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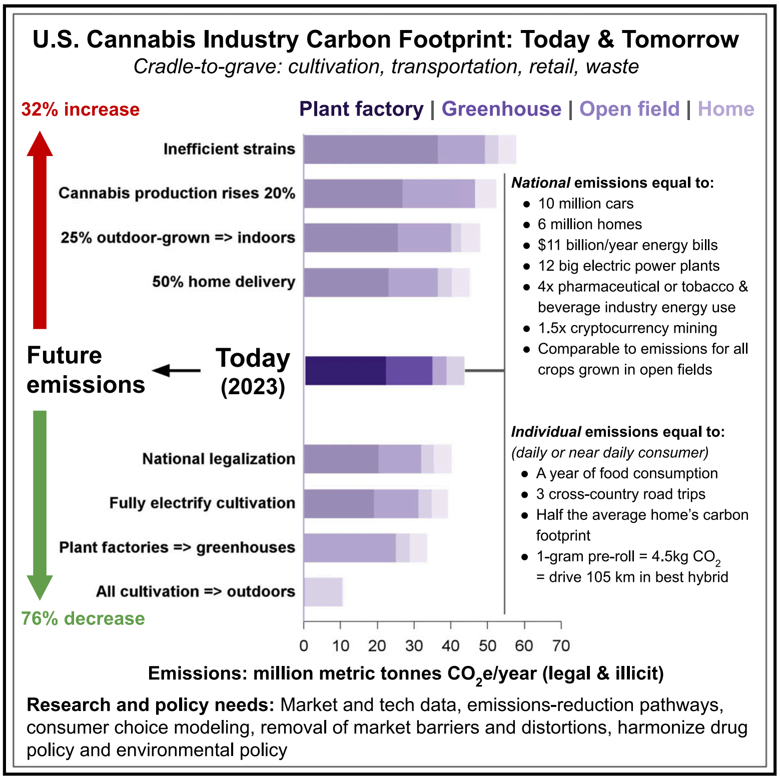
Article

Energy-intensive indoor cultivation drives the cannabis industry's expanding carbon footprint

Graphical abstract



Highlights

- The energy-intensive cannabis industry is a major emitter of greenhouse gases
- Life cycle assessment finds that outdoor cultivation could trim emissions up to 76%
- This approach requires less land than solar PV footprint for indoor cultivation
- Legalization alone will not achieve these savings; other policies are needed

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In brief

Two-thirds of the 24,000 t/year of legal and illicit US cannabis cultivation takes place indoors. Industry-wide life cycle emissions are 44 Mt CO_2e/year, equaling those of 6 M homes or 10 M cars, ~90% of which is associated with factory-farmed products. Energy use is four times that of beverage and tobacco or pharmaceutical and medicine manufacturing. Maximal reductions can be achieved by a policy-driven shift toward more outdoor cultivation, but this requires addressing market distortions and harmonizing drug and environmental policy.

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Article

Energy-intensive indoor cultivation drives the cannabis industry's expanding carbon footprint

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SCIENCE FOR SOCIETY Unquantified greenhouse gas emissions from rapidly expanding cannabis production in the US are hampering efforts by policymakers, industry stakeholders, and consumers to address climate change. Indoor cultivation can also yield worse outcomes for indoor and outdoor air quality, power grids, waste production, water use, energy costs, worker safety, and environmental justice. Key barriers to sustainable solutions include subsidies and other market distortions, low consumer and producer awareness, embargoes on public goods research, and uncoordinated drug and environmental policies. This life cycle emissions analysis encompasses energy and other cultivation inputs, transportation, retail, and waste disposal. The resulting national emissions from legal and illicit cannabis producers are more than some other industries and nearly half of a daily consumer's household carbon footprint. Since about 90% of these emissions arise from indoor producers, policy priorities should be focused there.

SUMMARY

While the local environmental harms of cultivating cannabis outdoors receive considerable attention, those from indoor cultivation are often overlooked. Windowless plant factories and high-tech greenhouses are vastly more energy intensive than open-field cultivation, conventional buildings, and some industries. With US cannabis production more than doubling over the past decade to ~24 Mt/year, the lack of greenhouse gas emissions inventories creates a serious information vacuum. This life cycle assessment finds industry-wide emissions of ~44 Mt CO_2e/year (half from legal producers), equaling those of ~10 million cars or ~6 million homes. The underlying 595 PJ/year energy consumption ($11 billion/year) is on par with that of all other crop production, four times that of the pharmaceutical and medicine or beverage and tobacco industries, one-third that of data centers, and half again greater than that of cryptocurrency mining. National legalization alone would achieve only modest reductions, but it could enable more potent policies; the most promising avenue could reduce emissions by up to 76% by shifting more cultivation outdoors.

INTRODUCTION

Controlled environmental agriculture—the industrialized cultivation of plants indoors, often without sun, wind, rain, or soil—is a burgeoning practice.[1] The associated new technologies and practices result in consequences that are still being understood. Among these are elevated resource requirements, including energy inputs. Cannabis has become the most energy- and carbon-intensive crop as cultivation has shifted from open fields to indoors, covering an area of ~5 million square meters (~270 average Walmart stores) in the US. This physical footprint is greater than that dedicated to artificially lit food production and floriculture across the country.[2,3]

By 2022, half of US adults had tried cannabis,[4] with 22% (62 million people over age 12) using it that year.[5] Of these, 17.7 million used it daily or almost daily—more than those who drink alcohol at similar frequencies, although use rates across the entire population are about one-third lower for cannabis than alcohol.[6]

US sales of legal cannabis products are projected to reach $31 billion in 2024,[7] not including the value of cannabidiol (CBD) products (an additional ~$4 billion/year)[8] and home cultivation, valued at approximately ~$7 billion/year (see the supplemental information). This suggests that total annual sales are on the order of $100 billion, given that two-thirds of the ~24 kt/year production still occurs in the illicit market.[2] For reference, revenues

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Sources of cannabis industry greenhouse-gas emissions

	Within study system boundary	Outside study system boundary
Site	• None	• Construction-related land-use changes (vegetation, soil carbon, etc.) • Energy embodied in facility construction, infrastructure, equipment
Cultivation energy (stages: clone, vegetative, and flower)	• Heating • Cooling • Dehumidification • Air movement • Lighting • Irrigation water heating • Water pumping	• Carbon-dioxide management • UV disinfection • Odor removal • Soil steaming after harvest for disinfection and reuse • Water recovery and wastewater treatment • Snow-melting (greenhouses) • In-field farm equipment • Data acquisition • On-site offices, storage, or other work areas • Miscellaneous equipment (motorized shading, processing, etc.) • Robotics and other automation • AI associated with process control (on-site and in data centers)
Emissions embodied in cultivation inputs	• Water (supply and treatment) • Carbon-dioxide for enrichment (purchased) • Fertilizers • Pesticides, fungicides, herbicides • Soils and other growing media • Fugitive emissions (refrigerant leakage)	• Carbon-dioxide for enrichment (if manufactured on-site) • Plastics (growing trays, netting, irrigation lines, etc.) • Packaging • Disposable goods (lamps, filters, etc.) • Greenhouse-gas fluxes from soil or other growing media
Net yield (volumetric sources and flows)	• Cultivated amounts: warehouse, greenhouse,and in-yield cultivation (legal and illicit production) • Product destruction due to testing failures for safety or mislabeling • Interdiction of illegal goods	• International import/export • Crop losses during cultivation (mold, disease, power outages, etc.) • Product destruction due to recalls • Product destruction due to overproduction
Post-harvest	• Drying/curing	• Cold storage • Extraction (process energy and increased cultivation due to losses) • Manufacture of derivative goods (edibles, beverages, vapes, etc.) • Packaging • Product testing
Transportation	• Worker transport • Materials transport • Waste transport	• Transport during facility construction • Consumer transportation to retail • Dispensary delivery services • Illicit interstate or transnational product transport
Retail	• Energy use of legal dispensaries	• Energy use of illicit dispensaries • Energy embodied in facility construction, infrastructure, and equipment • Land-use changes associated with facilities
Waste disposal	• Landfill operations • Fugitive methane from anaerobic processes • Landfill sequestration of biogenic carbon • Weathering of basalt in artificial grow media	• Carbonaceous materials used to dilute landfilled harvest residues • Methane generated in the wastewater system due to organics in effluent

Figure 1. System boundary for estimating the US cannabis industry's carbon footprint and factors included in this study

from corn were $89 billion in 2022.[9] As another indicator of scale, industry sources report 165,400 legal cannabis businesses operating across the US,[10] employing approximately 440,000 people.[11]

As federal lawmakers edge toward cannabis reforms, drug policy inadvertently finds itself at cross purposes with climate and energy policies. These dynamics have been largely overlooked, and the single peer-reviewed estimate of the industry's energy-related carbon footprint is more than a decade old, placing the national greenhouse gas emissions at 15 Mt CO_2e/year (equivalent to those of 3 million average cars).[12] Policymaking is thus being conducted without a clear grasp of the problem's current dimensions.

The present update identifies substantial recent growth in emissions, driven by the combination of elevated production levels and dramatic structural changes in the industry toward more energy-intensive cultivation methods. Disaggregating emissions into multiple sub-categories helps with pinpointing areas of specific relevance, developing quantitative analysis of future emissions pathways for a range of technology and policy scenarios, and identifying remaining data gaps and research needs.

In this analysis, "cradle-to-grave" greenhouse gas emissions are estimated for activities spanning cultivation, agricultural inputs, transport, retail, and waste disposal, building upon a previous life cycle assessment of cannabis cultivation in legal warehouse-type structures hereafter referred to as "plant factories."[13] The analysis significantly broadens the system boundary (Figure 1), allowing for a more comprehensive and nuanced emissions assessment that distinguishes among plant factories, greenhouses, open-field methods, and home cultivation while extending prior building-level results to the national scale, with separate treatment of legal and illicit cultivation practices, and providing a far broader array of indicators (e.g., national energy expenditure). This new work integrates extensive modeling studies and empirical data not available when the original 2012 assessment was conducted. The resulting estimated aggregate emissions are greater than those of several major industries and

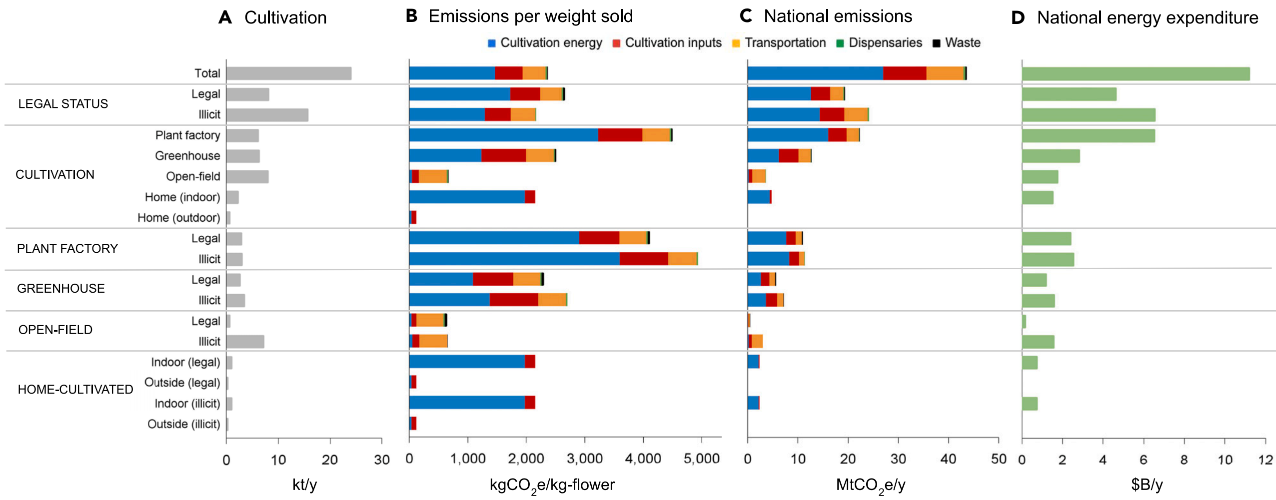

Figure 2. US cannabis production, normalized emissions, aggregate emissions, and energy expenditures by cultivation method and legal status (2023)

The higher per-weight amounts for illicitly grown cannabis are driven primarily by 5% of electricity production by off-grid diesel generators and eradication losses. With severe overproduction in the current market, the emissions per weight sold could be significantly higher across all categories. Values include energy use at the point of consumption, with electricity counted at 3.6 MJ/kWh. Data are shown in Tables S1 and S3–S7.

represent a significant part of individual consumers' carbon footprints. Emissions have risen substantially despite widespread state-level legalization efforts, which suggests that relying on market forces alone is not a viable climate strategy for this industry. More targeted policy initiatives are needed to manage emissions, and the greatest potential lies in guiding the industry toward a much larger share of open-field cultivation.

RESULTS

A growing carbon footprint

National emissions are determined by applying measured facility-level field data and model results to the corresponding production volumes and market segments. Specific sources of emissions considered include energy used directly in the cultivation process (Table S3) and embodied in growing media (Table S5), agricultural inputs,[13] and water supply; energy used at retail dispensaries (Table S6), associated with the transport of materials, workers, and waste; and fugitive emissions from leaking space-conditioning equipment refrigerants[14] and landfill-related methane releases from the decomposition and sequestration of carbon in buried biomass (Table S7). Not all sources of emissions could be quantified, reflecting a lack of data or reliable estimation methods.

Aggregate greenhouse gas emissions from the US cannabis industry reached ~44 Mt CO_2e/year in 2023 (Figure 2C). This represents 1% of total national emissions from all sectors of the economy and corresponds to an annual energy expenditure of ~$11 billion. The results are segmented by industry activity, facility type, and legal status (Figure 2; Table S1).

At the national level, energy used in the cultivation process is the dominant source of emissions (63% of the total), followed by emissions embodied in the manufacture of cultivation inputs (20%), transportation (17%), waste management (<1%), and retail dispensaries (<1%), with these shares varying widely depending on cultivation method and other factors (Tables S3–S7). Products cultivated without the assistance of daylight in plant factories and indoor home locations are associated with 62% of the industry's emissions, 29% for cultivation in greenhouses, and 9% for cultivation in open fields. Illicit operations produce 55% of total emissions, much less than their market share of flower production, thanks primarily to a larger proportion of open-field cultivation.

Cannabis energy demand and emissions are rising. The current estimate is three times greater than one published 13 years earlier.[12] After adjusting for system boundary differences between the two studies (the earlier of which analyzed plant factories only), the net effect is a 2.6-fold increase in overall emissions. During this period, a 40% reduction in per-unit electricity emissions from a progressively cleaner power grid offset some emissions growth; however, these gains were overwhelmed by a 1.4-fold increase in harvests and a nearly 5-fold increase in amounts grown indoors.

The corresponding average 2023 carbon emissions for commercial operations is ~4,500 kgCO_2e/kg-flower for plant factories, ~2,500 kgCO_2e/kg-flower for greenhouses, and ~700 kgCO_2e/kg-flower for open-field cultivation (Figure 2B). Due primarily to differences in energy mix, the average emissions of illicit operations are higher than those of legal ones. Less-intensive home cultivation produces roughly 2,150 kgCO_2e/kg-flower, half of plant factory emissions levels (Table S3).

Fueling the underlying intensive energy requirements, the indoor environment in plant factories is maintained at clear-sky tropical conditions, irrespective of the outdoor climate or time of day or year. Artificial lighting levels are brighter than the sun. Air is mechanically conditioned and often recirculated at 30–60 times the rate of that in homes, and dehumidification is essential to preempt mold growth, while other energy-intensive processes such as water purification and odor mitigation technology further elevate energy use. Industrial greenhouses

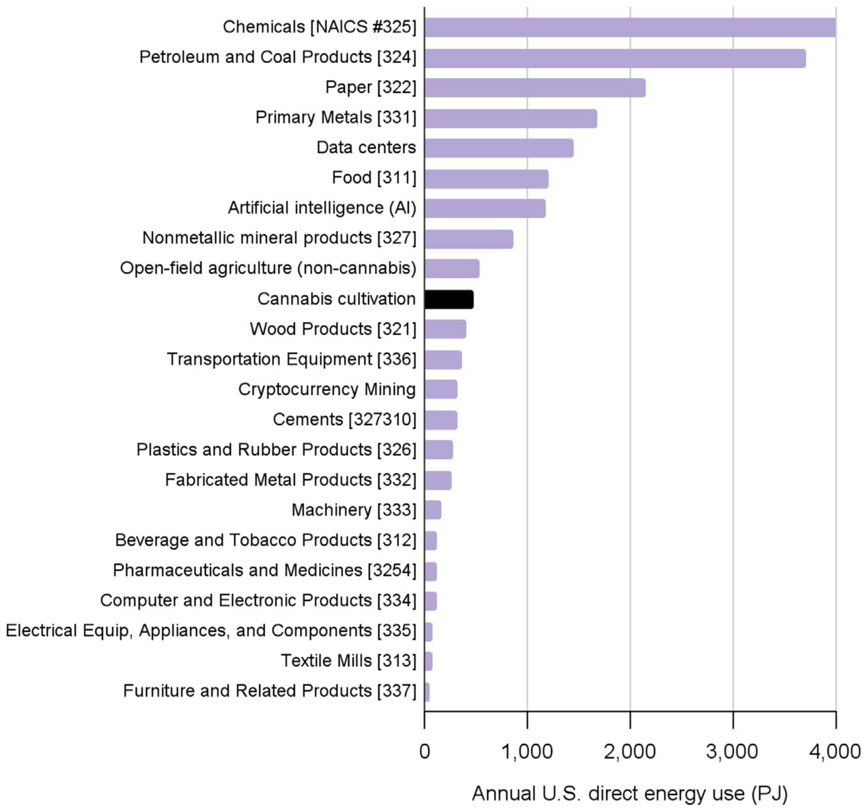

Figure 3. Energy use for cannabis cultivation in context with that of other US industries

Values for the non-cannabis sectors include direct on-site uses of fuel and electricity in the production process at US-based facilities, with electricity counted at 3.6 MJ/kWh. For comparability to other sectors, the values for cannabis include only those associated with cultivation and post-harvest processing, excluding energy embodied in inputs or that from retail activity, transportation, or waste disposal. Data are shown in Table S2.

heavily augment daylight with electric lighting, and their poor insulation and large glazed areas typically create significant air conditioning and heating needs. To accelerate plant growth, energy-intensive CO_2 enhancement maintains indoor levels 2–4 times outdoor ambient concentrations, which, together with other non-energy inputs, further increases embodied greenhouse gas emissions. In sum, cultivating a given amount of cannabis indoors results in approximately 30 times more emissions per kilogram than cultivating outdoors. When incorporating emissions from all other stages of the life cycle, cannabis cultivated in plant factories is 7 times more emissions intensive.

Indoor cultivation is also far more energy intensive than more familiar building types and manufacturing processes. For comparison, while a typical cannabis plant factory is similar in size to an average Walmart, it uses ~100 times more energy. Energy use per unit floor area is ~600 times that of conventional storage warehouses and ~40 times that of energy-intensive hospitals. Energy use per unit weight is ~200 times that of manufacturing best practices for aluminum, ~2,200:1 for blast furnace steel, and ~10,500:1 for Portland cement.

For further context, a set of equivalencies computed in Table S2 compares cannabis energy and emissions to national energy use, a wider variety of other building types, conventional agriculture, and a number of familiar activities ranging from diet to driving. Among these comparisons, the cannabis industry produces greenhouse gas emissions equivalent to those from ~10 million average cars or ~6 million US homes. The carbon footprint of energy use for cultivation in cannabis plant factories (per unit weight) ranges from 200 to 700 times that of cultivating lettuce and other common crops in similar facilities,[15] and accordingly, cannabis production nationally is comparable to the aggregate energy use in conventional indoor and open-field agriculture (excluding the livestock, poultry, and dairy segments) (Table S2).

The associated energy use can be compared to that of other industries (Figure 3). The direct, on-site use of fuels and electricity by the cannabis industry is 4 times that of domestic use by the US pharmaceutical industry and beverage and tobacco manufacturing. Energy use is a third of what is used by data centers nationally, and 1.5 times that of cryptocurrency mining, topics that have garnered considerable attention.[16]

From the individual's perspective, emissions associated with the average annual cannabis consumption are equal to 11% of the average home's energy-related emissions, rising to 24% for the average weekly consumer and 43% for the average daily or near-daily consumer. Emissions for this latter group (assuming cultivation in plant factories) are 105% of those associated with the average American diet and 155% of a healthy vegetarian diet, while values for the average cannabis consumer are 26% and 38% of the average diet, respectively.

Enormous potential exists for emissions reductions, but there is also a risk of increases

Market evolution and policy choices will significantly influence future emissions trajectories (Figure 4). Key upward pressures include rising demand for cannabis, changes in industry structure, reversion of legal producers to the illicit market (where electricity sources can be dirtier and less efficient) in response to what are perceived as overzealous regulations, and a trend toward derivative products[17,18] that embody added processing energy. For example, if 50% of sales are eventually conveyed to consumers by delivery services, then emissions would rise by 4% (1.5 Mt CO_2e/year). Reducing the emissions of industry vehicles by three quarters would lower overall emissions by 13% (5.5 Mt CO_2e/year). If 25% of open-field cultivation shifted indoors, then emissions would increase by 10% (4.5 Mt CO_2e/year). A 25% increase in cultivation energy resulting from new processes (e.g., increased artificial illumination, wastewater recovery, and automation) would increase overall emissions by

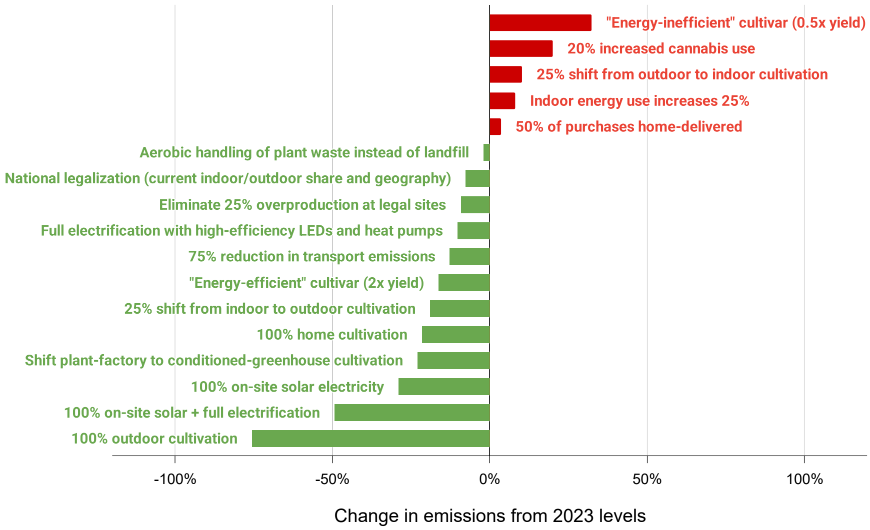

Figure 4. Industry-wide emissions impacts from changes in policy and market structure

Values apply to aggregate emissions from all forms of production (plant factory, greenhouse, and open field) and all segments (commercial/home and legal/illicit), including energy use, cultivation inputs, dispensaries, transportation, and waste disposal (baseline emissions of 44 Mt CO_2e/year). "Indoor" refers to conditioned greenhouses together with plant factories and indoor home cultivation. Note that the "full legalization" case does not model the possible effects of relaxing restrictions on interstate commerce or other policies that could be deployed in a legal market. The electrification, solar, and reduced transport emissions cases are technological thought experiments, irrespective of a cost-benefit analysis that would likely moderate these changes. The scenario values are not additive.

8% (3.5 Mt CO_2e/year). Choice of cultivar (sometimes loosely referred to as "genetics," "strain," or "variety") is a major source of variability (Figure 5), ranging from a 32% (14.1 Mt CO_2e/year) emissions increase to a 16% reduction (7.1 Mt CO_2e/year).

Potential moderating factors include manufacturer shifts away from indoor cultivation in response to regulatory changes, economic and reputational risks, decarbonization initiatives, increased transport efficiencies, and improved waste management practices. Meeting all existing electricity demands for cultivation with on-site solar would achieve a 29% emissions reduction (12.6 Mt). Conversely, full electrification plus trimming energy use via universal adoption (a stretch goal) of key energy efficiency technologies (unmoderated by cost-benefit considerations), such as light-emitting diode (LED) lighting and heat pumps, would achieve a 10% reduction (4.4 Mt CO_2e/year). Combining solar and electrification would increase these reductions to 49% (21.5 Mt CO_2e/year). Interestingly, in the solar-plus-efficiency case, some emissions remain due to the leaking of fugitive refrigerants, which are potent greenhouse gases, as well as a small amount of diesel fuel that continues to be used at off-grid locations where large solar systems are not practicable.

Technical nuances

Energy use and greenhouse gas emissions are key indicators and normalized by the functional units of cultivation area or the weight of the finished "flower" reaching consumers to create efficiency or productivity metrics. The resulting intensities, e.g., MJ/m^2-year, GJ/kg-flower, and CO_2e/kg-flower, vary systematically by cultivation method. They are applied to production volumes for scale-up to national energy use, emissions, and expenditures (Table S1). Weight-based metrics are useful for assessing and comparing production method use, while area-based metrics are useful for energy infrastructure planning at the facility and grid levels, as well as the scale of generation required for on-site energy production. Metrics of energy per unit product potency (Figure 5C) are more precise and useful in comparing energy inputs across different methods of processing but are very rarely provided in the literature.

Modeling and precision benchmarking of measured field data each yield important insights. The judicious use of these methods is valuable for facility designers, operators, and policymakers (discussed further in the supplemental information). Measured field data provide real-world insights that model-based analysis may not, an essential check on model accuracy, and opportunities to validate and calibrate models or create "digital twins" for making energy savings estimates. Cannabis field studies, however, are unstandardized, vary widely in quality and rigor, and are often poorly documented, especially in terms of the extent of the system boundary being evaluated.[21] The present analysis draws on an exhaustive literature review that yielded measured energy use estimates for 325 sites or trials at given sites and an additional 15 modeling studies (Figures S1 and S2).

The confluence of horticulture and energy issues makes for fascinating and sometimes surprising analyses, such as the non-proportionality of energy inputs and yields, evidenced by a 5-fold variation in energy requirements as a function of plant cultivar and significantly varying benefits of energy efficiency strategies such as LED lighting even for a particular cultivar (Figure 5), and the large role played by local climate and operational variables.[13]

Additional analytical subtleties are evident in that the highest modeled normalized carbon footprint (5,184 kgCO_2e/kg of finished flower[13]) for plant factories in a model-based study spanning all 50 states occurs in Hawaii, a climate normally thought of as well suited for high-quality open-field cannabis cultivation. Cultivating indoors there entails intense dehumidification and air conditioning in a hot climate compounded by the heat generated from high-wattage lighting, together with one of the country's highest electricity emissions factors nationally due to an electricity grid heavily dependent on oil.

As detailed in the supplemental information, applying emissions intensities to obtain aggregate (e.g., national) estimates begins with estimating national cannabis production and consumption; adjusting for second-order adjustments arising from crop failure, eradication, and post-harvest seizures; and products destroyed following consumer safety tests. The

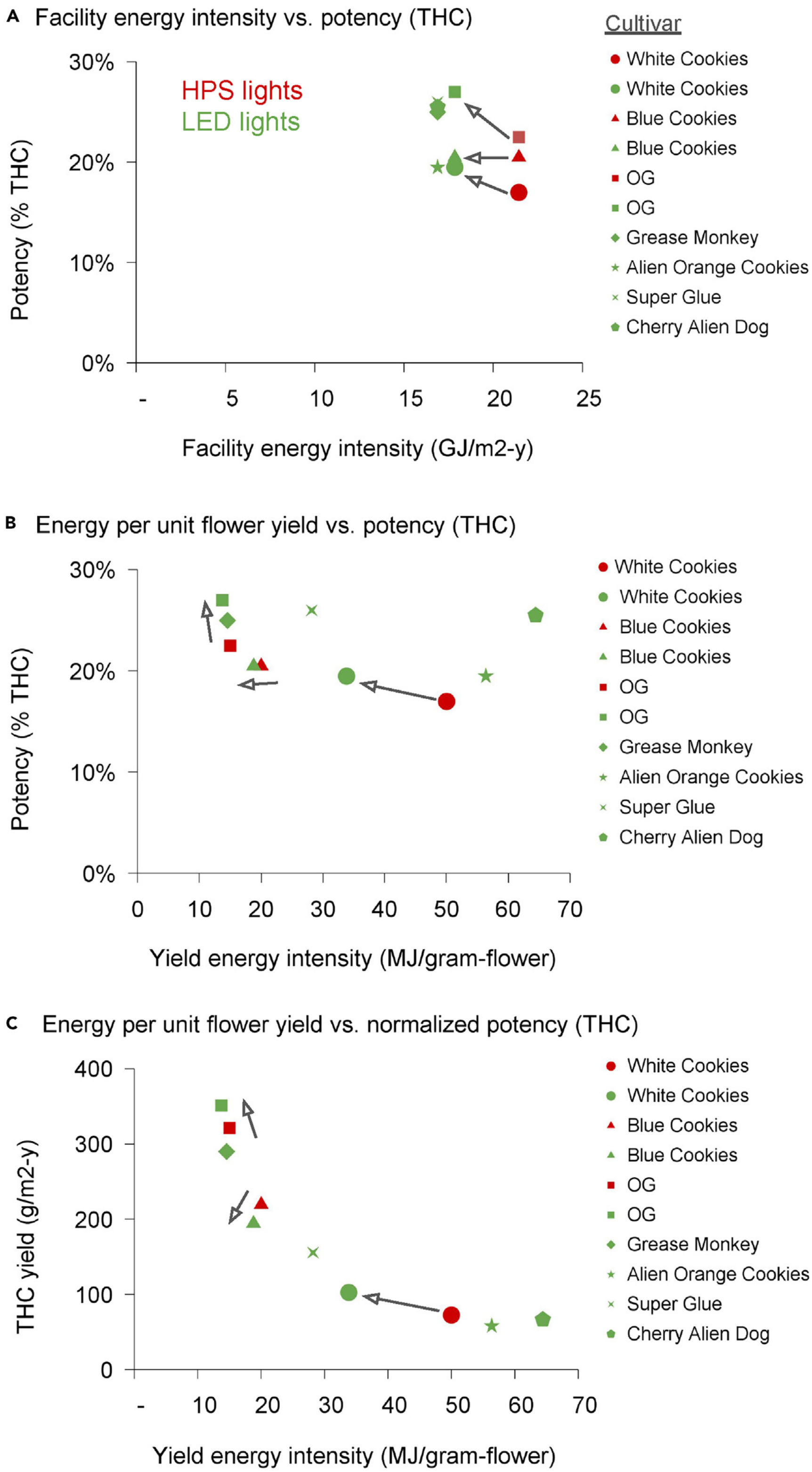

Figure 5. Ten cannabis plant factory cultivation trials with HPS versus LED lighting and seven cultivars

Lighting technologies: 1,000-W Nanolux Super DE high-pressure sodium (HPS; in red) and 660-W Fluence SPYDRx PUS light-emitting diode (LED; in green). Arrows indicate changes for the switch from HPS to LED for three paired cultivars, with energy savings per unit weight of finished flower ranging from 32% in one case to 9% and 6% in the remaining two cases.[19] Energy per THC (active ingredient) declined by 41%, 6%, and 24%. Four other cultivars were grown under LED only. Another study[20] found higher energy use per unit weight for cultivation under LED lights.

combined effect of these factors is that final consumption is about ∼20% less than gross cultivation, making the energy intensity of the product ultimately sold correspondingly higher. After these adjustments, energy use and emissions are allocated to 18.4 kt of cannabis flower ultimately reaching the market either directly or via derivative products.

Uncertainties and sensitivity analysis

Emissions would be higher were the processes outside the system boundary shown in Figure 1 incorporated. A few of those possibilities can be tested, e.g., the impacts of land-use change in forested areas (Table S8) and emissions associated with post-harvest extraction of active ingredients, although most lack sufficient data for in-depth evaluation and scale-up to the national level. Of particular interest, a scoping calculation of emissions from the common supercritical CO_2 extraction process to obtain oils for sale in the market or incorporation in derivative products suggests a non-trivial 11%–31% increase in total emissions per kilogram (Table S9).

With respect to estimates of energy use within the cultivation process adopted here from Summers et al.,[13] the greatest modeling uncertainties influencing facility-specific emissions, in order of decreasing importance, are the plant yields per unit cultivated area, hourly air change rates (ACHs), and the levels of supplemental carbon dioxide. Reductions in plant yields increase emissions per unit weight, implying more cultivation area (and associated energy use) to meet national production targets.

There are various noteworthy market uncertainties. Cannabis production levels and practices in the illicit market are less well characterized than those in the legal market, which are ostensibly reported to regulators and the trade press. While energy intensities for illicit producers may well be higher than those developed here for legal operations, there are no public domain measurements to guide a more nuanced assessment, so here they are assumed to be identical. Importantly, no allowance for overproduction is built into the emissions-intensity estimates, in which event emissions per unit of product reaching consumers would increase proportionately. As outlined in the supplemental information, however, overproduction is considerable in many parts of the country, as well as Canada.

Sensitivity analyses suggest robust findings insofar as they are well within the broad magnitudes of potential emissions reductions from most policy interventions (Figure S3). Cautious estimates have been adopted for analysis where multiple data sources are available.

DISCUSSION

Modeling how emissions *will* evolve is trickier than how they *might* evolve. Absolute emissions would rise with one-to-one proportionality were cannabis demand to increase and cultivation practices to remain the same. The prime driver toward lower energy intensity and emissions would be a substantial regulated or voluntary shift from indoor-grown to open-field cannabis. Indoor energy use could also be managed downward, but there is low interest among facility operators in energy efficiency and real limits to how much energy can be cost effectively saved or how much renewable energy could be applied. There are strong countervailing factors, including structural, market, and regulatory biases that favor indoor cultivation and a continuing trend toward the replacement of labor with machines and more energy-intensive indoor processes. Persistent gaps in available market data impede the quantification of these effects at national scales.

Potential drivers of increased open-field cultivation

Open-field cannabis cultivation is well established and, until the 1970s, was essentially the only method in use. Inducements to cultivate outdoors include legalization, substantially lower capital and operating costs thanks primarily to less expensive land, and the absence of energy-using equipment. Open-field cultivation also entails less waste in the form of spent lamps, artificial growing media (typically replaced with each cultivation cycle), assorted plastics, and contaminated wastewater. Furthermore, depressed product prices have put cultivators under severe economic stress, which has made the energy costs of indoor cultivation (often ~40% of total operating expenses) highly problematic and raised solvency risks for indoor cultivators, particularly in the off-grid illicit market, where costly diesel generators are often required. Increased product prices would reduce the role of energy in profitability and, thus, could reverse this trend.

A key factor shaping the extent of open-field cultivation in recent years has been a shift in consumer preferences toward extracts typically obtained from cannabis cultivated outdoors, a use for which flower appearance is unimportant to consumers. Between 2018 and 2023, marking a shift toward products based on extracts, the number of American consumers choosing cannabis flower dropped from 80% to 70%.[18] Among the products made with extracts, only edibles showed a marked upward trend (41%–59% of consumers), while other forms (concentrates, vape oils, topicals, tinctures, etc.) held roughly constant market shares. Whether this trend will continue and how growth in overall demand might offset any reduction in emissions per unit of consumption is unclear.

A shift toward consumer interest in the "green" attributes of cannabis products would also favor open-field cultivation, but there is little evidence of this at present. Instead, the dominant preference is for cosmetically appealing and higher-potency indoor-grown flower. Lack of consumer information, such as product labeling, certainly impedes environmentally based consumer decisions and increases vulnerability to greenwashing, and salespeople and other industry actors have also demonstrated low literacy about such matters.[22]

Potential drivers of increased indoor cultivation

In recent years, the cannabis industry has experienced profound structural change, including higher-intensity indoor cultivation at increasing scales. Perhaps counterintuitively, indoor cultivation expanded markedly following legalization at the state level. The share of indoor cultivation rose from ~33% in 2012[12] to ~65% in 2023[2] while widespread legalization ushered in an increased demand (up 142% since 2012)—implying a nearly 5-fold increase in the quantity grown indoors—together with a tripling in potency since 1995.[18] Today, indoor cultivation in the US—particularly in plant factories—is more common for cannabis than for any other field crop.[2,3] Eradication reports[23] demonstrate the presence of indoor cultivation in 32 of the 37 states—and one in five total sites—showing that illicit cultivation also commonly occurs indoors.

Drivers of indoor cultivation beyond secrecy and security include precision control, crop standardization, weather protection, steady production throughout the year (four to six harvests are typical), avoiding rogue pollen from male plants that can ruin a crop, increased potency, and local prohibitions on open-field cultivation. Desirable cosmetic appearance combined with preferential marketing have led to retail prices for indoor-grown products that are about twice the level of those for outdoor-grown products. Although a commonly stated rationale for indoor cultivation, medical and quality-related attributes of indoor-grown cannabis are not clearly superior by these measures,[24,25] fungus outbreaks can be more common,[26] and the marginally higher potency is not necessarily healthful.[27] Meanwhile, the prospect of enormous permitting revenues incentivize cities to promote urban cultivation, which must almost universally be done indoors.

Inertia to improved energy efficiency, electrification, and uptake of onsite renewable energy

Although cannabis—legal and illicit—is the largest US cash crop by value, the uptake of energy-saving measures in the indoor agriculture industry is slow, e.g., LED lighting is serving only 2% of lighting-supplemented greenhouses and 11% of plant factories.[3] This is perhaps a reflection of sinking profits and short financial planning time horizons. More than half of growers in one Colorado survey reported requiring at least a 33% return on energy-saving investments, while few measures evaluated for that same area offered such returns.[28] Creating further inertia, proposed mandatory requirements for LED lights have been met with industry skepticism and opposition,[29,30] and such equipment still uses prodigious amounts of energy. Perhaps fueling these concerns, one comparative assessment[19] (Figure 5) found widely varying savings from LED lights. Meanwhile, a recent study projected a meager ~10% energy savings "technical potential" for the full penetration of all viable measures—whether cost effective or not—for cannabis facilities in Canada and the US.[31]

Renewable energy has its own considerations and constraints. Covering conventional cannabis plant factory rooftops with solar panels would meet only ~5% of electricity needs for typical cultivation practices.[32] Full conversion to solar photovoltaic energy to serve existing cannabis producers' electricity needs nationally would require 33,000 ha (127 square miles) of land (many times that otherwise needed to produce the same yields with open-field cultivation), rising to 46,000 ha (178 square miles) were the sector to fully electrify (the only path to net zero emissions) (Table S2). Moreover, diverting finite renewable energy to indoor cannabis producers would slow progress toward decarbonization, particularly in light of growing electricity demand from electrification efforts and other expanding activities, such as artificial intelligence (AI), thereby contributing to delays in retiring fossil fuel power plants. For perspective, cannabis development under remaining entitlements in the southern California Coachella Valley desert communities would exceed the state's entire production of electricity from wind power.[32]

Of broader relevance to decarbonization goals, indoor cannabis cultivation is not particularly "grid friendly." The industry's current electricity use (35 TWh/year) is equivalent to 9 GW or the output of 12 typical electric power plants (Table S2). Unanticipated load spikes straining electrical infrastructure can lead to outages also affecting nearby customers (Table S10). Industry expansion and substitution of fuel with electricity to decarbonize will further elevate peak loads. Small producers are not readily able to shift operations to different times of day, and many larger producers have already diversified their load (to reduce costs) and remain highly constrained by the required continuous 12–18 h/day on times for lighting.[29] Electricity theft, industry expansion, and market volatility further complicate long-term utility planning.

Identifying optimal pathways

Given the specter of rising damages from human-caused climate change and the narrow potential for energy efficiency and renewable energy in this industry, excessive greenhouse gas emissions from indoor cannabis production are arguably a luxury that society cannot afford. Meanwhile, wise federal policymakers will also recognize that the boom-and-bust risks already manifesting in the industry are likely attributable, in part, to high energy costs.

Further fine-tuning the energy efficiency of indoor cultivation optimizes the suboptimal, in that there is no demonstrated path through which the indoor industry's emissions could be reduced to align with national climate stabilization targets. Reverting to conventional open-field cultivation methods—particularly as done in the illicit market when environmental protections are disregarded[33–35]—would achieve deep emissions reductions but could also produce environmental impacts, albeit many of which are avoidable via improved practices. Thus, as with many forms of agriculture, a more sustainable model for open-field cultivation is needed. The conventional wisdom that indoor production is less water and land intensive hinges on analyses with overly narrow system boundaries together with "apples-and-oranges" comparisons of highly optimized indoor cultivation with inefficient open-field methods based on a legacy of lower land costs and inexpensive or even free water. When both methods are optimized, open-field cultivation requires less of these resources per unit of final product (Figures S4 and S5).[36] Comparisons often assume only one open-field crop per year, while under ideal conditions, up to three can be achieved. Importantly, when accounting for water embodied in power production and additional land required for decarbonization via renewable energy production, even conventional open-field cultivation methods are less resource intensive.

A shift to purely open-field cultivation—following best practices for water and land use and employing other environmental safeguards—would achieve 76% (39.9 Mt CO_2e/year) emissions reductions. Even with current unoptimized cultivation methods, only 0.003% of American farmland would be required to meet the national demand in that scenario, which is similar to that already in cultivation for hemp. This is the most elegant solution.

In addition to climate benefits, with sustainable open-field cultivation, a set of related environmental issues are intrinsically addressed. These include hazardous wastes such as mercury in lamps, water use, occupational safety risks arising from indoor pollution in grow facilities, light and noise pollution, nuisance odors, and other emissions into heavily populated airsheds.[32,37]

The potential role of legalization

Legalization is often invoked as the means for solving problems in the cannabis industry. As of November 2024, 38 states, the District of Columbia, and four US territories had legalized cannabis for medical or recreational use.[38] Four additional states had decriminalized cannabis, and nine others allowed low-tetrahydrocannabinol (THC) products.[38] This advanced state of legalization offers a natural experiment with regard to greenhouse gas emissions impacts, although clearly the prospect of federal legalization has separate implications.

The first-order impacts of successful legalization—assuming all illicit producers transition to the licensed operations—would be the cessation of interdiction and the significant lost embodied energy in products that are subsequently destroyed, along with the reduced use of diesel-powered electricity generation in off-grid locations in favor of an electric grid that is cleaner in most areas. Offsetting factors would include increased energy use from replacing products destroyed following legally mandated safety testing, more regulated landfills of cultivation waste and the associated emissions, and more brick-and-mortar dispensary facilities with their associated energy use. Any incremental impact would be further moderated by the fact that half of illicit cultivation is already conducted outdoors.[2] The net effect of these factors is relatively modest direct emissions reductions of 8% (3.3 Mt CO_2e/year), assuming no geographic shift in cultivation.

In the event that interstate transport bans were lifted, related questions would be whether states with climates that do not favor open-field cultivation (albeit seasonal open-field cultivation does occur in all states) would opt instead to import from states where it is more feasible (and where indoor cultivation is also less energy intensive) and to what extent this benefit would be attenuated by existing large volumes already flowing over state lines from these locales via the illicit market. As indicators of the scale of illegal exportation, at one time, California was estimated to be producing ~7,000 t/year of cannabis while consuming only ~1,000 t in state,[39] and licensed production in Oklahoma exceeded in-state demand through the legal market by 32-fold.[40]

About two-thirds of the nation's current legal production already occurs in states with mild climates, yet indoor cultivation there remains widespread. As a prominent illustration, recent estimates suggest that California produces 45% of the nation's (legal and illicit) cannabis, much of which is grown indoors.[41] Were the geography of cultivation to recalibrate based on climate, shipping distances would increase, especially to markets that have, for decades, deemed products from western states to be superior, although the reduction of existing long-distance illicit transport (not quantified in this study) would offset that to some degree, perhaps significantly. These factors notwithstanding, second-order benefits of legalization could be very large, resulting from additional policies that can only be applied in legal markets.

Particularly vexing, experience to date suggests that illicit markets remain strong even where cannabis is legalized, thanks to retail prices that may be doubled by layers of taxation, onerous and costly licensing and reporting processes, mandatory product testing, retail restrictions, scarcity of banking and insurance services, and opposition of local governments to cultivation or sales.[42]

Policy prescriptions

National energy use and greenhouse-gas emissions associated with cannabis cultivation are on par with those of all other crops, yet it is rarely addressed by policymakers. This assessment suggests that rebalancing production in favor of open-field cultivation is the most promising policy measure for reducing these impacts. Despite its potentially low direct impacts, full legalization in the remaining twelve states, and federally, is essential to deploying and scaling up more impactful policies and structural changes such as those outlined in Figure 4.

Free markets are often touted as ensuring economic efficiency (a precursor to energy efficiency), but other studies suggest that cannabis markets are not, in practice, functioning in this manner following state-level legalization.[43] This appears to be borne out in the case of energy resources as well. Some existing policies in legalized markets exacerbate the problem, including resource-intensive packaging regulations that increase waste volumes[44]; multiple forms of subsidies or market distortions that differentially reward indoor cultivation, including hefty utility "rebates" for indoor facilities that attain small energy savings, while no incentive is offered for open-field operations saving vastly more[32]; and fee structures and grants that preferentially benefit indoor cultivators. Some states that have legalized cannabis prohibit cultivation outdoors, and some selectively require that only home cultivation be conducted indoors, while others make varying decisions at the local level, e.g., as seen by jurisdictions prohibiting open-field cultivation across about half of California's land area.[45] Meanwhile, state-level legalization has triggered overproduction (see supplemental information) and a shift toward indoor facilities, both of which boost energy use appreciably while fueling retail price drops[18] that, in turn, make it harder to justify investments in decarbonization. For context, if overproduction among legal commercial producers was currently at the hypothetical level of 25%, then rebalancing the market would directly yield 9% emissions reductions (4.0 Mt CO_2e/year).

Another defining issue is that large-scale legal indoor cultivation is increasingly concentrated in environmentally overburdened urban areas, as seen in Oakland and Denver, each of which host about 200 sanctioned plant factory operations. Measured emissions of potentially unhealthful volatile organic compounds (biogenic from cultivation and non-biogenic from solvent-based extraction) within a mile of the facilities have been found to be 4–8 times higher than the already-elevated background levels due to nearby transportation corridors and petroleum industry activity and hundreds-of-fold higher inside.[46,47] Producers located in these settings have also been cited for the illegal use of large diesel generators. One resulting concern is environmental justice, where workers and citizens most affected by the harms of indoor cultivation are disproportionately non-White and of lower income.[48] It is a troubling irony that these are the same populations often highlighted as victims of incarceration for past cannabis-related crimes.

Further dampening progress, the information environment is remarkably devoid of communication about the environmental profile of cannabis products—impeding market forces that otherwise might drive change. Examples of information that may be material to consumers include that the 4.5 kg emissions underlying a 1-g, plant-factory-grown "pre-roll" equal those from driving the most efficient plug-in hybrid 105 km (65 miles). Conversely, the average daily or near-daily cannabis consumer's emissions are equivalent to driving 8,411 km (13,500 miles) in an average car. On a per-weight basis, emissions are about 320 times that of producing cigarettes (Table S2). Analysts also lack important information. The fragmentation of cannabis markets, uneven state-level regulations, and proprietary treatment of producers' energy data, together with a large and persistent illicit market and lack of a unified national statistical profile of the industry, create a challenging context for policymakers.

There is much science to be done. However, while the constraints federal cannabis laws impose on medical research are widely recognized,[18,49] US federal agencies are reported to be barred from funding research on the energy and climate impacts of cannabis cultivation.[50] State-level cannabis research focuses almost exclusively on medical questions and environmental issues stemming from open-field cultivation. This state of affairs hampers progress on rigorous public domain data collection and peer-reviewed analysis. The collection and disclosure of data relevant to energy and environmental analysis by regulators and other state and local authorities is uneven and incomplete. If these obstacles can be overcome, then particularly promising research and development (R&D) frontiers include expanding the system boundary for life cycle assessments (Figure 1), improving analyses of indoor- versus outdoor-grown cannabis product quality attributes, understanding the role of cultivar choice in carbon emissions, clarifying the effect of improved energy efficiency on yields, quantifying the potentially significant additional carbon footprint of producing extracts (Table S9) and other derivative products, understanding the environmental and social dimensions of air quality impacts, bringing more rigor and efficiency to sustainable open-field cultivation, and probing the behavioral economics of consumer choices vis-a-vis sustainability.

Meanwhile, this research vacuum and the ongoing ineligibility of this industry for federal incentives to improve practices suggest voids that could be usefully filled by local jurisdictions. At the local and federal levels alike, and considering the large effect of cannabis consumption levels and product type on emissions, it is high time for drug policy and environmental policy to be harmonized.

METHODS

Details regarding the methods can be found in the supplemental information.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Evan Mills (evanmills1@gmail.com).

Materials availability

This study did not create new reagents, nor are there restrictions on the materials used.

Data and code availability

The original contributions presented in the study are included in the article and supplemental information, and further inquiries can be directed to the corresponding author.

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DECLARATION OF INTERESTS

The author declares no competing interests.

SUPPLEMENTAL INFORMATION

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One Earth, Volume *8*

Supplemental information

Energy-intensive indoor cultivation drives the cannabis industry's expanding carbon footprint

Evan Mills

Contents

Overview

To supplement and further document estimates of U.S. greenhouse-gas emissions associated with the cannabis industry presented in the main article, this companion document provides tabular results of the key findings and model inputs (Table S1) used to generate Figure 1 in the main article, and an extensive set of equivalencies to contextualize the results (Table S2).

The documentation also includes underlying emissions estimates for key cultivation inputs, transportation, dispensaries, and waste management referred to in the main document. Supplemental written and tabular information is also provided on production and consumption statistics underlying the energy use modeling and a compilation of measured data for actual cannabis facilities from the literature (Figures S1 and S2) to provide context to modeled results and to illustrate the wide variation in energy efficiencies occurring in the marketplace. A sensitivity analysis (Figure S3) is discussed and quantified. Additional supplemental information includes derivation of energy use and emissions for home-cultivation (Table S3), indoor setpoints and growing conditions (Table S4), the carbon-intensity of artificial growing-media (Table S5), retail-related emissions at dispensaries (Table S6), and emissions associated with landfill waste management (Table S7).

To substantiate discussion in the main article, further documentation is provided on water- and land-use efficiency (Figures S4 and S5). Factors not estimable in aggregate are scoped, including the potential impacts of land-use change due to encroachment of open-field cultivation into forest lands (Table S8) and emissions associated with post-cultivation extraction of active ingredients for commercial use (Table S9). Power outages triggered by cannabis operations (Table S10) augment discussion of the impacts of cultivation facilities on the electrical grid.

Terminology is highly non-standardized in the cannabis industry, and often deviates from that used by practitioners in the broader indoor agriculture and horticulture sphere. For the purposes of energy and carbon analysis, the useful standard distinctions of facility types include plant factories (referring to windowless warehouse-type facilities in the cannabis literature), greenhouses (mechanized greenhouses with space-conditioning and supplemental artificial lighting, often termed "mixed-light" production), and "open-field" (referring to non-mechanized "outdoor" or "sungrown" cultivation typically done in open fields but also in lightweight unconditioned and unlit greenhouse-like structures used to provide weather protection and to support light-deprivation techniques that accelerate flowering, often called "hoop houses"). The broader indoor-agriculture industry often refers to this mix of practices as "controlled environment agriculture" or "protected agriculture", but terminology is inconsistent in the literature. "Vertical farming" refers to an intensified growing strategy with either multiple vertical growing surfaces in a single-story building or multiple horizontal cultivation layers or stories. Cannabis is not grown in this manner to any significant degree.

Table S1. Cultivation, emissions, and expenditure data for Figure 2 in main article

				Cultivation method					Plant factory (commercial)		Greenhouse (commercial)		Open-field (commercial)		Home cultivation			
	Total	Legal	Illicit	Plant factory	Green house	Open-field	Home (indoor)	Home (outdoor)	Legal	Illicit	Legal	Illicit	Legal	Illicit	Indoor (legal)	Outside (legal)	Indoor (illicit)	Outside (illicit)
Cultivation (kt-flower/y)																		
Including amounts not reaching market	**24.2**	**8.3**	**15.8**	**6.2**	**6.5**	**8.2**	**2.4**	**0.8**	**3.0**	**3.2**	**2.8**	**3.7**	**0.8**	**7.4**	**1.2**	**0.4**	**1.2**	**0.4**
Emissions (ktCO2e/y)																		
Cultivation energy	26,951	12,589	14,362	16,007	6,273	259	4,388	24	7,709	8,297	2,649	3,625	25	234	2,194	12	2,194	12
Cultivation inputs	8,661	3,776	4,885	3,729	3,862	625	382	62	1,819	1,910	1,670	2,192	65	560	191	31	191	31
Transportation	7,327	2,690	4,637	2,334	2,397	2,596	0	0	1,225	1,109	1,124	1,273	341	2,255	0	0	0	0
Dispensaries	370	140	231	119	122	130	0	0	64	55	58	63	18	0	0	0	0	0
Waste	288	258	30	124	116	48	0	0	117	7	108	8	33	16	0	0	0	0
	43,598	**19,453**	**24,145**	**22,313**	**12,770**	**3,659**	**4,770**	**86**	**10,934**	**11,379**	**5,609**	**7,161**	**482**	**3,065**	**2,385**	**43**	**2,385**	**43**
Global warming potential (kgCO2e/kg-flower)																		
Cultivation energy	1,462	1,721	1,292	3,226	1,234	48	1,979	33	2,902	3,598	1,086	1,370	34	50	1,979	33	1,979	33
Cultivation inputs	470	516	439	752	760	115	172	84	685	828	685	828	87	120	172	84	172	84
Transportation	398	368	417	470	471	478	0	0	461	481	461	481	461	481	0	0	0	0
Dispensaries	20	19	21	24	24	24	0	0	24	24	24	24	24	0	0	0	0	0
Waste	16	35	3	25	23	9	0	0	44	3	44	3	44	3	0	0	0	0
	2,365	**2,660**	**2,172**	**4,497**	**2,511**	**674**	**2,152**	**116**	**4,116**	**4,935**	**2,300**	**2,706**	**651**	**654**	**2,152**	**116**	**2,152**	**116**
Energy expenditure ($B/y)																		
All energy uses	**11.2**	**4.7**	**6.6**	**6.6**	**2.9**	**1.8**	**1.6**	**0.0**	**2.4**	**2.6**	**1.2**	**1.6**	**0.2**	**1.6**	**0.8**	**0.0**	**0.8**	0.0

Cultivation dry weight per [S1], modified to account for crop losses, eradication at cultivation sites, other seizures, failed lab tests, etc. Electricity prices [S2]: commercial $0.1259/kWh, residential $0.1600/kWh. Illicit cannabis: 5% is assumed cultivated off-grid, powered with diesel generators at 27% efficiency per [S3], corresponding to $0.4639/kWh. Natural gas prices [S4]: commercial $10.92 $/ccf, residential $14.75 $/ccf. U.S. weighted-average electric heat rate for power generation: 7,802 BTU/kWh [S5] and 12,637 BTU/kWh for diesel generators. Motor fuel prices [S6]: gasoline: $4.18/gallon, diesel $5.07/gallon. Emissions factors: U.S. electrical grid average 373 kg CO_2e/MWh [S7]; diesel generation 922 kg/MWh [S3]; passenger cars and light trucks: 8.81 kg CO_2/gallon and heavy trucks 10.24 kg CO_2e/gallon [S8]. Vehicle fuel economy [S9]: cars 26 mpg, light-duty trucks 20 mpg, Heavy-duty vehicles (class 7-8) 6 mpg [S10].

Table S2. Comparisons and equivalencies to contextualize cannabis energy use and emissions
A. National dimensions

Total U.S. electricity sales to end users in 2023	4,000	TWh	[S6]
of which cannabis	35	TWh	This study
of which cannabis	**0.9%**		
U.S. primary energy consumption in 2023	98,803	PJ	[S6]
of which cannabis	595	PJ	This study (all uses)
of which cannabis	**0.6%**		
Total U.S. greenhouse-gas emissions in 2023	6,343	MtCO2e/y	
of which cannabis	43.6	MtCO2e/y	
of which cannabis	**0.7%**		

Cannabis on-farm energy v. other U.S. economic sectors*	*PJ/y*	*Ratio to cannabis*
Furniture and Related Products [337]	39	0.08
Textile Mills [313]	68	0.14
Electrical Equip, Appliances, and Components [335]	81	0.17
Computer and Electronic Products [334]	113	0.24
Pharmaceuticals and Medicines [3254]	120	0.25
Beverage and Tobacco Products [312]	124	0.26
Machinery [333]	154	0.32
Fabricated Metal Products [332]	268	0.56
Plastics and Rubber Products [326]	270	0.57
Cements [327310]	312	0.66
Cryptocurrency Mining	329	0.68
Transportation Equipment [336]	364	0.77
Wood Products [321]	408	0.86
Cannabis cultivation	**475**	**1.00**
Open-field agriculture (non-cannabis)	528	1.11
Nonmetallic mineral products [327]	866	1.83
Artificial intelligence (AI)	1,177	2.48
Food [311]	1,207	2.54
Data centers	1,449	3.05
Primary Metals [331]	1,675	3.53
Paper [322]	2,151	4.53
Petroleum and Coal Products [324]	3,710	7.82
Chemicals [NAICS #325]	4,023	8.48

* Industrial manufacturing energy from EIA [S11] data centers, artificial intelligence, and cryptocurrency from [S12]. For comparability, cannabis (this study) includes cultivation energy only (excluding energy embodied in inputs or associated with retail activity, transportation, or waste-disposal). Adding energy for cultivation of tobacco and malting barley increases Beverages and Tobacco value by ~14%.

Table 2 (cont'd): B: In context with the electricity sector and on-site renewable energy

Electricity use in terms of average electrical generating capacity				
Total electricity for cannabis	**35**	**TWh/y**	This study	
Average capacity factor (coal, baseload)	42%	2023	[S13]	
Equivalent generating capacity for cannabis	**9**	**GW**		
Typical base-load electric power plant	0.5	GW	[S14]	
	3.0	TWh/plant	[S14]	
Standard power plants required to generate electricity to operate current US cannabis cultivation	**12**	**power plants**		
Solar land area required to serve current cannabis cultivation and 100% electrification				
Market share (2019)				
Tracking arrays	67%	of GW	[S15]	
Fixed arrays	33%	of GW	[S15]	
Energy density (US national average output in 2019)				
Tracking arrays	447	MWh/acre-y	[S15]	
Fixed arrays	394	MWh/acre-y	[S15]	
Weighted average energy density	430	MWh/acre-y	Calculated	
Land area requirement	*Current*	*Full electrification*		
Cannabis electricity consumption	**35**	49	TWh/y	This study
Required photovoltaic array area	81,406	114,083	acres	
	127	**178**	**square miles**	
PV area required for cannabis	**32,944**	**46,168**	**hectares**	

Table 2 (cont'd): C: In context with other agriculture

As % of other U.S. agriculture energy and emissions

U.S. Agriculture - On-farm energy (excluding livestock, poultry, and dairy production)

- Direct energy use (non-cannabis)	500 TBTU/y (fuel and electricity)
	528 PJ/y (USDOE - *Today in Energy*, 17-Oct-2014)
Cannabis	475 PJ/y (this study)
Cannabis as a fraction of other agriculture	**90%**

U.S. Agriculture - On-farm emissions

- Direct emissions from fuel, urea, lime	39.1	MtCO2e/y	[S16]
- Indirect emissions from electricity	29.7	MtCO2e/y	[S16]
- Total	68.8	MtCO2e/y	[S16]
Cannabis	43.6	MtCO2e/y	This study
Cannabis as fraction of other agriculture	**63%**		

Comparison to on-farm energy requirement for conventional U.S. plant-factory crops

	kWh/kg-lettuce	*kgCO2e/kg product**	*Cannabis: Lettuce ratio*	
Cannabis: plant factory		3,226		This study
Lettuce: plant factory (various locations)	12	**7.3**	441	[S17]
Lettuce: plant factory (various locations)	15	**9.1**	353	[S18]
Lettuce: plant factory (Seattle, WA)	7	**4.4**	742	[S19]
Lettuce: plant factory (Yuma, AZ)	25	**15.2**	212	[S20]

* per national-average electricity emissions factor

Agricultural land requirements if all cannabis grown outdoors

National cannabis production (indoor and open-field, 2023)	45.4	million lb	This study (includes eradication and seizures)
Yield density for open-field cannabis cultivation	21	sf/lb-y	[S21]
Land area required for cultivation	958	msf	
Land required for cannabis cultivation	21,999	acres	
Total US cropland (2023)	653,852,458	acres	[S22]
Share of U.S. cropland needed to cultivate cannabis, if 100% grown outdoors	**0.003%**		
Currently planted in hemp	22,248	acres	[S22]

Table 2 (cont'd): D: In context with the buildings sector energy use

Comparisons to other building types	kBTU/sf-y		
Cannabis plant factory	8,540	*Cannabis multiple*	[S23]
Conventional plant factory (lettuce)	14	**441-742**	[Table S2]
Walmart store	96	**89**	[S25]
Hospital	209	**41**	[S24]
Equivalence in terms of emissions from U.S. homes			
U.S. cannabis industry emissions (2023)	43,598	ktCO2eq/y	This study
U.S. residential sector emissions (2022)	973.5	MtCO2e/y	[16]
U.S. households	125,736,353	households	[47]
Average home (2022)	7.74	tCO2e/y	
Number of equivalent homes	**5.6**	**million**	
One average home	7,742	kgCO2e/y	
Cannabis equivalent to one home's annual emissions	**1.7**	**kg (plant factory)**	
Household carbon footprint (energy)	7,742	kgCO2e/y-home	[S26]
Cannabis purchases per average user	184.8	g-flower/y	[S27]
Emissions for plant-factory cultivation	831	kgCO2e/y-home	
Cannabis use as % of household footprint	**11%**	**average user**	
Cannabis purchases per average at-least weekly user	412	g-flower/y	[S28]
Emissions for plant-factory cultivation	1,855	kgCO2e/y-home	
Cannabis use as % of household footprint	**24%**	**at least weekly user**	
Cannabis purchases per average daily user	748	g-flower/y	[S28]
Emissions for plant-factory cultivation	3,365	kgCO2e/y-home	
Cannabis use as % of household footprint	**43%**	**daily user**	

Table 2 (cont'd): E: In context with passenger car energy use

US cannabis emissions comparison typical cars					
Cannabis emissions (national)	43.6	MtCO2e/y			
Average miles driven per car per year	11,500		[S29]		
Average passenger car emissions	4.6	tCO2e/y-vehicle	[S29]		
Equivalent average U.S. cars' emissions	**9.5**	**m cars**			
Cannabis equivalent to one car's annual emissions	**1.02**	**kg (plant factory)**			
Miles driven compared to	*Miles*	*# of cross-country road trips*			
Average user	2,077	0.7			
Average weekly user	4,637	1.6			
Average daily user	**8,411**	**2.9**			

Equivalent distance driven in a car	*Plant factory*	*Green-house*	*Open-field*	
Cannabis emissions - 1kg (legal cultivation)	4,497	2,511	674	kg CO2e/kg-flower
Miles driven per kg of Cannabis				
Average U.S. Car @ 24.4 mpg [S9]	**12,496**	6,979	1,873	**m equivalent**
PHEV @ 127 mpg-equivalent [S30]	**65,042**	36,327	9,750	**m equivalent**
Miles driven per pre-roll (plant factory)				
1 g flower: Average U.S. Car @ 24.4 mpg	**12**	7	2	**m equivalent**
1 g flower: Best Prius hybrid @ 57 mpg	**65**	36	10	**m equivalen**t
0.5 g flower: Average U.S. Car @ 24.4 mpg	6	3	1	m equivalent
0.5 g flower: Best Prius hybrid @ 57 mpg	33	18	5	m equivalent

Table 2 (cont'd): F: Additional equivalencies

Emissions per standard "pre-roll"	*Plant factory*	*Greenhouse*	*Open-field*	
Average emissions factor	4,497	2,511	674	kg CO2eq/kg-flower (This study)
at 1 g flower per pre-roll	**4.5**	**2.5**	**0.7**	**kg CO2eq/pre-roll**
at 0.5 g flower per pre-roll	2.2	1.3	0.3	kg CO2eq/pre-roll

Equivalencies for energy-intensive materials

Cannabis	35,761	MJ/t	This study (legal plant factory)
Best Practices - Primary Energy (MJ/t)	*GJ/t*	*Cannabis multiple*	[S31]
Aluminum - primary	174	**206**	
Aluminum secondary	7.6	**4,705**	
Portland Cement	3.4	**10,518**	
Steel - blast furnace	16.3	**2,194**	
Steel - Scrap	6	**5,960**	

Compared to tobacco	*gCO2e*	*Cannabis multiple*	
Cigarette	14		[S32]
Cannabis			
Open-field (1g)	651	46	
Greenhouse (1g)	2,300	164	
Plant-factory (1g)	4,497	**321**	

Cannabis emissions (plant factory) as a percentage of American average dietary emissions

		Average diet	*Vegetarian diet*	
Emissions per average American diet	kgCO2e/y	3,191	2,167	[S33]

	Cannabis	*Emissions as % of dietary emissions*	
	kgCO2e/y	*Average diet*	*Vegetarian diet*
Daily or almost daily user	3,365	**105%**	**155%**
At least weekly user	1,855	**58%**	**86%**
Average user	831	**26%**	**38%**

Estimating Net Annual Aggregate Cannabis Production in the U.S.

Cannabis has become a widespread consumer product with rising production levels. First domesticated and grown for fiber ~12,000 years ago, the earliest evidence of cannabis consumption by people dates back ~2,500 - 4,500 years ago [S34, S35]. In modern times it has been widely criminalized, but as of May 2024 four U.S. territories, 38 states, and the District of Columbia had legalized the substance for medical or recreational use, four additional states had decriminalized cannabis, and nine others allow low-THC products [S36]. In 2022, half of Americans over the age of 18 had tried cannabis [S37], with 22% (62 million over the age of 12) using it that year [S38], of which 17.7 million were daily or nearly daily consumers [S39].

Gross production

Schimelpfenig et al. [S1] published the most granular breakout of commercial harvest-level estimates by cultivation type and legal status based on statistics developed by market analysts which, however, exclude non-trivial amounts of home cultivation as well as various forms of crop losses. Their projections for 2023 are adopted as a starting point for this analysis (Table S1). National production increased 142% since a prior national assessment in 2012 [S3], with average potency of interdicted cannabis increasing ~50% over the same period [S40]. Approximately 63% of cultivation remains in the illicit market.

While once the primary mode of cultivation, home-cultivated (or "home-grown") cannabis persists as a non-trivial secondary source of supply (Table S3). Indeed, it is sufficiently mainstream that *Sunset Magazine* provided guidance to its readers [S41]. Wadsworth et al. [S42] estimated such non-commercial cultivation is conducted at 7.3% of U.S. homes (compared with 5.23% in a Canadian study [S43], post-legalization), while Goggins [S44] reported 60% of household cultivation taking place indoors with harvests one to three times per year (no distinction between open-field versus indoor methods). A survey of 339 households [S45] identified average yields of 7.1 ounces per home-grown crop, which is adopted here in lieu of other published estimates but is very low compared to commercial yields. For the present analysis, these metrics are combined and home greenhouses are assumed to use only natural light and no mechanical heating or cooling. The total resulting home production is approximately 3 kt/y, or about 8% of the commercial total. As about half the states allow legal personal cultivation for medical or recreational purposes, total quantities are apportioned to the legal and illicit markets accordingly. Other estimates suggest substantially higher home-grown production of 5 kt/y [S46].

Table S3. Estimation of cannabis home-cultivation in the U.S.

	Indoor	Outside & greenhouse		
Fraction of US households growing at home	7.3%		[S42]	
o/w indoor	60%		[S44]	
Households (2022)	75,441,812	50,294,541	[S47]	
Growing households	5,507,252	3,671,502		
Crops per year	2	1		
Pounds/hh/crop (median)	0.44	0.44	[S45]	
Production				<u>**Total**</u>
Pounds/y	4,887,686	1,629,229		**6,516,915**
kt/y	2.2	0.7		**3.0**
Market value at $2.27/g [S48] ($B/y)	5.0	1.7		**6.7**

Crop losses

To estimate the energy and resource uses associated with gross production, harvest statistics must be adjusted to reflect crop failures and pre-harvest eradication of illicit operations. Post-harvest losses arise from failed safety tests, product recalls, and interdiction of illicit products. Overproduction also leads to product destruction or spoilage. Theft is another variable, and, while stolen cannabis only changes where in the market a product is sold, it is easy to envision growers attempting to offset stolen amounts with added cultivation.

Energy and emissions intensities are applied to the net result of the aforementioned factors, thereby allocating all energy use to quantities ultimately reaching consumers. The net effect of these factors (24.2 tonnes/y of gross cultivation for the year 2023) is included in Table S1, and is roughly consistent with another estimate of 22.1 tonnes for the year 2022 [S49], which appears to focus on commercial production to the exclusion of home-cultivation that does not enter the marketplace. It is not clear whether any of these sources include the net effect of imports and exports across the U.S. border, which is probably a positive number resulting in uncounted emissions from other countries.

Losses: Crop failure and contamination

As with any agricultural product, crop losses routinely occur during cannabis cultivation. For open-field operations this can result from natural hazards, including fire, drought, disease, rogue male pollen, and pests. For indoor cultivation, losses as a result of some of these factors, plus within days or even hours as a result power outages, loss of humidity and temperature control, etc. As a proxy for contamination losses, reports indicate that 10%-20% of cannabis fails microbial tests at the cultivation facility post-harvest [S50]. Legally, this material should be destroyed, but, if not, the intent is that it is caught again by required third-party testing prior to sale, or in subsequent recalls. This analysis assumes 10% losses of this kind occur. Statistics on losses arising from technological-failures such as power outages are not available in the literature, so this is a cautious estimate.

Losses: Eradication and other interdiction

Eradication efforts at illicit locations are led by local, state, and federal authorities. Pooled data have not been identified. The U.S. Drug Enforcement Agency provides annual statistical overviews, in 2022 reporting 5.7 million plants eradicated by federal authorities at cultivation sites (or 280 t, assuming 0.45 kg/plant, per Summers et al. [S23] and half of plants at maturity with marketable flower), of which 22% was cultivated indoors. These seizures also included an additional 445 t of processed cannabis flower, and large amounts of extracts and other derivative products [S51] at growing locations. Federal seizures at other locations were 309 t in the most recent published report [S52], of which the indoor fraction is assumed proportional to total cultivation amounts used in this study. The California Department of Cannabis Control reported an additional 960,212 plants eradicated by state authorities in 2022, plus 199 t of finished cannabis at cultivation sites [S53]. California does not report indoor- versus outdoor-grown seizures, so the total is apportioned according to federal eradication statistics. All quantities seized away from cultivation sites are allocated indoor-outdoor in proportion to overall annual production levels used in this study. Taken together, these values represent 5.5% of illicit indoor cultivation and 20.7% of open-field cultivation intercepted at cultivation sites, plus an additional 5% of indoor-grown harvest and 11.6% of open-field harvest seized at other locations. These are likely underestimates, as the national data span only 37 states, and state-led eradication/seizure data was only identified for California.

Losses: Third-party pre-sale safety-testing failures

State laws commonly require independent lab testing of cannabis products prior to sale. Documented causes of test failures (which typically result in product destruction) include detection of pesticides, mold, heavy metals, microbial contaminants, solvents, mycotoxins, salmonella, prohibited additives, and inaccurate potency labeling [S54]. A test lab in Maine reported a failure rate of 3.8% for legal recreational cannabis providers and a remarkable 20.7% failure rate for legal medical products [S55]. A range of 4.1% was reported in the California market [S56]. A rate of 4% is adopted for this analysis.

Losses: Product recalls due to post-sale safety testing

The widespread incidence of cannabis product recalls (in only 18 out of 37 reporting states where cannabis is legal) as of mid-2024 indicates that lab testing is not always efficacious [S57]. Through a review of approximately 10,000 samples taken from legalized jurisdictions nationally, Jameson et al. [S58] report a 2.3% post-testing/post-sales failure rate for flowers and 9.2% for extracts, with 679 responsible compounds identified. More specifically, their survey identified 551 pesticides, 74 solvents,12 inorganic compounds, 21 microbes, 5 mycotoxins, and 16 other contaminants. Data on quantities of product recalled are not available, but the number of recalls per year rose from 2 in 2015 to 71 in 2023, nationally. This suggests that improved safety testing would intercept more contaminated products. In 2019, after providing several weeks' advanced notice, state officials in Denver, Colorado conducted random tests for pesticides and microbial contaminants (only) at 25 dispensaries, resulting in an 80% failure rate [S59]. Prior tests resulted in a 10% failure rate in 2017 and 15% in 2018, suggesting that failure rates in the state were rising. Evaluation of 202 retail samples of cannabidiol (CBD) products found that 26% failed to meet safety standards for residues, pesticides, and heavy metals [S60]. Lacking national data, recalls are not incorporated in the baseline analysis.

Overproduction

One study determined a cannabis THC potency half-life of 500 days [S61], which makes storage of overproduced material problematic. Importantly, even when refrigerated or frozen, cannabis loses significant potency and marketability within about two years [S62, S63]. True overproduction, net of diversion from legal to illicit markets, is hard to quantify, as suggested by estimates that regulated production in Oklahoma exceeds demand through the legal market by 32-fold [S64]. However, as of 2022, the total U.S. licensed legal production capacity was greater than combined legal plus illicit national consumer demand [S49], and the excess is particularly pronounced in certain states. In 2024, the regulated cannabis market in New York reported destruction of 113 tonnes of surplus [S65], 83% of that year's production, and Oregon reported 1,361 tonnes of surplus, 31% of the prior year's production [S66] with inventory at one point equal to six years of sales [S67]. California's regulated market has been estimated to produce three-times that state's demand [S68]. The problem occurs in other countries as well. Canada recently destroyed overstocked cannabis equivalent to 58-127% of that year's harvest, with a remaining surplus of 1,470 tonnes in 2022 (approximately three-times the previous year's production) [S69], and the country is reported to have sold less than 20% of aggregate production in the three years following cannabis legalization [S70]. In the U.S., there are potential illicit markets for surpluses, which entails evading chain-of-custody tracking systems in the legal markets and transport to the decreasing number of states where it is still illegal, but these massive inventories are also at risk of losing potency and being unsaleable. Due to lack of comprehensive data for the U.S., product loss arising from oversupply is not included in the calculations. Similarly, the likely significant refrigeration energy use associated with such efforts to extend shelf light is also not estimated or included. While overproduction is arguably irrational in a free-market context, the activity appears to be significant while the causes are unclear.

Energy and Emissions Analysis for Estimating Life-cycle Emissions

The importance of metrics

Various energy metrics are employed in the broader agricultural literature. The most common, but also most problematic, metric is growing-area-normalized energy use (e.g. MJ/m^2-y). Confounding variance can be caused by differences in plant densities, illumination levels, climate and indoor environmental conditions maintained, unutilized space/volume in the building, cultivar choice, cultivation methods, accounting for crop losses (noted above), and other factors. Distinguishing between gross facility area and productive growing area is also important, a distinction rarely made in cannabis-industry reports.

A superior metric is energy used per the functional unit of weight yield (e.g. GJ/kg-flower). This measure controls for a number of the aforementioned sources of variation and is adopted in this study, including being independent of vagaries in the reporting of facility dimensions and of numbers of crops produced in a given year.

The choice of energy metrics is critical to meaningful performance benchmarking. Variations in normalized yields per unit floor area can mean that a "low" energy use is not necessarily reflective of energy efficiency, e.g., a facility that is underplanted will have relatively low energy intensity per unit of floor area but high energy per unit weight. Neither metric controls for potency (e.g. THC or CBD yield), which is rarely published, but an example of this approach is given in Figure 5 in the main article.

The complementarity of measured field data and model estimates

A small but growing literature provides data on measured energy use in cannabis cultivation. There are many nuances and potentially incommensurate factors to beware of when using and comparing data from such studies [S71], including climate and geographical variation influencing daylight availability and space-conditioning energy demand and humidity loads, inclusion of all relevant primary and peripheral energy sources (e.g. CO_2 manufacture, curing, refrigerated storage), and other ambiguities and inconsistencies in the broader system boundaries (Figure 1 in main article) within which measurements are made.

Not all studies (whether model- or measurement-based) capture every form of energy in use (e.g. many tabulate only electricity). Uncharacteristically, the sites described by Arnold [S72] lacked air conditioning. Two of the less energy-intensive sites measured by Leichliter et al. [S73] utilized more-efficient LED lighting, which is not the dominant practice in today's industry.

Measured data can help develop and validate modeling tools and identify best practices. Model studies offer some advantages insofar as they control for or at least make transparent the "noisy" variances underlying measured data, and enable sensitivity and scenario analysis. Examples of model studies include Desaulniers-Broussea [S74], Summers et al. [S23], and Mills [S3].

Various measurement and modeling studies have focused on operating cannabis facilities. Figure S1 gathers results for 325 facilities or distinct cultivation trials providing floor-area normalization of the results. Figure S2 shows the subset of 97 sites or trials where yield data are also available and allow calculation of the superior metric of energy use per unit yield. The red bars indicate sites that do not appear not to evaluate all sources of energy use. While most of the "all-sources" sites are in milder western states, the model results span all climates.

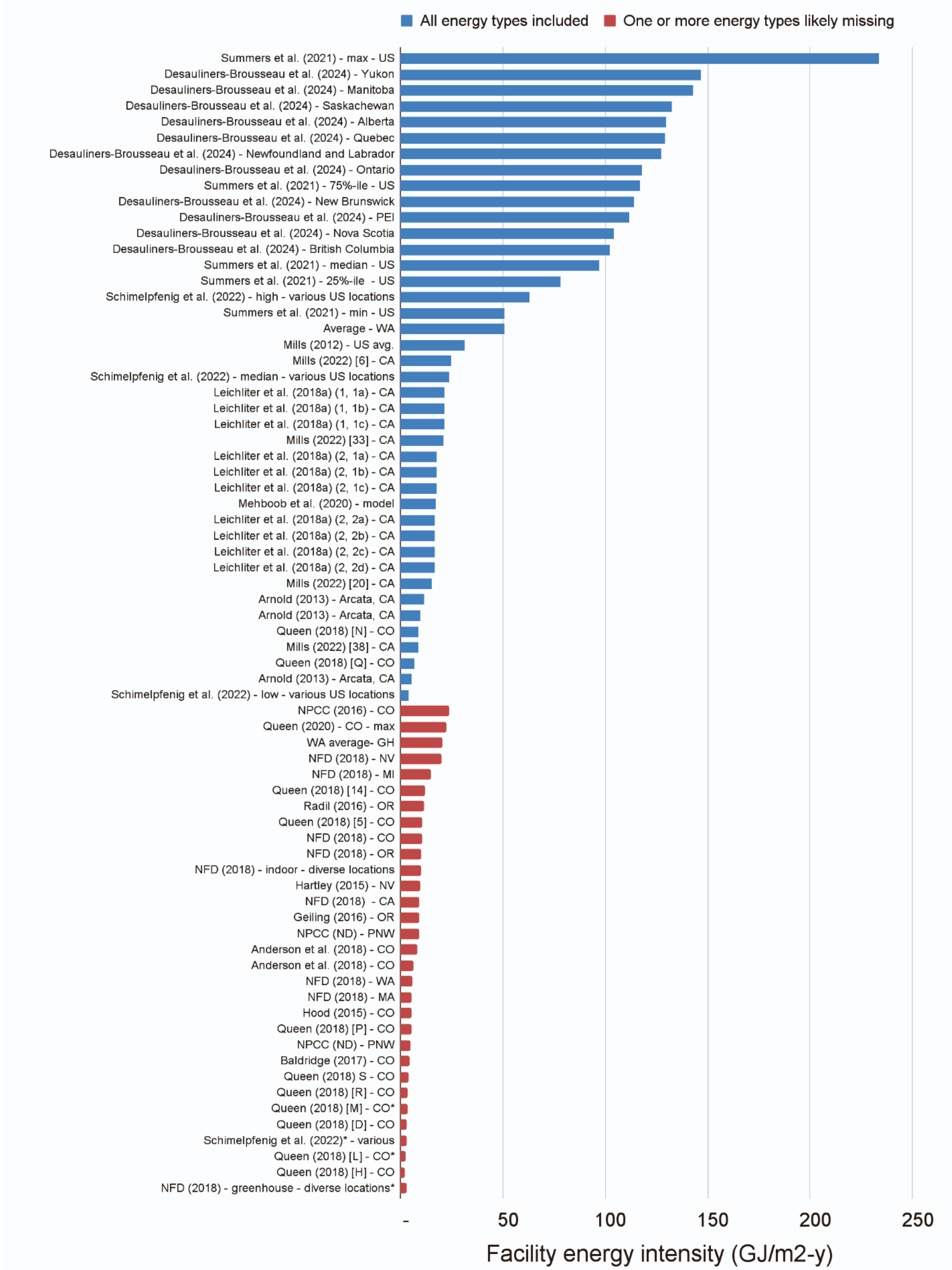

Figure S1. Compiled estimates of indoor cannabis cultivation energy intensity per m2 area
The red bars indicate known or likely missing data (e.g. electricity but not fuel uses are included in the source publication). Note: “*” indicates greenhouses. All others are plant factories. N=325 sites or trials and 15 model studies [S3, S21, S23, S72-75, S78, S86, S109, S111-119].

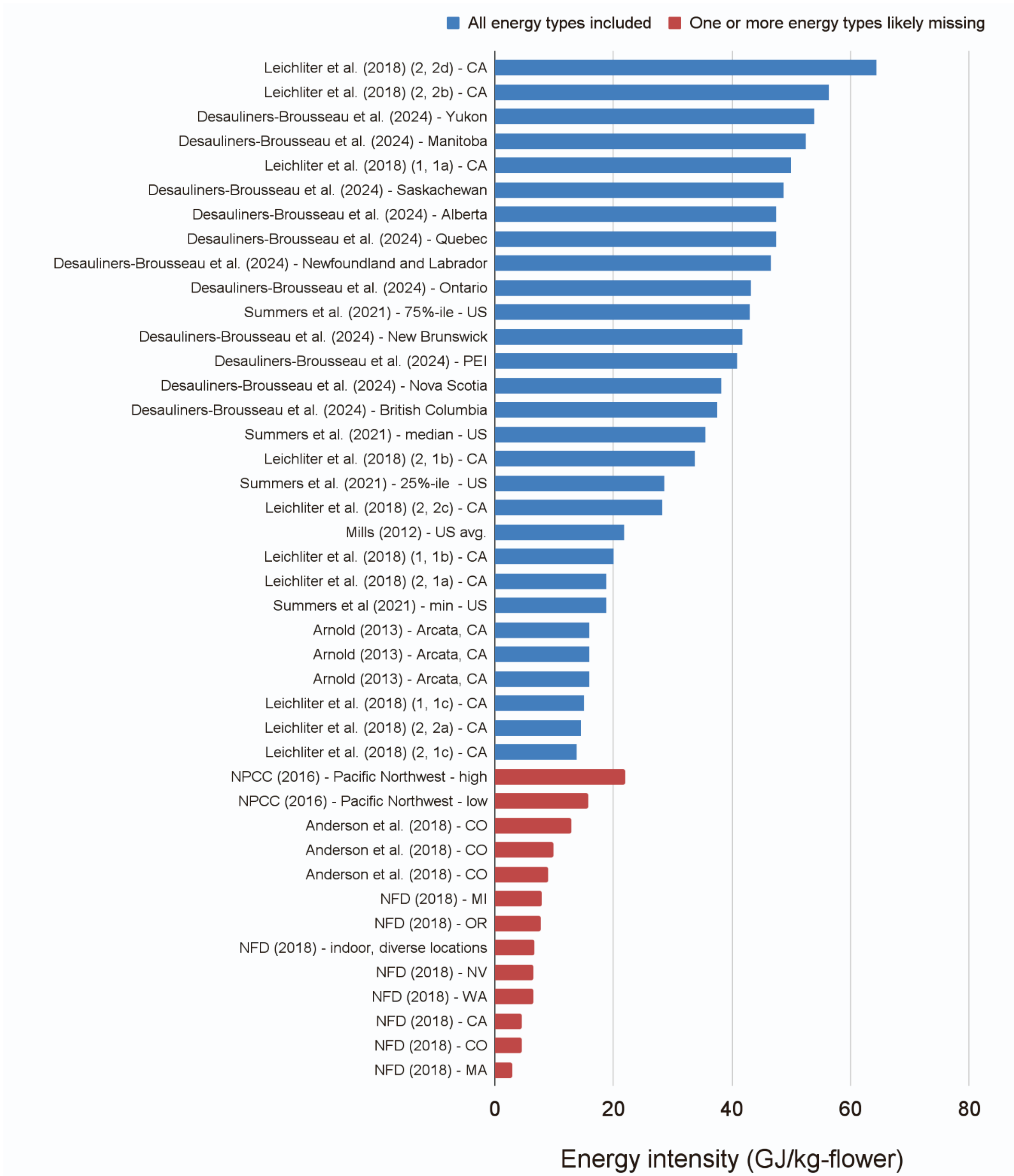

Figure S2. Compiled estimates of indoor cannabis cultivation energy intensity per kg flower
Shown are the subset of those in Figure S1 for which yield data were provided. N=97 sites or trials and 15 model studies [S3, S21, S23, S72-74, S111, S117]. The red bars indicate known or likely missing data (e.g. electricity but not fuel uses are included in the source publication).

Estimating facility-level energy use and emissions

The present analysis builds on the only prior comprehensive national energy use estimate of plant factories [S3], reflective of common practices at the time. A subsequent in-depth and validated study, modeled modern plant factories in 1,011 geographical (climate) locations across the United States [S23] and found that energy use ranged from 22.2 to 36.6 GJ/kg (median 35.8 GJ/kg). The authors based their analysis on a significantly higher yield density, partly due to attaining 6.2 harvests per year versus 4.7 in Mills [S3], but also more voluminous facilities with correspondingly higher ventilation volumes (at 30 air changes per hour), and higher CO_2 concentrations (Table S4). Comparative yields were 1,435 and 2,724 grams/m^2-y, respectively. Together this evolution in cultivation indicators is consistent with the significant industrialization and intensification of indoor cannabis cultivation that occurred in the decade between the two studies.

Table S4. Indoor growing conditions and setpoints (plant factories)

Parameter Name	Clone	Vegetative	Flower	Cure
Temperature High (°C)	26.7	23.9	29.4	23.9
Temperature Low (°C)	21.1	15.6	21.1	15.6
Relative Humidity High	70%	50%	50%	50%
Relative Humidity Low	40%	40%	40%	30%
Lighting Intensity (W/m^2)	404	404	673	30
Lighting Duration (hours/day)	24	18	12	18
CO_2 (ppm)	400	700	1400	400

Source: After [S23]

Industry surveys indicate that as of 2023 about 55% of cannabis cultivation occurred in plant factories, with an additional 18% in greenhouses that are typically also mechanically heated and/or cooled, and the balance outdoors [S48].

Direct fuel combustion is widely employed for space-heating in cannabis cultivation environments, particularly greenhouses [S75-S78]. One field-monitoring study found that 47% of the total energy used in greenhouses in the Boulder, Colorado area was heated with natural gas [S79]. Propane and oil heating each have higher emissions per unit of delivered energy than natural gas, but the market shares for other fuels are not known and thus emissions factors for natural gas are cautiously assumed here, per Summers et al. [S23]. This is a conservatism in the present analysis; e.g., propane systems are estimated to have a 33% share of heating in Washington, Colorado, and Oregon [S80]. For reference, a sensitivity analysis (see below) examines the effect of full electrification.

Yield intensities (weight per unit cultivated area or "canopy") as well as modeled energy intensities (GJ/kg-flower) for plant factories are adopted (median values) from Summers et al.

[S23]. For plant-factory cultivation estimated by Summers et al. [S23], facility-level energy-related emissions correspond to between 45% and 90% of the total found within the system boundary of this study (Figure 1 in main article), depending primarily on geography and the electric power generating mix.

For greenhouses, a large survey finding fuel use in cannabis greenhouses of 1,988 MJ/m^2 for heating is used [S76] together with measured electricity data for greenhouses at 27 sites around the United States indicating median intensity of 0.68 grams/kWh [S21]. These values compare well with a more recent and larger sample from the same database (57 facilities, some presumably overlapping) [S78]. For comparison, non-cannabis greenhouse heating fuel intensities modeled by Harbick and Albright [S81] in four different U.S. climate regimes averaged 2,488 MJ/m^2-y, so the value adopted here may be an underestimate. ERS [S79] found greenhouses to use about 30% less energy than plant factories per unit of floor area and 15% less on a per-unit-of-flower yield basis.

Median electricity intensities of 12.6 grams/kWh are applied for open-field cultivation, based on data from 20 cannabis farms across the United States [S21]. Desauliners-Brousseau et al. [S82] provide on-farm energy-use estimates, but their system boundary appears to include only post-harvest curing, to the exclusion of energy used for cloning, water pumping, and soil preparation. Estimates of fuel used by tractors and other farm equipment were also not found in the literature and thus this source of energy is not included in the analysis.

Electricity-related greenhouse-gas emissions are computed based on grid-level generation fuel mix, accounting for CO_2 and other gasses. Summers et al. [S23] used values for the year 2018 from EGRID [S7], with a mean value of 451 kg CO_2e/kWh. For the current analysis, this is updated to EGRID 2022 levels of 372 kg CO_2e/kWh (approximately 17% lower thanks to ongoing expansion of renewable energy and the phaseout of coal).

Grid-based electricity demand is converted to primary energy using the national fuel-weighted average power plant heat rate of 7,802 BTU/kWh [S5].

Some cultivation facilities, both legal and illicit, utilize onsite fossil-fuel power plants, often operating at significantly higher per-unit emissions than local grid. This is most common at illicit off-grid locations where up to 200,000 gallons of fuel have been found stored at a single site [S83-S85]. Illegal generator use has been observed even in city centers and other grid-adjacent locations when proper electrical service is inadequate and operators choose not to upgrade it in accordance with local regulations [S86, S87]. The carbon emissions of diesel-based power are 12% greater than the national average and 346% greater than that in California [S7]. Diesel-generation is applied to electricity use for 5% of illicit crops (indoor and open-field cultivation), down substantially from the 30% assumed over a decade ago in Mills [S3] largely as a reflection of the price collapse making off-grid cultivation less profitable. Diesel generator efficiency is estimated at 27%, corresponding to a heat rate of 12,637 BTU/kWh.

Energy-intensities for home cultivation are modified from those developed previously to represent the smaller-scale industry that existed circa 2012 [S3]. As the original analysis reflected commercial production, albeit at small scales, the following energy-using processes were eliminated or reduced to reflect further-reduced and less optimized home-production contexts: air-conditioning, 50% of dehumidification runtime, carbon dioxide production, irrigation water-temperature control, irrigation pumping, UV sterilization, and electric drying/curing (Table S3). These adjustments resulted in a 34% reduction in the electricity intensity of home production compared to the original study.

Fugitive emissions

Unintended fugitive greenhouse-gas emissions are associated with hydrofluorocarbons (HFCs) used for heat transfer in compressor-based heating, ventilating, and air-conditioning (HVAC) systems. These refrigerants have a very high global warming potential compared to carbon dioxide (typically thousands of times higher).

One of the largest cannabis producers in North America, Canopy Growth, disclosed their fugitive fugitive emissions for the year 2020 [S88]. With annual production of 137 tonnes of flower, Canopy Growth was the second largest producer in Canada at that time (20% market share). As discussed above, Canadian cultivators engaged in extreme overproduction during this time period. As the shelf life of cannabis is very limited (even if frozen), these emissions are appropriately allocated to one-third to one-fifth of gross production for the purposes of estimating the HFC emissions factor. Canopy reported 5,118 tons of carbon-dioxide equivalent HFC emissions, corresponding to 299 kg CO_2e/kg flower assuming one-quarter of the product reached the market during that period. As most indoor and industrial greenhouse cultivation sites utilize compressor-based HVAC for cooling (and some for heating as well), this value is applied in the current analysis for indoor cultivation. No fugitive HFC emissions are associated with open-field cultivation.

Emissions embodied in cultivation-related inputs

Cannabis cultivation requires numerous non-energy inputs. For indoor cultivation, the detailed per-kilogram life-cycle estimates by Summers et al. [S23] are adopted, based on the Ecoinvent database [S89] and NREL [S90]. These include nutrients in the form of ammonium nitrate, triple superphosphate, potassium chloride as well as pesticides in the form of Neem oil and fungicides. The most significant input for indoor operations is industrially manufactured carbon dioxide injected to concentrations of 1,400 ppm during the flowering stage (roughly three-times outdoor ambient concentrations) and 700 ppm during the vegetative stage to accelerate growth. Energy associated with water delivery is also included as a cultivation-related energy input. In the case of commercial open-field and all home cultivation, the carbon footprint of fertilizer and other inputs and materials are taken from Desauliners-Brousseau et al. [S82], using the average of their high- and low fertilizer input cases.

Growing media

The analysis from Summers et al. [S23] is updated by replacing "natural"growing media for indoor cultivation (Coco Coir and perlite) with mineral wool, which is far more commonly used in industrial-scale operations. This significantly reduces carbon flows to landfill (discussed below under waste management), but entails a new form of embodied energy and emissions for manufacturing (Table S5). For open-field cultivation (commercial and home) the potting-soil use case is adopted, after Desauliners-Brousseau [S82], with no-steam-cleaning of the used growing media.

Table S5. Carbon accounting for mineral wool growing media

Materials	Mineral wool weight (proxy "Rockwool", RW, product)	0.500	lb per 6x6x6" cub	(manufacturer data, Grodan)
	Cube volume	216	cubic inches (6x6x6")	
	Specific weight	4.0	pounds RW per ft3 of material	
		64	kg/m3 RW	
	Rockwool embodied CO2e	3	kgCO2e/kg RW	[S120]
	Rockwool embodied energy	40	MJ	center of range from [S120]
		0.00354	cubic meters per cube	
Application	Plant density per growing area	2.69	plants/m2	
	Volume of RW per growing area	0.0095	m3RW/m2	[S23]
Mass	RW mass per growing area	0.6101	kgRW/m2	
	RW emissions per growing area	1.83	kgCO2e/m2	
Intensity	Harvest per cycle	0.44	kg/m2	
Emissions factor		4	kgCO2eqRW/kg-flower	

Transportation energy

Transportation energy is expended in multiple modes throughout the cannabis production, distribution, retail, and waste-disposal processes. The accounting for emissions from transportation energy begins with the estimates from Summers et al. [S23]. Modes included are heavy truck, light truck, passenger car to and from cultivation locations, and trucks to and from landfill locations. For illicit operations, transportation energy for waste-disposal and processing is not counted, assuming that material remains on site (unless eradicated, in which case it is assumed landfilled). Given the context for home-cultivation being for personal use, no emissions are counted for transport energy (except that embodied in inputs such as fertilizer).

Worker transportation is added to this baseline, with energy use and emissions estimated by combining the U.S. average commuting distance of 29.4 miles [S91] and 250 work days per year for the labor force of approximately 440,000 [S92] across retail, cultivation, test labs, wholesale, processing/manufacturing, and ancillary job types. The result is apportioned per the legal and illicit production levels. Note that another industry source provides a higher estimate of the workforce at 545,000 workers in 2023 [S48]. The analysis uses an average fuel economy of 24.4 mpg for passenger cars, 17.8 mpg for light trucks, and 6.8 mpg for heavy trucks [S9], and gasoline price of $4.19/gallon (cars) and a diesel price $4.99/gallon (trucks) [S6].

Two additional categories of transportation are not well enough defined to be included in the baseline analysis. These include the combination of consumer travel to and from dispensaries and dispensary delivery services. Two cannabis delivery providers report a combined 5 million delivery trips per year [S93, S94]. Also not included are domestic interstate smuggling or transnational smuggling, each of which involve much longer transport distances than legal intra-state transportation. Dispensary-provided home deliveries are modeled as a sensitivity scenario.

Licensed retail dispensaries

Legally-produced cannabis is distributed to consumers through dispensaries, estimated to number 12,156 in early 2024 [S95]. Other industry observers put the value at 14,932 [S96] and 16,520 [S97]. Large numbers of illicit dispensaries are reported as well, likely exceeding the number of licensed facilities. As an indication, one study found 1,110 dispensaries in California as of 2018, of which only 448 (40%) were legally licensed [S98], while a later media investigation tallied a total of 2,835 in California in 2019, of which 873 (31%) were legal [S99]. In a newer market, New York City, only 13 legal dispensaries were reported in operation, plus 2,000 unlicensed ones [S65].

An estimate of dispensary energy use and associated greenhouse-gas emissions is developed by applying energy uses (electricity, natural gas, and heating oil) and energy intensities for each of the four major Census Regions using survey data for the regional mercantile building type as the closest proxy for dispensaries. This likely underestimates energy use, as dispensaries commonly have cold storage and in some cases kitchen operations. The dispensaries in each state were assigned to Census Regions so that relatively localized mercantile energy use could be associated. No dispensary energy use is associated with home cultivation.

Dispensary size was estimated by weighting reported floor areas of recreational (400 m^2) and medical dispensaries (292 m^2) [S100] in proportion to the national population living in states with corresponding laws [S96]. Grid-based emissions factors [S7] were applied to the electricity use estimates for each state. The resulting emissions are shown in Table S6. These values exclude illegal dispensaries, for which robust statistics are not available. The result is thus likely a significant underestimate of the actual number and energy use of dispensaries.

Table S6. Carbon accounting for legal cannabis dispensaries by major Census Region

	North- east	Midwest	South	West	Other**		
Mercantile building energy use intensity (commodity units) (2018)							
Elect EUI (kWh/sf)	15	15	18	17	18	[S24]	
Natural Gas EUI (cf/sf)	42	41	29	37	29	[S24]	
Heating oil EUI (gallons/1000sf)	92	17	15	17	15	[S24]	
Total Mercantile floor space using a given fuel (million sf) (2018)							
Electricity	1,389	2,625	4,463	2,300	*4,463*	[S24]	
Natural gas	1,127	2,483	3,436	1,946	*3,436*	[S24]	
Heating oil	121	266	571	269	*571*	[S24]	
(Mercantile as % of total)	9%	10%	13%	12%	*13%*	[S24]	
Fuel-saturation-weighted energy intensity - Assumes dispensaries have the same fuel shares as other mercantile buildings							
Elect EUI (kWh/sf)	15	15	18	17	18		
Natural Gas EUI (cf/sf)	34	39	22	31	22		
Heating oil EUI (gallons/1000sf)	8	2	2	2	2		
Dispensaries (#, 2024)	1,327	1,670	3,487	5,326	346	12,156	
Aggregate energy use by dispensaries (commodity units/y)						**Total**	**PJ**
Elect EUI (M-kWh)	81	104	251	371	25	833	6.9
Natural Gas EUI (million cf)	183	265	314	677	31	1470	1.6
Heating oil EUI (million gallons)	0.04	0.01	0.03	0.04	0.00	0.13	0.02
							8.5
Dispensary emissions (kt CO2e/y)						**Total**	
Electricity	21.9	47.1	85.2	118.3	15.5	**288**	
Natural gas M	10.1	14.6	17.3	37.3	1.7	**81**	
Heating oil	0.5	0.1	0.3	0.5	0.0	**1**	
Total	**32**	**62**	**103**	**156**	**17**	**370**	
Energy expenditures ($M/y)						**Total**	
Electricity	10.2	13.1	31.7	46.7	3.1	**105**	
Natural gas	2.0	2.9	3.4	7.4	0.3	**16**	
Heating oil							
Total	**12**	**16**	**35**	**54**	**3**	**121**	

* Other is modeled using the results for the South Census region, as these are territories in the Pacific and Caribbean.

Waste disposal
A wide variety of waste is generated throughout the cannabis cultivation and processing phases [S101]. Sources include biomass residues, spent lamps and other supplies, used biological or artificial growing media, contaminated wastewater, and plastics. The emissions dynamics associated with cannabis waste disposal are multifaceted. Plant residues are generated during normal cultivation and following harvest, but also result from crop failures, seizures, products diverted due to failed pre-sale lab testing, product recalls, and nonmarketable products resulting from overproduction. Even where other modes are permitted, landfill tends to be the preferred approach given its relatively low cost [S102]. Waste streams are smaller with open-field cultivation, as there are fewer synthetic inputs [S103].

After Summers et al. [S23], this analysis assumes that total plant biomass from harvest is 7.73-times that of the final marketable flower, by dry weight. Additional associated emissions or sequestration occur when the waste stream is mixed with other organic refuse (e.g. sawdust), typically 1:1, as required by many laws. These added flows are not counted here, given uncertainty about the fraction diluted by biomass versus other materials or what fraction of those streams would reach landfill anyway.

Key sources and sinks of greenhouse-gas emissions from landfill activities include those from equipment and operations, CO_2 sequestered when the plant materials are properly buried, methane produced when decomposition is anaerobic, and possible weathering and carbon capture by reactive materials used in artificial growing media. Net emissions of methane depend on landfill management and capture efforts, if any. Of the 2,635 major municipal solid waste sites in the US, 536 (20%) were reported to have methane-recovery systems in place as of March 2024 [S104], although it is not clear what proportion of those site surface areas have achieved methane containment and recovery.

Summers et al. [S23] assume the use of organic growing media, which results in significant added volumes of carbonaceous waste, much of which is assumed to result in sequestered carbon. For the present analysis, mineral wool is the assumed standard growing medium. A significant fraction of crop residues are generated from the extraction process, and likely reach landfill in a shredded and moist state, ideal for anaerobic (methane-forming) decomposition. To calibrate to the most similar waste types used in developing emissions factors in EPA [S105], “yard waste” is adopted as a proxy for the dried plant residues and “non-meat food waste” for the mineral wool growing media, which is a dense matrix with high water content saturated with fine biological sediment together with roots. The assumed feedstock carbon content, methane conversion and capture rates, and carbon sequestration rates are after EPA [S105].

Since mineral wool is manufactured from stone, there is no carbon-sequestration benefit from landfilling it. However, under the appropriate conditions, basalt (the primary constituent of many grow-media products), will capture CO_2 from the surrounding air via reactions during the weathering process. The literature, however, showing a range up to 0.88 kg COe per kg of basalt when particles are very small (<1 um) [S106], suggests that such sequestration is quite limited, particularly for relatively coarse mineral wool material (>100 um diameter is assume here).

Landfilled volumes collectively comprise 176 kt/year of solid plant waste generation by legal and illicit producers, plus 63 kt/year of discarded growing media, for a total of 239 kt/year solid waste production (excluding other streams). This is approximately 13-times the weight of the final, merchantable product.

The net effect of the abovementioned factors, per Table S7 is an emissions rate of 46.3 kg CO_2e/kg-flower (about 1% of total emissions for the entire cannabis process). These assumptions are cautious in light of recent detection of landfill-methane emissions far in excess of the levels previously believed to occur [S107].

For this analysis, all debris from legal growers is assumed land-filled, per local laws. Secondary crop losses described above and plant waste from eradicated illicit operations are subsequently properly landfilled, whereas the balance is left on the surface at the cultivation location, resulting in no net carbon sequestration or methane emissions if decomposition is aerobic. It is also assumed that the relatively small amount of home-cultivated plant waste is not landfilled and aerobically decays or is composted (resulting in little or no methane production or long-term carbon storage).

Wastewater systems generate methane as well, and cannabis wastewater would contain relevant biological precursors. Lacking literature and data on capture efficiency, this methane source is not included in this analysis.

Table S7. Greenhouse-gas emissions factors for landfilled cannabis residues

	Dry plant waste	Growing media waste		
Methane (CH4) emissions factors				
Total waste material	1	1	kg dry material to landfill	
Waste material per kg flower, by weight	*7.73*	6.1	kg biogenic waste/kg-flower	[S23]
Methane generation	2.2	6.6	in Mt CO2e/MT ton dry waste	[S105] Proxy: Yard waste: average of "Grass", "Leaves", and "Branches". Food waste, "Non-meat", Table 6-7, p 6-8
	16.9	**40.4**	kg COe2/kg-flower	[S105] Per Section 6.2.2.3, this includes capture at landfills with collection systems.
Carbon sequestration emissions factors				
Total material to landfill	1	1	kg mineral wool + biomass interspersed biomass	
of which biological	1	0.77	kg biomass per kg of total waste	
Carbon fraction in disposed biological material	47%	51%	kg C/dry kg waste to landfill	
Fraction stored	-72%	-17%	C	
CO2 stored	-1.23	-0.25	kg CO2/kg dry waste	Pure CO2, no other GHGs
Waste material per kg flower, by weight	*7.73*	4.7	kg biomass waste/kg-flower	[S23]
	-9.5	**-1.2**	**kg CO2e/kg-flower**	
Mineral wool media (basalt-weathering factors)				
Carbon sequestered per kg mineral wool	-0.1	-0.1	kg CO2e/kg mineral wool > 100 um diameter	[S106]
Mineral wool	0.227	0.227	kg (dry weight) mineral wool per plant or cube	Manufacturer data
Flower yield	0.164	0.164	kg per plant or mineral wool cube	
	-0.1	**-0.1**	**kg COe2/kg-flower**	
subtotal	**7.3**	**39.1**		
Total		**46.3**	kg CO2e/kg-flower	

Uncertainties and sensitivity analysis

As noted above, estimated emissions would be higher were the many unquantified factors contributing to greenhouse-gas emissions from the cannabis industry included in the analysis (see Figure 1 in the main article). Where multiple estimates are available (e.g. crop losses, numbers of dispensaries, overproduction, etc.), this analysis has tended to use the lower (more cautious) ones. In other cases, where baseline assumptions are uncertain the analysis uses values deemed most representative of industry practices. For the most significant factors, sensitivity analysis has been conducted to bracket the uncertainties (Figure S3).

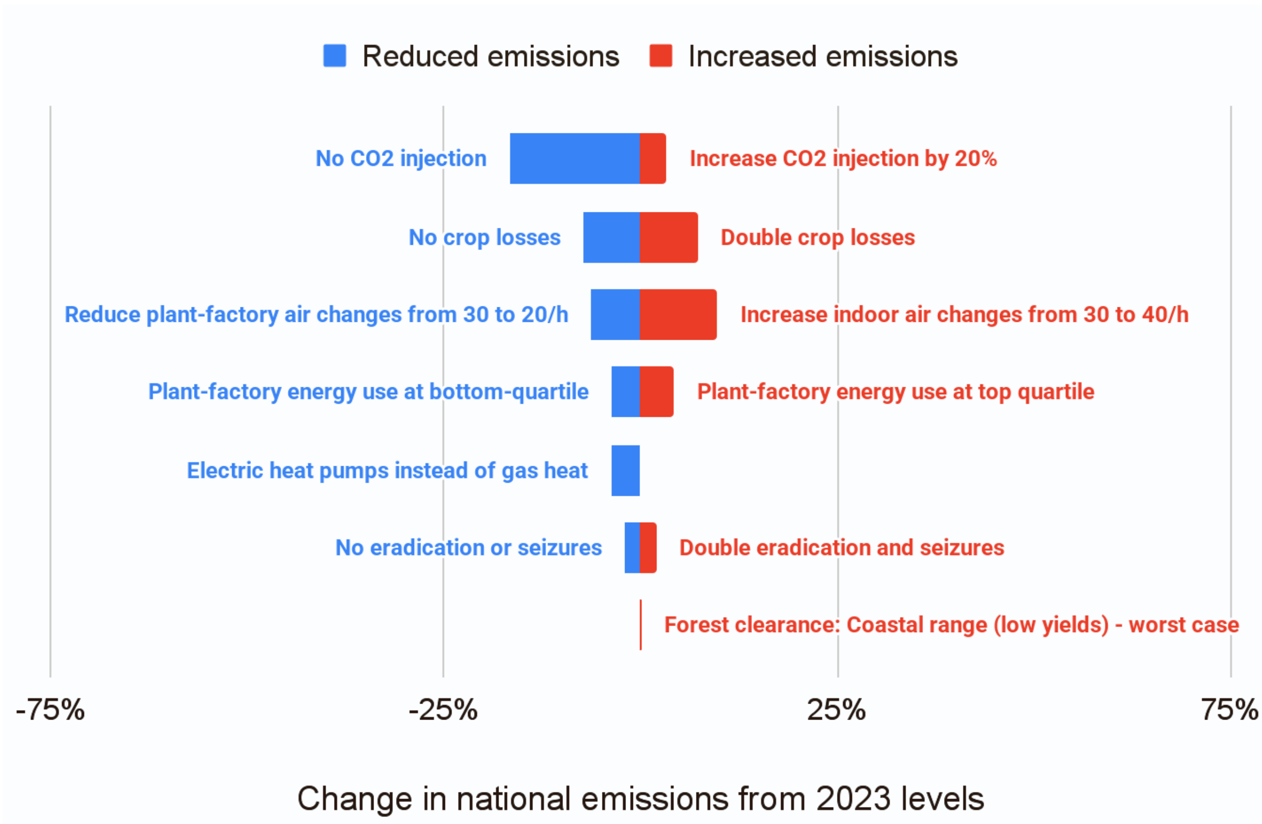

Figure S3. Sensitivity analysis

Values apply to aggregate emissions from all forms of production (baseline 44 kt/y). Forest clearance values reflect the highest emissions case in Table S8, i.e. the most productive forest (coastal mountains and the lowest open-field cannabis yields (0.11kg flower/m^2-y). The calculation assumes 20% of cultivation involves clearing of forestlands, and the site is cultivated for five years; carbon storage from foregone tree growth is not estimated.

The effects of injected CO_2, energy intensities, and fuel choices are tested. Amounts of supplementary CO_2 could arguably be lowered where air is recirculated at high rates, thanks to lower losses. Conversely, CO_2 is occasionally recommended even for open-field cultivation [S108], but that application is not assumed here. The influence of CO_2 injection can be usefully bracketed by the limiting case of no usage (resulting in a 17% reduction in industry-wide CO_2e emissions) from the baseline level of 1,400 ppm to an increase of 20% (resulting in a 3% emissions increase). Note that Summers et al. [S23] did not model changes in yield as CO_2 is varied, suggesting that the real-world carbon-intensity sensitivity range is narrower than shown here. All commercial indoor sites (not homes) are assumed to do so in this analysis.

The assumed facility air-change-per-hour (ACH) values from Summers et al. [S23] are arguably high in cases where CO_2 is supplemented, and reducing air-change rates from the default value of 30 ACH by 30% reduces facility-level emissions intensity by 8%-22% depending on climate zone, while increasing it by the same amount elevates emissions by 21%-26% [S23]. Per Figure S3, the aggregate (industry-wide) effects of the outer limits of these ranges on total national emissions range from -6%-10%.

Sensitivity to energy-use intensity is bracketed by recomputing national results across 1,011 sites using proxies of the lower quartile of energy use (11.3% below base case) found by Summers et al. [S23], resulting in a 4% emissions reduction and the upper quartile (a 13.3% increase from the base case) resulting in a 4% emissions increase.

Summers et al. [S23] make a simplified stipulation that heating is provided with natural gas. Alternatively, modeling all legal and illicit cultivation being done with electric heat pumps results in a relatively minor (3.8%) change in overall national emissions. This last effect is small because of the relatively close emissions factors of the U.S. grid and heat pumps versus gas combustion, and that much of production still occurs outdoors.

Note that the uncertainty analysis presents variance in aggregate national emissions across all energy uses and types of cultivation. Thus, percentage variance will tend to be higher for the corresponding market sub-segment. For example, inclusion of the worst-case land-use change in forests, results in less than a 1% increase in national emissions, but a 15% increase for a specific site at which this is in fact done. These levels of variance do not alter the qualitative finding that emissions are high and poorly managed and the current policy environment could be improved to foster improved outcomes, but underscore the value of further research and data collection.

Variance analysis can also be usefully applied to test the potential for certain market and policy pathways (Figure 4 in main article). One of the more impactful factors is the choice of plant cultivar, which has been seen to influence energy use per unit yield by a factor of four under otherwise similar growing conditions [S73, S109, S110]. The scenario of electrification using high-efficiency equipment includes 100% conversion to LED lighting assuming a 34% end-use share of total electricity and 40% lighting energy savings [S73] and 100% of fuel-based heating converted to efficient electric heat pumps with COP 3.25 [S23]. The net effect is a 10% reduction in industry-wide emissions.

Water- and Land-use Intensity

Water and land use have important energy implications for the assessment of indoor versus open-field cannabis cultivation, as energy use is embodied in water production and treatment, water is embodied in energy production, and land use is a constraint to the adoption of on-site renewable energy. Superior land- and water-use efficiency are often asserted as reasons that indoor cultivation is more environmentally benign than open-field production.

A comparative assessment of typical and best-practice land and water-use was developed by pooling data from the literature representing 188 sources and 503 specific cultivation sites or trials representing 29.8 million square feet of cultivation area [S121]. When best practices are examined – utilizing compost-enriched soils with high water retention properties together with intensive plantings to minimize evaporation – open-field cultivation can be more land- and water-efficient than indoor practices.

The irrigation process embodies energy and other resources that should be included in cannabis life-cycle resource assessments. Water use intensity (gallons of water per unit weight of marketable flower) for typical open-field cultivation is nominally~50% greater than that of plant-factory cultivation, falling to ~50% less than plant-factory intensities with demonstrated best practices and ~75% less per current improvement targets (Figure S4). Moreover, when the system boundary is drawn to include water used for electricity production, far more water is required to run electricity-intensive plant-factories than even conventional open-field cultivation [S122].

Nominal land-use intensity (square meters per unit weight of marketable flower per year) for typical open-field cultivation is ~5-fold greater than that of plant factories, falling to less than twice that level with demonstrated best practices and ~25% less than plant-factory intensities per current improvement targets (Figure S5). With two or more open-field crops per year, outdoor cultivation with demonstrated best cropping practices requires less land than current indoor cultivation practices. Were plant factories to convert to solar electricity (greenhouses cannot utilize solar panels, as they would shade the plants), the land area required falls within 10- to 20-times the cultivation area (and far more in northern climates), resulting in substantially more land use than open-field production [S122].

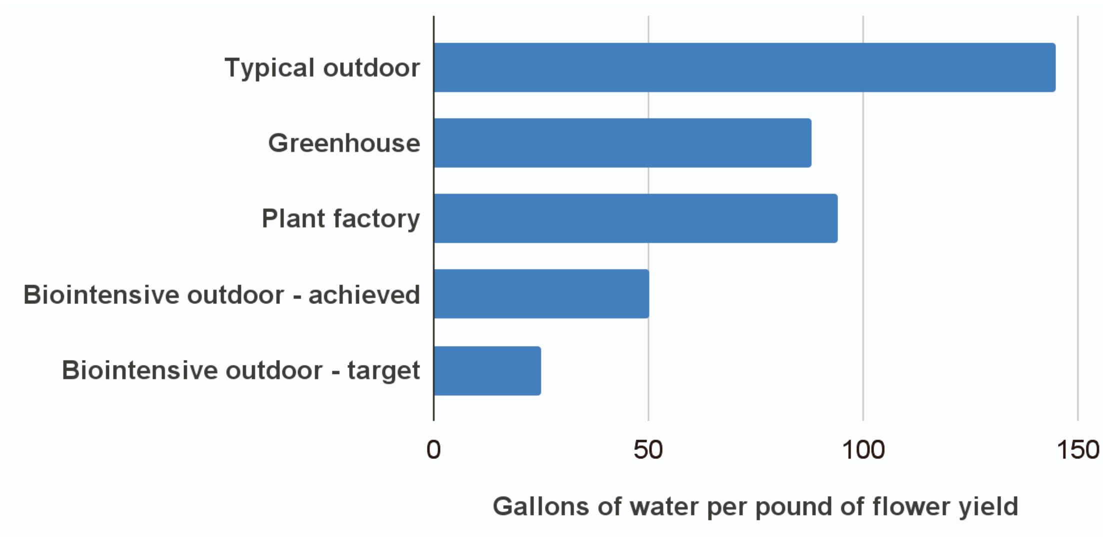

Figure S4. Direct water use for various cannabis production methods (median values)
Water quantities exclude rainfall [S121].

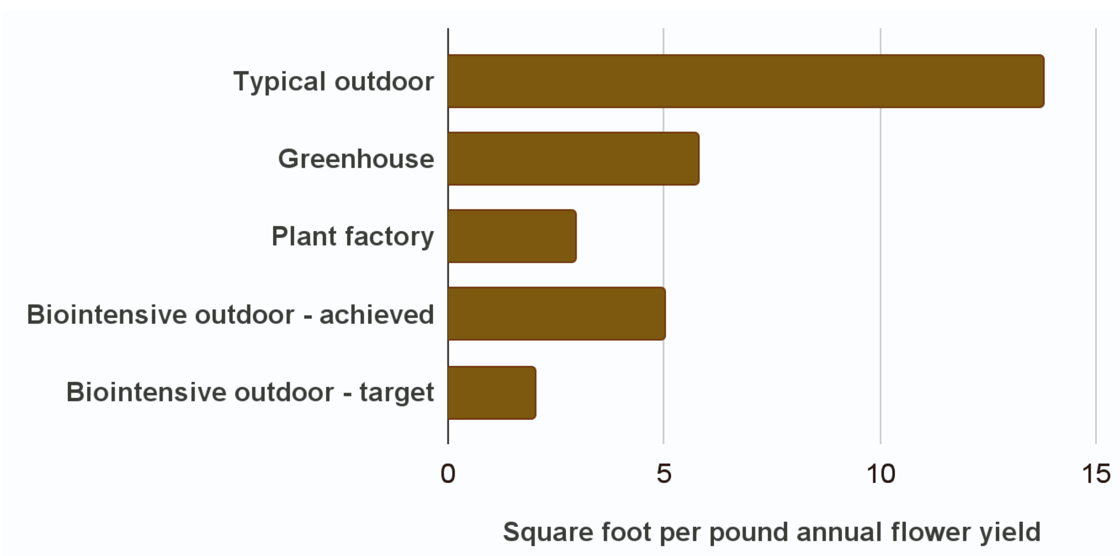

Figure S5. Direct land use for various cannabis production methods (median values)
Note that the biointensive site here grows only one crop per year in eastern British Columbia; results could be markedly improved in milder climates [S121].

Land-use Change

Second-order greenhouse-gas emissions can result from land-use change, particularly in the case of illicit open-field production encroachment into forestlands, degrading peat bogs, etc. Such clearing is common [S123]. In one Northern California study area, Bustic et al. [124] found that 90% of the land in cannabis cultivation (not all necessarily illicit) had been covered with natural vegetation only 10 years earlier, in 41% of the cases the cover was forestlands. While deforestation in the 8,067 km^2 northern California study area (62 watersheds) impacted a much larger area than cannabis cultivation, Wang et al. [S125] found that deforestation due to cannabis had a larger effect on a per-square-kilometer basis than logging. Emissions from clearing young forests range from 10.6 $kgCO_2/m^2$ to 51.3 to $kgCO_2/m^2$ depending on geography (Blue Mountains and western coastal forests, respectively) and tree species [S126]. One study [S21] documented median open-field yields ranging from 0.11 kg (lower quartile) to 0.42 kg flower/m^2-y (upper quartile), which corresponds to emissions of 25-477 kg CO_2/kg-flower across the range of localities and yields when allocating all the emissions from deforestation to a single year of harvest Table S8). Lacking aggregate data on land use and numbers of harvests conducted on a given location, this factor is not included in the primary analysis, but is tested as a sensitivity in Figure S3.

Table S8. Normalized ratio of displaced forest carbon displaced to cannabis yields

	Forest-type characteristics			Forest CO2 released per cannabis harvest* (kgCO2/kg-flower)		
Region	Live biomass (kg C/m2) - young	Dead biomass (kg C/m2)	Total kg CO2/m2	Low cannabis yield	Median cannabis yield	High cannabis yield
Blue Mountains	1.9	1.0	10.6	99	46	**25**
Coastal range	10.9	3.1	51.3	**477**	222	122
East Cascades	3.0	0.8	13.9	129	60	33
Klamath Mountains	5.2	1.5	24.6	228	106	59
Sierra Nevada	3.8	0.8	16.9	157	73	40
West Cascades	6.2	3.1	34.1	317	147	81
* carbon emissions allocated to 1y cannabis harvest; to be prorated over years of site operation. Array average						**135**

Sources: Forest carbon [S126], for young (<80-year) forests. Cannabis yields from [S21].

Extraction of active ingredients

Post-cultivation processes also involve energy use and associated greenhouse-gas emissions. For example, Cannabis product manufacturers increasingly seek to extract active ingredients such as THC and CBD from dried flower material for use in topicals, edibles, beverages, and vaporization cartridges [S54]. There are a variety of extraction processes, suited to different scales, budget constraints, safety consideration, and ingredients being targeted. Importantly, actual extraction efficiencies (fraction of active ingredient successfully extracted) vary widely, depending on process and cultivar [S127], with one review [S128] identifying a range of 26%-96% across all constituents (THC, CBD, etc). In their literature review, Qamar et al. [S129] find the following range of extraction efficiencies, by solvent: chloroform 98%-99%, hexane 80%-90%, ethanol 50%-60%, and petroleum ether 88%-95%. Efficiencies below 100% imply added cultivated volume compared to direct consumption of plant material.

Solvent-based methods are preferred to mechanical methods given their higher recovery efficiency. They include Soxhlet, both static and dynamic maceration, ultrasonic-assisted extraction, microwave-assisted extraction, supercritical fluid, and pressurized liquid extraction and the most common solvents are alcohol, hydrocarbons, and supercritical CO_2 [S130]. Some processes occur at high temperatures while others require cooling, implying additional energy requirements. The manufacture of solvents requires energy inputs, and some can also result in the release of CO_2 if combusted during or after the extraction process.

Additional unquantified emissions subsequently arise from post-extraction processing (e.g. "winterization" to remove undesired botanical wax residues using super-cooling methods), product manufacturing (e.g. baking), and the manufacture of delivery devices that utilize these extracts (e.g. battery-powered vaporization).

Aggregate national emissions from extraction are not estimated in this analysis, as there is no data on the quantity of extracts produced annually by type or extraction process, and little information on energy use or other sources of emissions by process.

One report from the industry's trade literature [S131] makes it possible to impute emissions intensity for the supercritical CO_2 extraction process (Table S9). According to one manufacturer of extraction equipment [S132], the energy use of this process is higher than that of butane-extraction processes and lower than that of ethanol processes, each of which are also popular methods. The example suggests an added carbon intensity of 31% for open-field cultivation, 14% for greenhouse cultivation, and 11% for plant-factory cultivation, assuming an extraction efficiency of 92% [S133].

Table S9. Scoping estimate of cannabis extraction carbon footprint using supercritical CO_2 method

Flower input	149.7	kg flower/week	[S131] 4 days/week
	7783.9	kg flower/y	
Electricity cost	$6,730	$/week	[S131]
	$349,960	$/y	
Imputed electricity use			
Electricity price	$0.107	/kWh	[S6] value for 2018, to match [S131]
Electricity use	3,279,850	kWh/y	
Emissions from extraction process			
Emissions factor (US grid, 2022)	373	grams CO2e/kWh	[S7]
Total emissions	1,224,633	kg CO2e/y	
Extraction emissions factor	157	kg CO2e/kg flower	
Extraction efficiency (Active ingredient recovery from input plant material)	92%		[S133] highest-efficiency
Emissions increment over range of upstream emissions factors (kg CO2e/kg flower)			
Cultivation mode	Open-field	Greenhouse	Plant factory
Emissions prior to extraction (this study)	674	2,511	4,497
Extraction emissions	157	157	157
Extraction-efficiency losses	54	201	360
Total emissions	211	358	517
Fraction of pre-extraction emissions	31%	14%	11%

Grid disruptions

Table S10. Examples of power outages attributed to indoor cannabis cultivation activities

Year	Location	Description	Impacted Utility
2014	Florida	68 plants at a house	Unknown
2014	Colorado	Transformers blowing in converted factories	Excel Power
2015	California	2,100 plants in 13-14 rooms. Transformer blew, leaving many nearby businesses without power	Los Angeles Department of Water and Power
2015	Oregon	Legal cannabis operations responsible for 85% of transformer problems in residential areas	Portland General Electric
2015	Oregon	7 transformers in 3 months. Just one or two in-house growing operations on a circuit could overload the local grid and cause an outage	Pacific Power
2015	Oregon	33,000 plants. Multiple transformers blown. 7 blackouts in one summer	Unknown
2019	California	6,000-7,000 plants. Blew transformer. Property owner deemed responsible, a dozen adjacent businesses without power for several months	Pacific Gas and Electric
2022	Oregon	Utility replacing ~40 transformers a year (10% of all replacements) due to overloading caused by cannabis operations	Portland General Electric
2020	California	Transformer fuses blown	Pacific Gas and Electric
2021	California	PCB leak from transformer: 18-hour outage	Pacific Gas and Electric
2022	California	Non-specific outage	Pacific Gas and Electric

Source: [S86]

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