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Global Perspective

Cannabis and the Environment: What Science Tells Us and What We Still Need to Know

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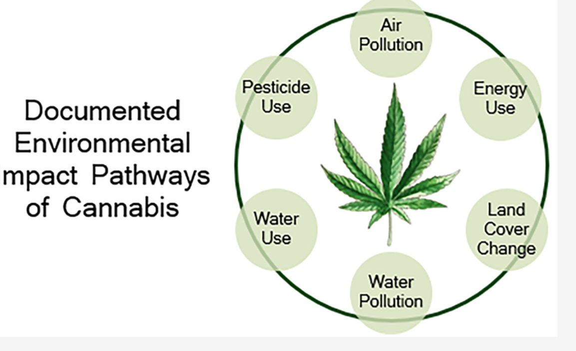
ABSTRACT: Riding the global waves of decriminalization, medical or recreational use of cannabis (*Cannabis sativa* spp.) is now legal in more than 50 countries and U.S. states. As governments regulate this formerly illegal crop, there is an urgent need to understand how cannabis may impact the environment. Due to the challenges of researching quasi-legal commodities, peer-reviewed studies documenting environmental impacts of cannabis are limited, slowing the development of policies and agricultural extension guidelines needed to minimize adverse environmental outcomes. Here we review peer-reviewed research on relationships between cannabis and environmental outcomes, and identify six documented impact pathways from cannabis cultivation (land-cover change, water use, pesticide use, energy use, and air pollution) and consumption (water pollution). On the basis of reviewed findings, we suggest policy directions for these pathways. We further highlight the need to formalize existing traditional and gray literature knowledge, expand research partnerships with cannabis cultivators, and ease research restrictions on cannabis. Finally, we discuss how science might contribute to minimize environmental risks and inform the development of regulations for a growing global cannabis industry.



INTRODUCTION

The past two decades have seen increases in worldwide legalization of medical and recreational cannabis cultivation and consumption.[1] As of October 2020, cannabis is legal for recreational use in Uruguay, Canada, and 12 states in the United States and for medical use in 36 countries.[2] We use the word "cannabis" here to refer to *Cannabis* spp. (subspecies "sativa" or "indica") with a high dry weight tetrahydrocannabinol (THC) content of >0.3%[3−5] (commonly termed marijuana), distinguished from low-THC forms of the same plant (commonly termed hemp). As legal markets for cannabis develop and illegal markets continue to thrive, policy makers are tasked with regulating cannabis cultivation, distribution, and consumption in new ways.

The combined economic values of legal and illicit global cannabis markets have been estimated at $214−344 billion.[3,4] Legal markets are projected to grow significantly by 2025.[5] Still, today's global markets remain dominated by illicit channels. While accurate estimates of cultivation area and production quantities are not feasible due to a lack of empirical data,[6] cannabis cultivation has been reported in 151 countries for the period of 2010−2018, highlighting the broad geographical scope of production activities. Today, most cultivation appears to be outdoors; however, there have been indications of recent increases in indoor cultivation, particularly in the United States, Canada, Chile, Uruguay, Colombia, and Ecuador.[6]

Early stages of legalization offer policy makers a unique opportunity to anticipate and manage adverse environmental outcomes of the cannabis industry.[7] Environmental concerns are already being incorporated into the design of some regulations (e.g., in California and Canada).[8,9] Research interest in the environmental impacts of cannabis is also growing, partly fueled by increasing public concerns and news coverage of the topic (Figure 1a). Due to cannabis' quasi-legal status in many countries and to persistent societal stigma, researchers investigating cannabis and the environment have faced logistical and regulatory hurdles.[10] However, as legal permissions to conduct research on cannabis increase, a new body of peer-reviewed literature around cannabis and environmental impacts is emerging.

Before 2012 (Figure 1b), few scientific studies documented links between cannabis and environmental degradation.[11−13]

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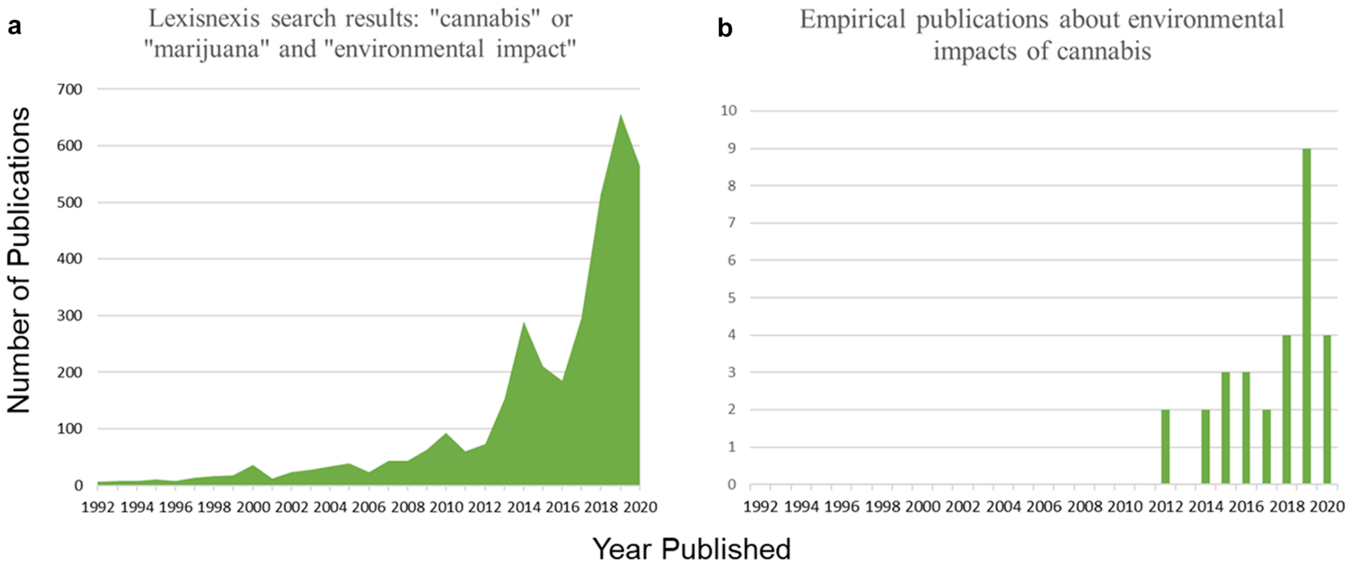

Figure 1. (a) Published global news articles based on a Lexisnexis Academic Database search and (b) published research studies identified in our literature review for the period from January 1992 to October 2020, covering the environmental impacts of cannabis.

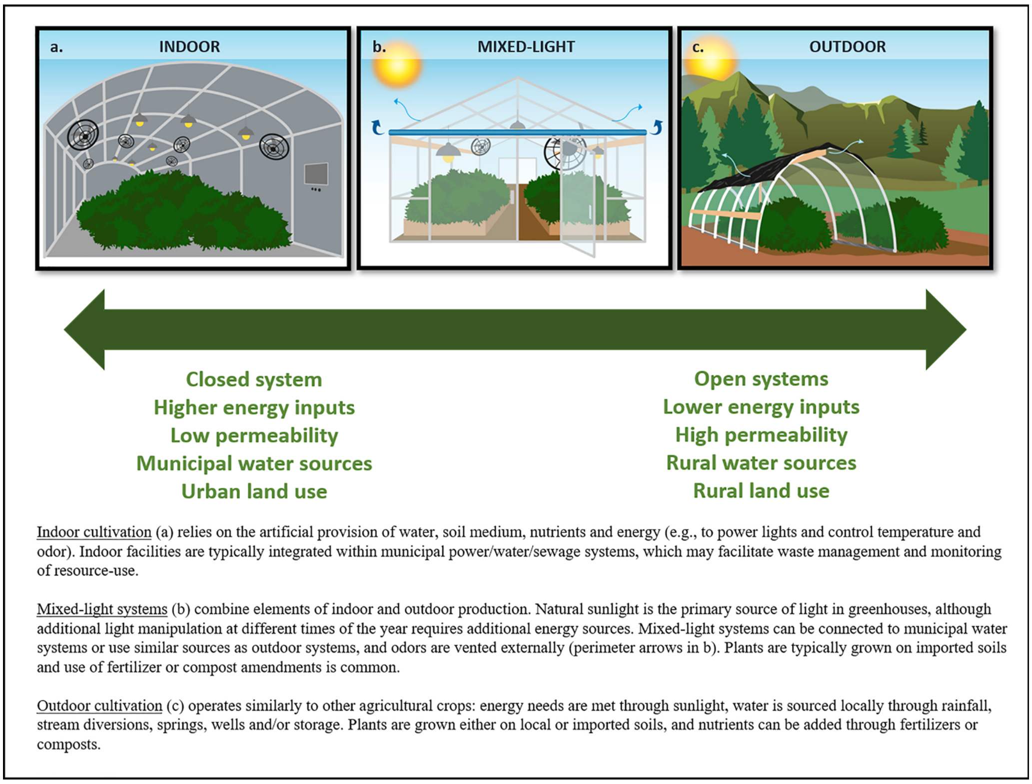

Figure 2. Cannabis production systems and links to potential environmental impact pathways.

Since then, empirical studies have slowly started to quantify the environmental consequences of cannabis cultivation, and to some extent its consumption; therefore, an aggregated analysis of these studies is now possible. The goal of this review is to examine our current understanding of cannabis and the environment and to identify knowledge gaps. Specifically, we (i) review existing peer-reviewed literature documenting relationships among cannabis cultivation, consumption, and environmental outcomes, (ii) identify significant research findings and knowledge gaps, and (iii) propose policy recommendations for regulating the legal cannabis industry. Our aim is to create a resource that provides science-based guidance for policy makers and identifies pressing research needs.

A Brief Background on Cultivation Systems. We recognize three primary typologies of legal cannabis cultivation systems based on existing regulations: indoor, mixed-light, and outdoor.[8] These three production systems may impact the environment through different pathways (Figure 2). Indoor and mixed-light cannabis cultivation systems may require higher external inputs (e.g., energy[14] and fertilizer) but are also associated with higher yields and reduced concerns about ecosystem degradation. Outdoor farms may require fewer resource inputs, but poor management or siting can disrupt surrounding ecosystems. Both indoor and outdoor cultivation systems may be associated with air pollution risks from biogenic volatile organic compounds (BVOCs) that can be precursors to ozone formation. To date, these various concerns have not been systematically researched. Moreover, in practice, there are countless variations and combinations across production systems. For example, in a single farm, mother plants may be kept indoors, while cloning occurs in mixed-light environments, and full plants are grown outdoors.

In examining the effects of these systems, we start with the understanding that adverse environmental impacts may be minimized in legal, well-managed indoor, mixed-light, and outdoor systems. We note, however, the existence of an additional cannabis cultivation subtypology: trespass systems, which refers to illegal outdoor cannabis cultivation sites on public land. In these systems, water is typically drawn without permission from local sources, energy is provided by sunlight, fertilizers are imported to amend local soils, and toxic pesticides are often used. As illegal trespass grows represent an exception to the idea that well-managed cannabis cultivation may be environmentally sustainable, we examine their environmental impacts separately from other forms of production.

Finally, we note that while industrial hemp has traditionally been grown using techniques more similar to large-scale grain farming and therefore is not a good surrogate for cannabis production, there is potential for convergence of these two production systems in the future. Hemp includes high-cannabinoid (CBD) content flowers grown using production methods similar to those used for cannabis. Future hemp production may thus have impacts similar to those of cannabis, and future assessments of hemp production for CBD content might serve as a surrogate for studying similar cannabis impacts. On the contrary, as extracted THC becomes a larger share of the cannabis market, we may see large-scale cannabis production in which the total biomass, not just the flowers, is important. Similarly, existing research on hemp production may inform future assessments of cannabis production for biomass and/or fiber.

Identification and Selection of Studies. We evaluated peer-reviewed literature sources that quantify the effects of cannabis cultivation or consumption on the environment. Gray literature sources, though numerous, may be of variable quality and were therefore not considered. We excluded peer-reviewed studies that (i) provided only qualitative evidence of cannabis impacts on the environment, (ii) addressed other impacts of cannabis such as on human health, (iii) focused on other plants, including *Cannabis* spp. used for hemp production, or (iv) commented on environmental impacts without presenting new empirical data (e.g., through synthesis or review of previous studies). Peer-reviewed literature on industrial hemp was not included due to divergent production methods for industrial hemp versus cannabis. Research examining the environmental impacts of other illegal drugs[15,16] was also not included. Indeed, the focus of our review is not on illegal drug plant cultivation per se, but rather squarely on cannabis.

On the basis of published commentaries on cannabis and the environment,[10,11,13] we identified relevant studies through a list of search terms (see the Supporting Information) that we applied in the Web of Science. We screened titles and abstracts of resulting studies in May and June 2020 according to the eligibility criteria noted above and included relevant publications referenced in these studies in our final review. On the basis of the final 28 peer-reviewed studies included (see the Supporting Information for a full list), we identify six distinct documented pathways through which cannabis may impact the environment: land-cover change, water use, pesticide use, energy use, air pollution, and water pollution.

■ RESULTS, POLICY RECOMMENDATIONS, AND DISCUSSION

Despite the broad geographic range of cannabis cultivation, we identified few empirical studies on the environment originating outside of the United States, with the exception of literature on the effects of cannabis on water pollution in urban areas. Water pollution was the only pathway for which we found peer-reviewed documentation on the impacts of cannabis consumption, highlighting a significant knowledge gap regarding other consumption-related consequences such as wildlife or domestic animal poisoning by cannabis product litter or THC-contaminated waste. For all other pathways (land-cover change, water use, pesticide use, energy use, and air pollution), reviewed studies focused on cannabis cultivation impacts. We further note that, with the exception of one study by Butsic and Brenner,[17] which examined land-cover change and water use impacts in California, all reviewed studies focus on single environmental pathways, suggesting that systematic or cumulative analyses of cannabis cultivation impacts are currently lacking.

Land-Cover Change. Globally, agricultural land-use occupies roughly one-third of the earth's ice-free land area.[18] Agricultural expansion, particularly in the tropics, is a leading driver of forest clearing, carbon dioxide (CO_2) emissions, and biodiversity loss.[19] Even with continued cannabis cultivation expansion, we expect the total amount of land cultivated for cannabis to remain relatively small, especially compared to other crops. In California, an approximate 460 ha of permitted cannabis (a fraction of the 9.8 million ha of 2019 agricultural land in the state[20]) is already producing enough to supply the state's market.[21]

There is a paucity of studies quantifying land-use impacts of cannabis cultivation despite reports of significant cultivation activity in North and sub-Saharan Africa, the Americas, and Asia.[22−24] Butsic and Brenner[17] developed a framework for spatially characterizing cannabis cultivation sites across landscapes using satellite imagery. In a follow-up study, Butsic et al.[25] examined satellite data for Humboldt County, California, which showed a high concentration of cultivation sites in remote, ecologically sensitive areas. The study indicated a relatively limited impact of cannabis cultivation on land-cover change, with a contribution of 1.1% of forest canopy area loss compared to 53.3% from timber harvest in 2000−2013. However, remote cultivation sites were linked to landscape perforation as they created gaps in forest patches, reducing forest core areas and increasing open edges. Due to historic prohibition, cannabis is cultivated on marginal agricultural land of high ecological importance in many countries.[26] Predicted expansion of the cannabis industry may thus increase landscape-wide forest fragmentation, and resulting degradation of ecosystem function and related environmental services.[27] Land-use change from cannabis has the potential to directly and indirectly impact natural ecosystems at multiple scales. While further research on this topic is needed, recent results from a camera-trap study conducted by Parker-Shames et al.[28]

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in Oregon point toward species-specific changes in wildlife behavior near private cannabis farms, which may potentially deter larger wildlife species. The spatial distribution of remote outdoor, mixed-light, or trespass cannabis farms, in addition to their total land-use footprint, may thus be a significant determinant of possible environmental impacts.

Other studies offer insights into social drivers of land-cover change that may be useful for policy makers and managers. Cannabis prices and law enforcement risks emerged as important factors determining siting decisions of illegal markets in California, Oregon, and Washington.[29] Butsic et al.[30] documented strong network effects among growers in Humboldt County, leading to physical clustering of cultivation sites, which seemed to be more important than biophysical factors such as soil quality or terrain. Klassen and Anthony[31] identified differences in state enforcement capacities, poverty, and unemployment rates as potential factors leading to a decline in discovery of illegal farms in Oregon, but not Washington, following legalization in both states.

Water Use. Unsustainable water use for agricultural production can have negative ecological impacts through surface water and groundwater depletion. Globally, an estimated 70% of freshwater use goes to agricultural irrigation, accounting for ∼40% of worldwide food production.[32] Like those of other crops, the water requirements of cannabis are highest during the growing season. In semiarid growing regions, this generally means drier summer months. In a warming climate, drought frequency and intensity are increasing in many regions, causing water rights to surpass available flows during dry years.[33] Several peer-reviewed studies investigated the water footprint of outdoor, mixed-light, and trespass cannabis cultivation in terms of water extraction, storage, and use. In a 2015 study, Bauer et al.[34] used satellite imagery to estimate the number of total outdoor, mixed-light, and trespass cannabis plants in northern California, and predicted that watershed-scale water consumption could exceed local streamflow during the cannabis growing season. These results were based on assumptions that (i) on average, a cannabis plant consumes 22.7 L (6 gal) of water per day throughout the growing season, (ii) this water is predominantly accessed through surface water diversions, and (iii) water application equals water extraction. The authors suggested that, during dry years, cannabis farming could completely dewater some streams. In a study characterizing the spatial footprint of outdoor, mixed-light, and trespass cannabis cultivation, Butsic and Brenner[17] applied a similar methodology and estimated annual water use for cannabis irrigation in Humboldt County, California, as 11000 m^3, equivalent to 0.0002% of the annual water use for crop irrigation in the county.[35]

These findings highlight the potential impacts of outdoor, mixed-light, and trespass cannabis cultivation on water resources, but their validity is limited by a lack of actual water-use data. Two additional studies in California examined cultivator-reported water use for permitted outdoor and mixed-light cannabis cultivation at the farm scale. High variability in water use and extraction practices was documented, likely driven by variation in seasonal growing patterns, farm size, or cultivation methods. In these two analyses, Wilson et al.[36] [58 independent respondents (n)] and Dillis et al.[37] (n = 608) confirmed that water-use rates were highest during peak growing season. Respondents reported lower water-use rates throughout the rest of the year. Dillis et al. further assessed monthly water use on permitted cannabis farms; their findings indicated that water extraction patterns, distinct from water application, were highly dependent on the water-storage capacities of farms and their reliance on seasonal water sources.[37]

In two separate survey-based assessments of farm-scale water extraction practices, Wilson et al.[36] and Dillis et al.[38] (n = 901) showed that groundwater wells, rather than surface water diversions, may be the primary source of water for many northern Californian outdoor and mixed-light cannabis farms. Groundwater extraction may thus threaten connected watersheds if annual extraction exceeds recharge rates, as subsurface water reserves tend to recover more slowly from overuse than do surface sources. Consequences of groundwater use and depletion are relevant for cannabis and beyond, and constitute issues of growing global concern.[39] In the Navarro watershed in California, Zipper et al.[40] confirmed increased groundwater pumping rates during the cannabis peak growing season. More than 50% of this increase was driven by a limited number of wells, generally located within 1.2 km of streams. Combined well observations and model projections for multiple locations in the Navarro River watershed in Northern California further indicated that groundwater extraction for cannabis irrigation could contribute to 1.9% of monthly stream baseflow depletion after 50 years of pumping, compared to 9.3% of monthly stream baseflow for residential use.[40] The lack of empirical research on water use dynamics in other cannabis growing regions constitutes a fundamental knowledge gap. Still, data from California indicate that in the absence of regulation, cannabis irrigation could significantly exacerbate water stresses in drought-prone regions.

Pesticide Use. An estimated 5.6 billion pounds of pesticide is applied annually for agricultural cultivation.[41] Pesticides are associated with numerous negative environmental impacts on terrestrial and aquatic ecosystems and human health,[42,43] yet to the best of our knowledge, no quantitative studies have documented environmental impacts of pesticide use on private land or in legal cannabis cultivation systems. Globally, national-level guidelines for pesticide application in legal cannabis cultivation are lacking,[44,45] although Canada has set pesticide contaminant limits and approved 96 pesticide and fungicide compounds for legal use on cannabis.[46,47] In the United States, some anticoagulant rodenticides (ARs) are heavily restricted at the federal level, and individual states with legalized cannabis have provided lists of allowed pesticides that exclude ARs.[44,45] Other forms of agriculture and food production sites, in the United States and globally, may still use ARs. There are currently no international- or national-level standardized protocols for testing for pesticides in cannabis products or for ARs in general. Nevertheless, this topic has garnered an increased level of attention due to the potential human health impacts of pesticide residues on cannabis products,[48] as evidenced by recent reviews of analytical methods of detection of pesticides and trace elements on cannabis.[44−46]

While most outdoor cannabis production does not use ARs, trespass grows, however, may be a unique pathway for environmental contamination through ARs on local wildlife species. Anticoagulant rodenticides are known to bioaccumulate, and their use on trespass cultivation sites has been documented in California.[49] For example, contamination by highly toxic ARs was documented for an endangered predator, the Pacific fisher (*Pekania pennanti*), using a combination of field data collection, laboratory data analysis, and spatial

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correlation.[49,50] Despite high AR exposure levels (79% of 58 sampled animals and 85% of 46 sampled animals), both studies reported small numbers of animals dying directly from AR exposure (4 and 1, respectively). Nevertheless, AR poisoning may impact animal fitness and thereby mortality rates, as shown for California fisher populations[51] (167 sampled fishers), with increasing prevalence from 2007 to 2014. Anticoagulant rodenticide contamination was also documented in northern spotted owl (*Strix occidentalis caurina*) and barred owl (*Strix varia*) populations, likely through secondary poisoning from predation on contaminated rodents.[52,53] While differential effects of chronic versus acute exposure to ARs are unclear, and despite some limitations due to small sample sizes, these studies draw attention to a potential ecological threat posed by trespass outdoor cannabis cultivation methods.

Energy Use. For cannabis, the annual average electricity intensity has been estimated to range from 78 MJ m^{-2} (outdoor) to 10152 MJ m^{-2} (indoor),[14] compared to average annual energy consumption ranges of 600−2827 MJ m^{-2} for greenhouse vegetable and flower cultivation in Canada, Europe, and North Africa.[54,55] Energy consumption in indoor, mixed-light, and outdoor cannabis cultivation systems is driven by a range of processes, including water pumping or fertilizer production. Overall, most energy use from cannabis cultivation is ascribed to lighting, and water and air circulation, in indoor and mixed-light systems. In a 2012 study, Mills documented energy use for indoor and mixed-light cannabis cultivation in the United States[56] and estimated a total electricity-use footprint of 20 TWh annually, leading to the annual emission of 15000000 Mt of CO_2. This value is equivalent to the energy consumption of the entire U.S. agricultural sector.[57] Mills' calculations were based on U.S. indoor cannabis cultivation estimates and "typical" energy use. However, accurate data documenting total cannabis cultivation area, average planting densities in different production systems, or average energy use by different growers are not available. Ultimately, the study's findings may not accurately represent energy use by the U.S. cannabis sector today or among other production regions worldwide; this is due to uncertainties in modeling approaches, the likelihood that cultivation practices have become more efficient in recent years, and the influences of regional variations in climate, daylight, and other environmental factors on energy use.

We are not aware of other published studies regarding energy use in the cannabis sector. However, a recent third-party report[14] offered updated insights. The 2019 New Frontier Data report provides a detailed assessment of current cannabis energy use across all types of cultivation systems by combining estimated U.S. cannabis demand and cultivation area with self-reported data from cultivators (n = 81). Combined illegal cultivation and legal cultivation were estimated to consume 4.2 MWh annually, equivalent to 428191 Mt of associated CO_2 emissions. These estimates did not account for off-grid energy use (e.g., solar), transportation, fertilization, or irrigation, and were significantly lower than the numbers reported by Mills in 2012.[56] In addition, initial data from Colorado suggest that indoor cultivation facilities are responsible for a significant proportion (4%) of the energy use in Denver,[58] further highlighting the potential role of the indoor cannabis industry in terms of energy consumption, particularly in urban areas.

Air Pollution. Agriculture has been recognized as a major contributor to air pollution through the emission of gases like methane (CH_4), ammonia (NH_3), or nitric oxide (NO_x). These emissions occur from activities such as inorganic fertilizer amendments, animal husbandry, or transportation associated with food production. These gases can contribute to the formation of nitrate aerosols and fine particulate matter ($PM_{2.5}$) pollution, which has been linked to severe human health consequences.[59−61] Primary air pollution impacts from cannabis appear to be different from these other agricultural air pollution pathways. Our review identified three recent studies that assessed the impacts of indoor cannabis cultivation on air quality. Wang et al.[62] measured biogenic volatile organic compounds (BVOCs) emitted by cannabis plants grown under conditions mimicking greenhouse cultivation. Despite author-acknowledged limitations related to small sample sizes, suboptimal growing conditions, and a lack of access to common cannabis strains for testing, the results suggested BVOC emissions from indoor cultivated cannabis in Colorado could contribute to ozone formation and particulate matter pollution. In a follow-up study, Wang et al.[63] estimated terpene emissions and regional ozone impacts from indoor cannabis cultivation in Colorado using the Comprehensive Air Quality Model. This approach was limited by the reliance on estimates and assumptions in the absence of data regarding emission capacity of most cannabis strains, the number of plants, and plant biomass. Nevertheless, preliminary findings predicted increases in hourly ozone concentrations, indicating that concentrated indoor cannabis cultivation could influence ozone pollution through BVOC emissions (including terpenes), particularly in areas where nitrogen oxides are not limiting factors in ozone formation.[62,63]

A third pilot study conducted in four commercial indoor-growing facilities in California and Nevada[64] identified β-myrcene, D-limonene, terpinolene, and α- and β-pinenes as the most abundant BVOCs emitted by cannabis plants. This study also found high butane concentrations in cannabis-processing facilities using butane extraction, which could additionally contribute to ozone formation. These results are in line with those of Wang et al.[62,63] and highlight potential indoor air quality issues in production facilities, which may have consequences for worker safety. Current findings also suggest that concentrations of volatile compounds may decrease significantly outside of indoor cultivation facilities due to passive dilution into the ambient atmosphere. Lower BVOC emissions would occur from indoor facilities that filter air through carbon scrubbers or use similar emissions controls prior to exhaust. The full environmental implications of preventing external BVOC emissions would have to account for energy demands in powering mechanical equipment to treat and handle odorous air emissions. We found no published studies that systematically addressed these concerns. Nevertheless, as all three studies acknowledge, additional data are needed to fully understand the potential risks and implications of indoor cannabis cultivation on air quality.

Water Pollution. In addition to water contamination from agricultural pesticide use,[43] eutrophication of freshwater and coastal ecosystems from agricultural leaching has been recognized as a global problem.[65] However, although surface water and groundwater pollution from the cannabis industry is a likely environmental risk,[11] we found no peer-reviewed studies quantifying the impacts of cannabis cultivation on water quality. There is, however, a significant body of literature documenting the effects of pollution from the consumption of illegal drugs, including cannabis, on water quality in urban areas. This work has been highlighted in two recent publications: a synthesis of illicit drug occurrence in and effects on aquatic ecosystems[66] and a review of occurrences and potential mechanisms of removal of CBDs in wastewater treatment systems.[67] Reviewed studies evaluated concentrations of CBDs, 11-nor-9-carboxy-Δ^9-tetrahydrocannabinol ("carboxy-THC" or THC-COOH), or 11-hydroxy-THC (11-OH-THC), presumably originating from human consumption, in wastewater and drinking water. The presence of cannabinoids was evident in raw (influent) and biologically treated (effluent) municipal wastewater, as well as in surface waters, across major cities in Europe, the United States, Costa Rica, Colombia, and Martinique.[66,67] Reported CBD concentrations fluctuated across studies but were generally lower in treated effluent than in raw wastewater. Nevertheless, accumulation of these compounds may contribute to waterway contamination downstream from wastewater effluent discharges in urban areas, although likely to a lesser extent than other illicit drugs.[68] While these studies primarily aim to document the scope of illegal cannabis consumption, they also point toward potential cannabis-derived contamination impacting downstream freshwater ecosystems.

Our current understanding of the consequences of wildlife exposure to cannabis-related chemicals remains limited. Parolini et al.[69] attempted to bridge this gap through experimental exposure of zebra mussels (*Dreissena polymorpha*) to concentrations of cannabis active compounds Δ-9-THC and THC-COOH. Their results showed that prolonged exposure could contribute to oxidative and genetic damage. Experimental exposure to cannabis extracts further led to negative physiological or behavioral impacts in carp (*Cyprinus carpio* L.),[70] tilapia (*Oreochromis niloticus*),[71] and zebrafish (*Danio rerio*)[72] and induced high mortality rates in mosquitoes (*Aedes albopictus*) and snails (*Physella acuta*).[73] Still, given knowledge gaps with regard to actual Δ-9-THC and THC-COOH concentrations in aquatic ecosystems and the effects of the compounds on mussels or other organisms in the wild, it is difficult to draw broader conclusions about potential environmental risks posed by exposure to active cannabis compounds for aquatic organisms.

Policy Recommendations. On the basis of our review, we propose five policy recommendations that can be applied to regions where cannabis cultivation is legalized and subject to regulations. We note that our recommendations should be revisited as new research findings emerge.

1. Land Use: As Cannabis Has Traditionally Been Grown in Environmentally Sensitive Areas, Planning Could Minimize Negative Environmental Impacts Linked to Cannabis Expansion. In rural areas where the total cultivation area of cannabis is currently small relative to other land-use activities,[27] land-use planning strategies could regulate the location or size for newly established cannabis farming areas or could incentivize the voluntary relocation of existing grows onto suitable agricultural land (e.g., Humboldt County's "Retirement, Remediation, and Relocation" program[74]). While such measures should also consider socioeconomic impacts, they could minimize expansion into environmentally sensitive areas. In conjunction, wildlife-conscious farming practices could be encouraged to prevent further impacts on wildlife habitat. In urban areas, zoning policies may ensure that impacts from cultivation facilities (e.g., air or noise pollution) do not disproportionately affect vulnerable communities. Existing best practices to minimize land-use impacts include the application of regenerative agriculture practices and the implementation of land-use planning that takes into account site characteristics and predicted impacts of cultivation activities.[75]

2. Water Use: Cannabis Is Often Grown in Areas Where Managing the Timing and Location of Water Extraction Is Crucial for the Environment. Although the water-use footprint of cannabis remains small relative to those of other agricultural crops,[17,35] managing the timing and amount of water extracted for cannabis cultivation is crucial considering the large amounts of cannabis produced in semiarid and drought-prone landscapes. Incentivizing efficient water management (e.g., through precision-irrigation practices[76,77]) and establishing water licensing systems (as has been done in California[78]) could further alleviate pressure on surface water and groundwater reserves. Existing best practices for managing water use include the use of rainwater storage, automated irrigation technology, and implementation of water treatment and reuse strategies to reduce waste.[36,75]

3. Pesticide Use: Human Exposure Pathways for Pesticide Residues on Cannabis Are Unique, as They May Be Inhaled at High Temperatures or Ingested. It Is Thus Essential That Pesticide Controls Go beyond Those of Normal Agriculture. Developing rigorous testing standards for contaminant residues on legal cannabis products, coupled with certification schemes and educational resources for producers on alternative pest control methods, could contribute to market normalization of pesticide-free or limited-pesticide cannabis. For instance, California currently requires testing for 66 pesticides in all legal cannabis products.[79] Such initiatives may limit pesticide contamination by incentivizing legal producers to avoid the use of nonpermitted chemicals. Robust supply chain tracing and environmental monitoring systems for legal cultivators and distributors could further curb cannabis sourcing from trespass sites or illegal markets. Existing best practices include the application of biologically derived pesticide products (e.g., microbial pesticides or compost tea) and the implementation of integrated pest management methods (e.g., the introduction of predatory insect species).[36,75]

4. Energy Use: Incentivizing Best Practices Could Reduce Energy Footprints of Indoor and Mixed-Light Cannabis Cultivation. Some emerging regulations (e.g., in Massachusetts[80]) require indoor cultivators to develop energy plans, comply with existing best practice standards, and monitor and report energy usage. Setting up similar locally relevant policies could encourage energy efficiency, support the development of data sets on energy consumption, and eventually allow regulators to set realistic energy efficiency goals. Existing best practices include prioritizing the use of energy-efficient light sources (e.g., light-emitting diode lighting) and renewable energy sources, and scheduling around peak energy demand times.[75]

5. Air Pollution: Prioritizing Science-Based Best Practices Could Reduce Air Pollution and Air Quality Impacts. Ozone-formation simulations should be used to guide permitting practices. It should also be recognized that human olfaction is unreliable for assessing the toxicity of BVOCs[81] or, in cases in which masking of cannabis odors with exogenously applied industrial chemicals is permitted, for establishing the absence of hazards. Rather, how odors are mitigated should be scientifically understood and transparent, such that health

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risks of mixtures, including those from combined masking agents and BVOCs subject to photoactivation, are understood and minimized. Existing best practices include the application of carbon filtration, as well as the use of closed-loop cannabis extraction systems.[75]

It is important for policy makers worldwide to consider potential unintended consequences of policy decisions due to environmental trade-offs across cultivation methods. For example, stringent water-use regulations for outdoor cultivation may incentivize cultivators to turn to alternative indoor cultivation methods. While this shift may alleviate water stress, it may also increase the carbon footprint of cannabis by encouraging energy-intensive indoor cultivation. In addition, the social and economic impacts of shifting the location of cannabis production should be considered when developing policies. Identifying and understanding trade-offs within and across cannabis cultivation systems is thus important, and cannabis regulations should be systemic and comprehensive at regional scales to prevent the transfer of impacts among production pathways.

Frontiers of Future Research and Policy. The emerging literature on cannabis and the environment provides insights to guide policy. Still, most studies reviewed here were individual case studies, and mostly geographically limited to Northern California. Given global projected increases in cannabis consumption and cultivation,[82] similar research is needed across broader contexts to inform the generalizability of existing results, to avoid exporting environmental problems, and to prevent negative impacts in newly legalized jurisdictions. A recent systemic assessment of the environmental footprint of global tobacco supply chains[83] highlights the magnitude of the tobacco industry's impacts and identifies opportunities for concerted regulatory action. Filling research gaps about the environmental impacts of the global cannabis industry may lead to similar insights.

Most of the literature reviewed here relies on observational or model-based methodologies drawing on surveys, satellite imagery, or publicly available data sets. Such methodologies constitute important mechanisms for overcoming legal barriers to cannabis research. In addition, however, experimental research is needed to understand basic agroecological functions and processes governing cannabis cultivation, and to explore how expansion or consolidation of existing cultivation operations may impact ecosystem service provision at landscape scales. Limited research focused on best practices for cannabis cultivation[84] suggests that such experimentation is already starting, and may inform the development of agricultural extension guidelines for cannabis farmers. In addition, encouraging knowledge exchange between cannabis cultivators and researchers could help fill existing "formalized" knowledge gaps.[85] This should include integrating traditional- or industry-based knowledge, including information from "gray literature", into the formal scientific literature.

Cannabis cultivation and consumption may lead to additional environmental impacts. For instance, little is known about the impacts of solid waste generated by the cannabis industry or about the carbon footprint of the cannabis supply chain. Life-cycle assessments of the cannabis sector could provide valuable information about how to increase its efficiency and sustainability. Similarly, little is known about environmental impacts associated with the use of equipment and solvents during harvesting and extraction processes. Other important areas for future research could include cannabis consumption impacts (e.g., smoke pollution or contamination through cannabis-related litter); soil health impacts; odor, light, and noise pollution risks to humans and wildlife; and more sustainable cannabis farming (e.g., aeroponics or agroecological approaches). These topics, and many others, should make the study of cannabis-related environmental impacts a rich field for discovery for many years to come.

Analysis of the environmental effects of cannabis agriculture, and how these might be mitigated, will be further enhanced through research on relationships between policy changes and cannabis cultivation practices. Traditionally, cannabis has been cultivated remotely and at small scales. So far, legalization appears to alter this through cultivation expansion, shifts toward urban areas, and increased size of cultivation facilities.[86] The intensification of cultivation activities at large-scale facilities may magnify negative environmental impacts. Conversely, economies of scale may increase the efficiency of larger facilities. Larger facilities are also less likely to be in remote sensitive areas than historical smaller farms, but these may displace other forms of agriculture or lead to livelihood trade-offs in rural areas. Researchers should study these trade-offs and prioritize the identification of solutions that minimize them. Diligence by policy makers and consumers is needed to ensure that potential movement toward industrialization does not intensify environmental and social issues, and researchers must document shifts in the industry's supply chain and their environmental impacts.

In conjunction with medical or recreational legalization, social and ecological certification schemes could reduce adverse environmental impacts of the cannabis industry. Emerging programs such as Sun and Earth Certification,[87] or planned appellation designations,[88] constitute first steps in this direction. They could help offset the potential costs of implementing sustainable management practices for cannabis farmers through added value of certified products. By contributing to consumer awareness and providing incentives for growers to produce in sustainable ways, these programs may pave the way for developing a more environmentally protective cannabis sector.

Questions around cannabis cultivation and the environment echo larger debates about the environmental impacts of agricultural production in general. Current discourse on the optimal ways to address shifts in the cannabis sector touches upon fundamental sustainability framings like land sparing versus sharing, intensification versus expansion, technology-driven agriculture versus agroecology, and the role of smallholder farmers versus industrial-scale facilities. Robust agricultural research programs, often funded by national governments, play a crucial role in agricultural sustainability, and cannabis agriculture should be no different. Like for industrial hemp, research on the environmental impacts of cannabis could be financed through national funding programs, which could be implemented without altering the legal status of cannabis as a consumer product. In the United States, for example, this would lower barriers created by the disharmony between federal and state cannabis laws. Moreover, formulating national-level research strategies, as is currently done in Canada for the health impacts of cannabis,[89] will facilitate more systematic research covering current knowledge gaps about cannabis and associated environmental impacts.

Policy makers working with cannabis have strong interests in developing effective regulations following legalization and are also dealing with regulatory "blank slates". This may equip

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them with a novel combination of increased freedom and institutional capacity to test and evaluate the effectiveness of multiple policy approaches. Ultimately, successes and failures of environmental regulations for cannabis may lead to broader lessons learned for agriculture.

Key Messages

1. Increases in worldwide legalization trends for medical and recreational cannabis consumption are likely to fuel the growth of an already important global cannabis industry. To minimize negative environmental outcomes, a systemic understanding of cannabis' environmental impacts is essential.
2. Although the total land-use footprint of cannabis cultivation is small compared to other agricultural crops, outdoor cultivation sites tend to disproportionally be located in remote and ecologically sensitive areas; this can lead to habitat loss and increased wildlife exposure to chemical, noise, air or light pollution.
3. In semi-arid, drought-prone regions, cannabis' water-use footprint can contribute to groundwater and streamflow depletion. In urban areas, compounds from human cannabis consumption persist in treated wastewater and could contribute to downstream contamination of aquatic ecosystems.
4. Despite known deleterious effects of pesticides on ecosystems and human health for other crops, there are currently no standardized guidelines for pesticide application on legal cannabis crops, or for testing consumer products for pesticide residue.
5. Indoor cannabis cultivation has a high energy consumption footprint compared to other greenhouse crops and may contribute to energy use, ozone formation, and air pollution in urban areas.
6. As with other agricultural crops, best management practices can minimize environmental impacts. We suggest cannabis-specific policies to minimize impacts from cannabis.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.0c00844.

Table of search terms used for literature retrieval and table of studies included in the review (PDF)

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Notes

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