's (EPA's) Emissions and Generation Resource Integrated Database (eGRID¹²; Supplementary Table 7 and Supplementary Fig. 11). Electric grid GHG emissions data were generated using the eGRID methodology of combining region-specific total output GHG emission rates with grid gross losses, accounting for transmission and distribution line losses. Natural gas GHG emissions were not considered geographically specific and were therefore held constant across all locations as a combination of production GHG emissions from ecoinvent v3.4 (ref. ¹³) and combustion GHG emissions from NREL's US LCI Database¹⁴. The production GHG emissions system boundary encompasses manufacturing, pressurization and distribution, and losses such as flaring, venting and fugitive GHG emissions up to obtaining natural gas at a service station. Additional energy for delivery from service station to cannabis facilities was assumed negligible. All GHG emissions data from ecoinvent v3.4 and the US LCI were equated to CO₂e values by methods outlined in the EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) version v2.1 (ref. ³⁴), which uses the same 100-year global warming potential factors as the Fourth Assessment Report of the Intergovernmental Panel on Climate Change³⁵.

Materials that required physical transport to the cultivation facility, and thus transportation GHG emissions accounting, included soil, fertilizers, fungicides, pesticides and bottled CO₂. GHG emissions data for cradle-to-gate production and transportation were sourced from ecoinvent v3.4 (ref. ¹³) and converted into CO₂e values using the TRACI v2.1 methodology³⁴ (Supplementary Tables 8 and 9). Distances from the point of manufacturing to distribution centres, distribution centres to small retail and small retail to cannabis grow facilities were modelled as 500 mi (805 km), 50 mi (80 km) and 10 mi (16 km), respectively, for all locations. GHG emissions accounting for water was also cradle-to-gate, including the necessary pipeline infrastructure to be delivered to the cultivation facility. At the end of grow facility operations, several states that have legalized cannabis cultivation require disposal of all organic waste, including the remaining plant portion that is not product, soils and fertilizers. These waste products were modelled as transported to a municipal solid waste (MSW) landfill. Transportation of organic waste to the MSW landfill and heavy-equipment operations GHG emissions data were obtained from ecoinvent v3.4 (ref. ¹³), whereas landfill organic decomposition GHG emissions were obtained from Morelli and Cashman³⁶ and Lee et al.³⁷.

One component of the GHG emissions assessment, carbon accounting, is worthy of further discussion to clarify the environmental burden assignment. The production of supplemental bottled CO₂ stems from compressing a gaseous form to a liquid form and then bottling it. The gaseous form of CO₂ is a necessary byproduct of ammonia production. As a result, it was assumed that without bottling, the CO₂ would be released into the atmosphere. Therefore, any CO₂ not used by the cannabis plants and released into the atmosphere does not contribute a burden to the cannabis facility and is instead attributed to ammonia production that is outside the system boundary of this study. Thus, the only contributing GHG emissions from bottled CO₂ are a result of the upstream materials and energy needed to transform the CO₂ gas into a liquid and deliver it to the facility. A portion of the bottled CO₂ is considered to be stored by the plant product (dried flower) based on the assumed system boundary and the final carbon content of this biomass modelled as 48% (ref. ³⁶). The carbon associated with the remaining cannabis plant matter and soil that are transported to the MSW landfill was modelled as (1) decomposing organic material leading to methane (CH₄) and CO₂ generation or (2) non-degradable, or inert, carbon that is stored in the landfill. The CH₄ generated was modelled as collected and combusted to form CO₂, oxidized to form CO₂ or released into the atmosphere as CH₄ (ref. ³⁷). The collected and combusted and oxidized CH₄ streams were not counted toward GHG emissions as they are of biogenic origin and therefore balance with the carbon uptake by the plant biomass. The only GHG emissions contribution in the system boundary comes from the CH₄ portion of degradation that is not collected and was accounted for as having radiative forcing 25 times that of CO₂ (ref. ³⁵). Stored CO₂ was accounted for as a negative GHG emission toward the overall GHG emissions from indoor cannabis production. The details of carbon accounting can be found in Supplementary Table 10.

There are additional materials required to operate an indoor grow facility, such as drip irrigation materials, plastic pots for various grow stages, cleaning supplies, latex gloves and masks for employees. It was determined that the amount

of each material required to make a 1% contribution to overall GHG emissions would greatly exceed the amount of material that cannabis facilities could feasibly consume, and therefore these GHG emissions were omitted. The GHG emissions associated with the construction of the indoor growth facility were not included as it was assumed that due to collocated grow and retail facilities, the warehouse would have been previously constructed and require minimal modifications. Additionally, the embodied GHG emissions associated with infrastructure materials were not included as they were assumed to be minimal over the operating lifetime of the indoor cannabis facility³⁸.

Cumulative GHG emissions were obtained for all 1,011 locations across the United States (Supplementary Table 12) and serve as the foundation for the US map presented in Fig. 1a. Location data and GHG emissions estimates were interpolated and displayed using Esri ArcGIS Pro v2.4 (ref. ³⁹). Values were interpolated using the kriging method, with a spherical model and lag size of 25,000 m, and masked to the boundary of the United States. GHG emissions values were interpolated two ways: first, continuously throughout the United States and second, masked to each eGRID region. The interpolated surfaces for each region were then mosaicked together for the entire United States. All calculations were carried out with a cell size of 5,000 m in the North America Albers equal area projection.

Model validation. A baseline comparison of the foundational energetic loads was made by configuring the indoor cannabis model as a standard office building to compare energy requirements with those reported in the literature. Configuring the model to a standard office building included changing lighting intensities, air exchanges and internal processes, for example, lowering the heat from lights and removing humidity from plants while also adding heat from computers and occupants. The resulting energetic intensities, measured as energy use indices, yield a median value of 456 kWh m⁻² yr⁻¹, which can be compared with the value provided by Energy Star for commercial office buildings of 581 kWh m⁻² yr⁻¹ (ref. ⁴⁰). Modelling modifications were made to simulate a laboratory facility having ACH values closer to those found in indoor cannabis facilities. The resulting energy use indices yielded a medium of 937 kWh m⁻² yr⁻¹, which compares with the Energy Star median value of 1,004 kWh m⁻² yr⁻¹ (ref. ⁴¹). These comparative energetic metrics identify that the foundational thermodynamic and heat transfer methodologies are accurate.

Further model comparisons were performed for the energy intensities observed in the literature. In these comparisons a specific energy intensity, lighting, was observed to require 2,246 kWh m⁻² of growing space and was validated at 2,460 kWh m⁻² based on model results¹⁰. In addition to lighting loads, a comparison of overarching holistic values was performed through monthly electric bills, energy and GHG emissions of cannabis grow facilities. Electricity intensities from the indoor cannabis cultivation model ranged from US\$35.96 to US\$105.22 per grow cycle per m² of grow facility, similar to values reported in the literature (US\$15.50–121.56 per grow cycle per m² grow facility)^{41,49}. As previously mentioned, the differences in energy and GHG emissions from growing cannabis indoors, in a greenhouse and outdoors were analysed in some preliminary investigations^{6,7}. Although these studies are limited in that the only source of energy considered was electricity, the results do provide a comparison metric. The range of electricity consumption for indoor production in the two reports is 1,270–6,100 kWh kg⁻¹ of flower produced annually and the results of this work are in the range 1,817–4,576 kWh kg⁻¹ of flower produced annually^{6,7}. Additionally, both reports provide values for GHG emissions from electric-based operations ranging between 562 and 3,000 kg CO₂e kg⁻¹ and the results of this work range between 541 and 3,452 kg CO₂e kg⁻¹ produced annually. Mills¹⁰ also reports 4,600 kg CO₂e kg⁻¹ final product, which is within the range observed in this study of 2,283–5,184 kg CO₂e kg⁻¹.

Limitations. We acknowledge that limitations and uncertainty exist within this body of work. Simplifications and assumptions were made primarily due to limited data availability and are most prevalent within the geographic considerations, transportation and system boundary. However, further refinement would likely lead to an increase in overall GHG emissions if modelling resolution improved, as all modelling inputs and assumptions were chosen to represent either average or conservative practice. The geographic resolution included in this analysis was limited to meteorological data and electric grid mix. However, the electric demand and variations in grid mix have the largest geographic discrepancy, and therefore improved resolution is expected to have a minor impact on overall GHG emissions. Areas of the work that would benefit from improved geographic resolution are natural gas production and distribution and material transportation distances. The system boundary considered here is cradle-to-gate and ends at the point of finished cannabis flower. However, expansion of the system boundary to include transportation to retail, packaging, use and end of life would improve the findings of this work. Additionally, several products can be manufactured from cannabis, and each product supply chain would yield different GHG emissions results.

Preliminary work was performed to investigate the uncertainty within the model, including a sensitivity analysis, as described previously. The results indicated that air exchanges, temperature and humidity ranges, and bottled CO₂ amount were the most sensitive variables to GHG emissions and therefore warrant particular attention when designing and optimizing individual indoor facilities.

Data availability

All data analysed or generated during this study are included either in this published article (and its supplementary material) or are available at GitHub at <https://github.com/haisummers/research>. Source data are provided with this paper.

Code availability

The custom computer code used to generate the results of this study, supporting data files for the code and data results from the code can be located through GitHub at <https://github.com/haisummers/research>.

Received: 13 March 2020; Accepted: 4 February 2021;

Published online: 08 March 2021

References

- Córdova, L., Humphreys, H., Amend, C., Burack, J. & Lambert, K. *Marijuana Enforcement Division - 2018 Annual Update* (Colorado Department of Revenue, 2019).
- The U.S. Cannabis Report - 2019 Industry Outlook* (New Frontier Data, 2019).
- National Survey on Drug Use and Health: Trends in Prevalence of Various Drugs for Ages 12 or Older, Ages 12 to 17, Ages 18 to 25, and Ages 26 or Older: 2016–2018* (National Institute on Drug Abuse, 2018).
- Anderson, B., Policzer, J., Loughney, E. & Rodriguez, K. *Energy Use in the Colorado Cannabis Industry - Fall 2018 Report* (The Cannabis Conservancy, 2018).
- State of the Cannabis Cultivation Industry* (Cannabis Business Times, 2020).
- The 2018 Cannabis Energy Report* (New Frontier Data, 2018).
- O'Hare, M., Sanchez, D. L. & Alstone, P. *Environmental Risks and Opportunities in Cannabis Cultivation* (BOTEC Analysis Corporation, 2013).
- Warren, G. S. Regulating pot to save the polar bear: energy and climate impacts of the marijuana industry. *Columbia J. Environ. Law* **40**, 385–432 (2015).
- Crandall, K. *A Chronic Problem: Taming Energy Costs and Impacts from Marijuana Cultivation* (EQ Research, 2016).
- Mills, E. The carbon footprint of indoor cannabis production. *Energy Policy* **46**, 58–67 (2012).
- Wilcox, S. & Marion, W. *Users Manual for TMY3 Data Sets* (National Renewable Energy Laboratory, 2008).
- Office of Atmospheric Programs Clean Air Markets Division *The Emissions & Generation Resource Integrated Database (eGRID 2018)* (US EPA, 2020).
- Wernet, G. et al. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* **21**, 1218–1230 (2015).
- U.S. Life Cycle Inventory Database* (National Renewable Energy Laboratory, accessed 2020); https://www.lcacommons.gov/lca-collaboration/National_Renewable_Energy_Laboratory/USLCI/datasets
- ASHRAE Standard 62.2-2016. *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings* (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2016).
- Guidelines for Environmental Infection Control in Health-Care Facilities* (Centers for Disease Control and Prevention, 2003); <https://www.cdc.gov/infectioncontrol/guidelines/environmental/appendix/air.html>
- Chandra, S., Lata, H. & Khan, I. A. Photosynthetic response of *Cannabis sativa* L., an important medicinal plant, to elevate levels of CO₂. *Physiol. Mol. Biol. Plants* **17**, 291–295 (2011).
- Inventory of U.S. Greenhouse Gas Emissions and Sinks Report No. EPA 430-R-20-002* (US EPA, 2020).
- Office of Energy and Environmental Affairs *Cannabis Energy Overview and Recommendations* (Massachusetts Department of Energy Resources, 2018).
- Cannabis Sustainability Working Group *Cannabis Environmental Best Management Practices Guide* (Denver Department of Public Health & Environment, 2018).
- Booth, K., Becking, S., Barker, G., Silverberg, S. & Sullivan, J. *Controlled Environment Horticulture Report No. 2022-NR-COV-PROC4-F* (California Energy Code, 2020).
- Madigan, M. J. *Illinois House Bill 1348* (Illinois General Assembly, 2019).
- Carah, J. K. et al. High time for conservation: adding the environment to the debate on marijuana liberalization. *BioScience* **65**, 822–829 (2015).
- Heald, S. *Colorado Greenhouse Gas Inventory 2019 Including Projections to 2020 & 2030* (Colorado Department of Public Health & Environment, 2019).
- Çengel, Y. A. & Boles, M. A. *Thermodynamics: An Engineering Approach* (McGraw-Hill Education, 2015).
- ASHRAE Standard 90.1-2019. *Energy Standard for Buildings Except Low-Rise Residential Buildings* (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2019).
- Fitz-Rodríguez, E. et al. Dynamic modeling and simulation of greenhouse environments under several scenarios: a web-based application. *Comput. Electron. Agric.* **70**, 105–116 (2009).
- Joudi, K. A. & Farhan, A. A. A dynamic model and an experimental study for the internal air and soil temperatures in an innovative greenhouse. *Energy Convers. Manag.* **91**, 76–82 (2015).
- Steinfeld, A. *Cannabis & Water Regulation* (The Water Report, 2019); <https://www.bhfs.com/Templates/media/files/TWR%23181.pdf>
- Nemecek, T. & Kägi, T. *Life Cycle Inventories of Agricultural Production Systems* (Ecoinvent, 2007); https://db.ecoinvent.org/reports/15_Agriculture.pdf
- Soil Feeding Schedule* (FoxFarm Soil & Fertilizer Company, 2019); <https://foxfarm.com/feeding-schedules>
- Environmental Management – Life Cycle Assessment – Principles and Framework ISO 14040:2006* (International Organization for Standardization, 2006).
- Environmental Management – Life Cycle Assessment – Requirements and Guidelines ISO 14044:2006* (International Organization for Standardization, 2006).
- Bare, J. *Tool for the Reduction and Assessment of chemical and Other Environmental Impacts (TRACI) version 2.1 User's Guide* (US EPA, 2012).
- IPCC *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. et al.) (Cambridge Univ. Press, 2007).
- Morelli, B. & Cashman, S. *Environmental Life Cycle Assessment and Cost Analysis of Bath, NY Wastewater Treatment Plant: Potential Upgrade Implications 3–9* (US EPA, 2017).
- Lee, U., Han, J. & Wang, M. Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways. *J. Clean. Prod.* **166**, 335–342 (2017).
- Guggemos, A. A. & Horvath, A. Comparison of environmental effects of steel- and concrete-framed buildings. *J. Infrastruct. Syst.* **11**, 93–101 (2005).
- ArcGIS Pro v2.4* (Environmental Systems Research Institute, 2019); <https://www.esri.com/en-us/home>
- Data Trends: Energy Use in Office Buildings* (Energy Star Portfolio Manager, 2016); <https://www.energystar.gov/buildings/tools-and-resources/datatrends-energy-use-office-buildings>
- U.S. Energy Use Intensity by Property Type* (Energy Star Portfolio Manager, 2018); <https://portfoliomanager.energystar.gov/pdf/reference/US%20National%20Median%20Table.pdf>

Acknowledgements

We acknowledge the Colorado State University GIS Centroid for generating the US results maps, specifically E. Tulanowski, S. Linn and C. Norris. We also acknowledge individuals for their continued support in reviewing this work, namely D. Browning, D. Quinn, J. Barlow, D. Trinko, K. DeRose and W. Stainsby.

Author contributions

J.C.Q. conceived the study. H.M.S., J.C.Q. and E.S. designed the study. H.M.S. and E.S. developed the HVAC modelling approach and LCA framework. H.M.S. developed the code, performed the analysis, wrote the initial manuscript and designed figures, excluding the US maps, with contributions from E.S. and J.C.Q. All authors contributed to the interpretation of the results, discussion, revisions and messaging of the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41893-021-00691-w>.

Correspondence and requests for materials should be addressed to J.C.Q.

Peer review information *Nature Sustainability* thanks Melissa Bilec, Michael Martin and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2021