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

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Authors

Wartenberg, Ariani C
Holden, Patricia A
Bodwitch, Hekia
et al.

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Cannabis and the environment: An emerging science

Wartenberg, C. A.[1*], Holden, P. A.[2], Bodwitch, H.[1], Parker-Shames, P.[1], Novotny, T[3]., Harmon, T.[4], Hart, S.[5], Beutel, M.[4], Gilmore, M.[4], Hoh, E.[3], Butsic, V.[1]

[1] Department of Environmental Science, Policy and Management, University of California, Berkeley, CA, 94720, USA
[2] Bren School of Environmental Science & Management, University of California, Santa Barbara, CA, 93117, USA
[3] School of Public Health, San Diego State University, San Diego, CA, 92182, USA
[4] Environmental Systems Graduate Program, Sierra Nevada Research Institute, University of California, Merced, CA, 95343, USA
[5] Department of Life & Environmental Sciences and Sierra Nevada Research Institute, University of California, Merced, CA, 95343, USA

* corresponding author: ariani.wartenberg@gmail.com

Abstract

Concurrent with a worldwide trend of decriminalization, medical or recreational use of cannabis (*Cannabis sativa spp.*) is now legal in over 60 countries and US states. There is therefore an urgent need to understand how cannabis production and consumption may impact the environment. Research documenting the environmental impacts of cannabis remains limited. Nevertheless, an emerging body of literature provides insights which could inform the sustainable development of growing cannabis industries. Our review identifies six documented environmental impact pathways from cannabis: water use, energy use, land-cover change, pesticide use, as well as air and water pollution. Based on reviewed findings for these pathways, we suggest policy directions for water, energy and pesticide use as well as land planning. We further highlight the need for additional research on this topic and discuss how science might contribute to minimize environmental risks and improve the sustainability of the global cannabis industry.

Keywords

Cannabis cultivation, environmental impacts, legalization

Introduction

The last two decades have seen a worldwide liberalization of cannabis production and consumption (e.g. Bahji and Stephenson 2019). As of January 2020, recreational use of cannabis is legal in Uruguay, Canada and 12 US states, and medical use is partially or fully legal in 36 countries (Chouvy 2019). As legal markets for cannabis develop, policy makers are tasked to regulate its production, distribution and consumption in new ways.

With rising liberalization, researchers have taken a growing interest in the potential environmental impacts of cannabis – a dynamic partly fueled by growing public concerns and news coverage of the topic, which increased by over 500% from 1992 to 2019 (Fig. 1). If implemented successfully, legalization could give regulators a chance to anticipate and regulate the environmental outcomes of the cannabis industry as it expands (Bodwitch*, et al.* 2019). Some current regulatory schemes (California 2016, Canada 2018) already reflect this priority through the inclusion of specific language meant to reduce environmental impacts which can arise from land, water and energy use, application of chemicals, or other pathways (e.g., Carah*, et al.* 2015).

There are four primary classes of cannabis production (indoor, mixed-light, outdoor and trespass) which may impact the environment through different pathways and at different magnitudes (Fig. 2). These production systems are not always clearly distinct in practice: for instance, in a single farm, mother plants may be kept indoors while cloning occurs in mixed-light and full crops are produced outdoors. Aside from trespass systems (Fig. 2d), which we describe separately due to the specific practices associated with them, the cannabis production systems we describe can exist legally or illegally.

There are distinct trade-offs between production systems. Indoor systems are associated with few concerns about wildlife habitat destruction, water diversion or pollution, but require high external inputs such as energy and fertilizers. Conversely, outdoor farms may require fewer resource inputs, but poor management or siting could disrupt surrounding ecosystems. Well-managed systems (both indoor and outdoor) can minimize environmental impacts. We note that trespass grows are generally only associated with negative environmental impacts.

Researchers investigating interactions between cannabis and the environment have faced historic hurdles – often due to cannabis' legal status – which include societal stigma, funding restrictions, safety concerns and difficult access related to remote cultivation sites, as well as regulatory obstacles such as complex licensing requirements and restrictions on cultivar testing (Short-Gianotti et al. 2017). Despite such limitations, a new science around cannabis and the environment is starting to emerge.

Our objective here is to review existing literature documenting environmental impacts of cannabis, to identify significant research findings and knowledge gaps and to suggest policy recommendations. As shown in Fig. 3, before 2012 only a handful of studies suggested links between cannabis and environmental degradation (e.g., Carah*, et al.* 2015, Chouvy and Afsahi 2014, Miller 2018). Recent empirical studies, however, have started to quantify specific environmental impacts of cannabis cultivation and consumption. While limited in size and scope, this first generation of studies provides an opportunity to identify and summarize both what is known about cannabis and the environment, and what knowledge gaps persist. This review highlights the emerging science around cannabis and the environment. We hope it can serve as a catalyst to encourage more research in this area and as a resource to provide science-based guidance for policy-makers.

Identification and Selection of Studies

We evaluated peer-reviewed and non-peer-reviewed sources that quantified the effects of cannabis cultivation or consumption on the environment. We excluded studies and reports that: (i) addressed other impacts of cannabis such as on human health; (ii) focused on other plants or other illicit drugs; or (iii) commented on environmental impacts without providing data.

Based on published commentaries on cannabis and the environment (Carah*, et al.* 2015, Miller 2018, Gianotti*, et al.* 2017), we identified a list of terms to search the Web of Science for relevant studies in June-July 2019 (Table 1). We screened titles and abstracts of resulting studies according to the three eligibility criteria noted above, yielding a total of 14 peer-reviewed articles for which we reviewed the full text. We incorporated nine additional studies referenced in these studies in our final review (Table 2). We also searched for non-peer-reviewed literature on Google in July-August 2019 (using the same search criteria) and included documents found in the first five pages of results. Our final review includes two non-peer-reviewed reports and a book series (Table 2).

Results

Water Use

We found six peer-reviewed studies that investigated the water footprint of cannabis cultivation (water extraction, storage and use), all of which focus on northern California. Bauer, *et al.* (2015) used satellite imagery to estimate the number of cannabis plants in northern California and used this to predict that watershed-scale water consumption may exceed local streamflow during the growing season. These results were based on assumptions that: (i) on average, a cannabis plant consumes 22.7 liters (6 gallons) 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. Butsic and Brenner (2016) applied a similar methodology to estimate annual water use for cannabis irrigation at 11,000 m^3 – equivalent to 0.001% of annual agricultural water use (Schultz 2017) – in Humboldt County, California.

These findings highlight the potential impacts of cannabis on water resources, but their accuracy is limited by a lack of actual water use data. Three additional studies in California examined cultivator-reported water use for cannabis 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. Wilson, *et al.* (2019; independent respondents n = 58) and Dillis, *et al.* (2019; n = 600) both confirmed that water use rates among California cannabis farmers approximated the 6 gallon per-plant figure reported by Bauer, *et al.* (2015). However, this was only the case during peak growing season and respondents reported lower water use rates throughout the rest of the year. Wilson, *et al.* (2019) also documented monthly water use on average-sized farms in California and found that while water *application* to cannabis plants exceeded this rate during cannabis' growing season, water *extraction* from rainwater, surface and sub-surface sources remained far below it for most of the year. In separate assessments of farm-scale water extraction practices, Wilson*, et al.* (2019) and Dillis*, et al.* (2019; n = 901) (n = 901) showed that sub-surface wells, rather than surface-water diversions, may be the primary source of water for many northern Californian growers. Sub-surface water extraction may threaten connected watersheds if annual extraction exceeds recharge rates, as sub-surface water reserves tend to recover more slowly from overuse than surface sources.

Energy Use

We found one peer-reviewed study and one gray literature report focused on cannabis and energy use. Mills (2012) estimated that indoor US cannabis production uses 20 TWh of electricity annually, leading to the annual emission of 15,000,000 tons of CO_2. This value is equivalent to the energy consumption of the entire US agricultural sector (Schnepf 2004), or to 1% of US total national electricity use. Mills' calculations were based on national cannabis cultivation estimates and assumed "typical" energy use for indoor production and relevant transportation processes. A more recent report (NewFrontierData 2018) combined estimated US cannabis demand and cultivation area with self-reported data from cultivators (n = 81) to provide a detailed assessment of current cannabis energy use. Combined illicit and legal cultivation were estimated to consume 4.1 MWh annually, equivalent to 472,000 tons of associated CO_2 emissions. These estimates did not account for off-grid energy use, transportation, fertilization or irrigation, but were significantly lower than the numbers reported by Mills (2012). We note that Mills' findings may not accurately represented energy use by the US cannabis sector today, as cultivation practices have likely become more efficient in recent years.

Land Cover Change

Studies quantifying land-use impacts of cannabis remain scarce despite reports of significant cannabis cultivation activity in North and Sub-Saharan Africa, the Americas and Asia (e.g., Bradford and Mansfield 2019, Laudati 2019, Moore*, et al.* 1998). We found five empirical studies from the US which assessed cannabis and land-use dynamics. Satellite data for California showed a high concentration of cultivation sites in remote, ecologically sensitive areas (Butsic*, et al.* 2018). In Humboldt County, cannabis' impact on land cover change from 2000 to 2013 was relatively limited, contributing 1.1% of forest canopy area loss compared to 53.3% from timber harvest (Butsic*, et al.* 2018). However, remote cultivation sites were linked to landscape perforation as they created gaps in forest patches, reducing forest core areas and increasing open edges. This could contribute to landscape-wide forest fragmentation and resulting wildlife habitat degradation if current expansion rates persist (Wang*, et al.* 2017). The spatial distribution of cannabis farms, in addition to total land-use footprint, may thus be significant determinant of potential environmental impacts.

These reported spatial dynamics suggest that the factors driving the location of both legal and illegal cannabis cultivation are distinct from those of other crops. Cannabis prices and law enforcement related risks emerged as important factors determining siting decisions in California, Oregon and Washington's illicit markets (Koch*, et al.* 2016). Butsic*, et al.* (2017) documented strong network effects amongst growers in Humboldt County, which led to clustering of cultivation sites and appeared to be more important than biophysical factors such as soil quality or terrain. Klassen and Anthony (2019) identified state enforcement capacities and poverty and unemployment rates as potential factors leading to a decline in illegal farms discovered in Oregon, but not Washington, following legalization in both states.

Pesticide impacts

Although pesticides used in cannabis production are likely to impact the environment, to our knowledge no quantitative studies have documented these impacts on private land or legal cannabis production systems. We found five peer-reviewed studies which focused on impacts of anticoagulant rodenticides (ARs) on local wildlife species in trespass grows. ARs are presumably used to control rodent populations; they are frequently encountered on trespass production sites (Fig. 2d) in California and can bioaccumulate in the food chain (Thompson*, et al.* 2014). In northern and central California, field-studies documented contamination by highly toxic ARs in an endangered predator, the Pacific fisher (*Pekania pennanti*), using a combination of field-data collection, lab data analysis and spatial correlation (Thompson*, et al.* 2014, Gabriel*, et al.* 2012). Despite high AR exposure levels (79% of sampled 58 animals and 85% of 46 sampled animals, respectively), both studies reported very low numbers of animals dying primarily from AR exposure. Nevertheless, AR poisoning may significant impact mortality rates in Californian fisher populations (Gabriel*, et al.* 2015; number of sampled fishers n = 167), with increasing prevalence from 2007 to 2014. AR contamination is not limited to mammals. It 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 (Franklin*, et al.* 2018, Gabriel*, et al.* 2018). Despite some limitations due to small sample sizes (e.g. Franklin et al.'s study with n = 1), these studies draw attention to a potential ecological threat posed by illicit cultivation methods.

Far less is known about application of chemicals in legal growing operations, which vary greatly by region and country. While some ARs are illegal or heavily restricted in the United States, various other pest-control methods have been reported for cannabis (Wilson*, et al.* 2019). In the US, due to the crop's federally illegal status, no commercially available pesticides have been approved for use on cannabis (although states with legalized cannabis provide lists of allowed pesticides). In Canada, 25 pesticide and fungicide compounds have been approved for legal use on cannabis (HealthCanada 2019).

Air Pollution

We found two peer-reviewed studies assessing cannabis cultivation impacts on air quality. Wang*, et al.* (2019) measured biogenic volatile organic compounds (BVOC) emitted by cannabis plants grown under conditions mimicking greenhouse cultivation. Results suggested BVOC emissions from indoor cultivated cannabis in Colorado could contribute to ozone formation and particulate matter pollution. The authors acknowledged limitations due to small sample sizes, sub-optimal growing conditions, and a focus on only 4 out of 620 reported cannabis strains. In a follow-up study, Wang*, et al.* (2019) estimated terpene emissions and regional ozone impacts from indoor cannabis cultivation facilities in Colorado using the Comprehensive Air Quality Model. Results predicted increases in hourly ozone concentrations which may have consequences for regional air quality. This approach was limited by reliance on estimates and assumptions in the absence of data regarding emission capacity of most cannabis strains, number of plants and plant biomass. Nevertheless, preliminary findings indicated that concentrated indoor cannabis cultivation could influence ozone pollution through BVOC emissions from terpenes, particularly in areas where nitrogen oxides are not the limiting factors in ozone formation (Wang*, et al.* 2019).

Water Pollution

Surface- and ground-water pollution from the cannabis industry, including from soil erosion, pesticide and fertilizer in run-off, chemical processing or waste disposal operations, is a likely risk (e.g. Carah*, et al.* 2015). Nevertheless, we found no peer-reviewed study quantifying the impacts of cannabis *cultivation* on water quality, although current pilot projects in California are underway. We did find an academic book series and five peer-reviewed publications documenting the effects of pollution from cannabis *consumption* on water quality. These studies used THC-COOH concentrations in sewage systems, presumably originating from human consumption, as a proxy. Evidence of THC-COOH presence was found in both raw and biologically treated wastewater across major European cities (Castiglioni and Zuccato 2010, Terzic*, et al.* 2010, Thomas*, et al.* 2012) as well as in raw wastewater in the US (Burgard*, et al.* 2019). Concentrations of chemical compounds derived from cannabis were lower in treated 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 (Zuccato*, et al.* 2008). While these studies primarily aim to document urban cannabis consumption, they also point towards potential contamination issues impacting downstream freshwater ecosystems.

Our current understanding of the consequences of wildlife exposure to cannabis-related chemicals remains limited. Parolini*, et al.* (2017) sought to bridge this gap through experimental exposure of zebra mussels to concentrations of cannabis active compounds Δ-9-THC and THC-COOH. Results showed that prolonged exposure could contribute to oxidative and genetic damage in the mussels. Still, given the lack of knowledge regarding actual Δ-9-THC and THC-COOH concentrations in aquatic ecosystems, and the lack of documentation of the compounds' effects on mussels or other organisms in the wild, it is difficult to draw broader conclusions about potential environmental risks posed by exposure to active compounds in cannabis for aquatic organisms.

Policy Recommendations

Results from existing studies already point towards specific policy suggestions regarding cannabis:

1. *Managing the timing and location of water extraction may minimize cannabis' water-use impacts.* Though cannabis' water-use footprint may be small relative to other agricultural crops (Butsic and Brenner 2016, Schultz 2017), managing the timing and amount of water extracted for cannabis cultivation may reduce future water-use impacts, particularly in drought-prone habitats. Incentivizing efficient water management (e.g. through modern irrigation practices, surface-water diversion and impoundments or sustainable groundwater extraction) could further alleviate pressure on stream ecosystems and groundwater reserves.

2. *Incentivizing best-practices could reduce the energy footprint of indoor cannabis cultivation.* Lower energy use at indoor or mixed-light production facilities could be encouraged through mechanisms like tax incentives or low interest loans. For example, regulations in Massachusetts (2019) require indoor cultivators to develop energy plans, comply with existing best-practice standards, and monitor and report energy usage. This type of policy may be useful in building baseline datasets needed to inform decisions while allowing regulators to set realistic energy efficiency goals. Similar laws could be applied broadly to ensure indoor and mixed-light cultivators are maximizing energy efficiency.

3. *Cannabis' land-use footprint is still small and comprehensive land-use planning may minimize future environmental impacts.* As the total production area of cannabis is small relative to other land-use activities (Wang*, et al.* 2017), land use planning strategies could encourage the protection of natural areas without necessarily affecting production

outcomes. For instance, policies could encourage land-efficient cannabis production, limit cannabis farming to existing agricultural land and prevent expansion into environmentally sensitive areas.

4. *Eradication and clean-up actions may mitigate chemical use in trespass cultivation sites.* In the US, the persistent finding of ARs at trespass cultivation sites suggests that they are a significant source of environmental contamination. Strengthening institutional capacity and resources to support enforcement activities, near-term remediation and long-term monitoring at these sites can minimize environmental contamination from left-over and already dispersed AR products. In addition, given evidence that ARs deployed outside of the cannabis sector also negatively impact predator species (Herring*, et al.* 2017), restrictions on the production and sale of these chemicals should be explored.

5. *Rigorous chemical residue testing may discourage use of harmful chemicals.* Developing rigorous testing guidelines 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 cannabis. California, for instance, currently tests for residue from 66 pesticides in all legal cannabis products (Seltenrich 2019). Such initiatives may limit pesticide contamination by incentivizing legal producers to avoid the use of non-permitted chemicals.

Because there are environmental trade-offs across production methods, it is important for policy makers to consider the potential unintended consequences of policy decisions. For example, in California, stringent water-use regulations for outdoor production may incentivize cultivators to turn to alternative indoor production methods. While this shift may alleviate water-stress in sensitive ecosystems, it may also increase the carbon footprint of cannabis by encouraging energy-intensive indoor production. Identifying and understanding trade-offs within and across systems is thus important, and cannabis regulation should be comprehensive in order to prevent impacts from being displaced from one pathway to another.

Frontiers of future research and policy

The emerging literature on cannabis and the environment already provides useful insights to guide policy. Still, the majority of studies reviewed here were individual case studies, mostly geographically centered in Northern California. There is a tremendous need for similar studies to be carried out across different biophysical, socioeconomic, historical and cultural contexts, both to confirm the generalizability of these results and to avoid exporting environmental problems from the developed to the developing world. We expect that continued liberalization worldwide will provide expanded geographic scope for this work for years to come, and researchers should be ready to act on this expansion.

Most of the literature reviewed here relies on observational or model-based methodologies (Table 2). While these approaches provide insights, experimentation is fundamentally needed to understand basic agroecological functions and processes governing cannabis cultivation. Trials quantifying the energy footprints, water use, and nutrient requirements of different cultivation and management methods are also needed to improve the efficiency of production systems. Given increased liberalization trends, we expect to see a normalization of cannabis-related research. Scientists should be encouraged to carry out a range of experiments (Crowder 2019) to bolster scientific capacity to assess the environmental impacts of an expanding cannabis sector. Additionally, as regulations around cannabis cultivation are implemented, long-term studies are needed to understand how these regulations affect cannabis cultivation practices.

Cannabis cultivation may lead to additional environmental impacts, which remain scientifically undocumented to our knowledge. For instance, solid waste management of materials originating from cultivation, packaging, or other production processes, will need to be addressed. Life-cycle assessments of the cannabis sector could provide information on how to minimize such waste and more generally increase the efficiency and sustainability of cannabis production processes. Other potential areas for future research include odor pollution risks in communities where increased cannabis production has led to farms being sited near residential areas, cross-pollination issues between cannabis and hemp (DeDecker 2019), alternative cannabis farming (e.g., aeroponics or agroecological approaches) or transportation efficiency. These topics, and many others, should make the study of cannabis' environmental impacts a rich field for discovery for many years to come.

Traditionally, cannabis has been cultivated remotely and at small scales. Legalization is altering this through cultivation expansion, shifts toward urban areas, and increased size of production facilities (California 2019), which may in turn affect the environmental impacts of the industry. The intensification of cultivation activities at large-scale facilities may magnify negative impacts. Conversely, economies of scale may increase the efficiency of larger facilities which may have broader capacities to invest in sustainable production processes. Larger facilities are also less likely to be located in remote sensitive areas than historical smaller farms, but may lead to land-use trade-offs with other forms of agriculture. Continued diligence by policy makers and consumers is needed to ensure that the move towards industrialization is not a move away from sustainability - and researchers must continue to document shifts in the industry and their environmental impacts.

In conjunction with legalization, social and ecological certification schemes could increase environmental performance of the industry. Emerging programs such as Sun and Earth Certification (Sun+EarthCertified 2019) or planned appellation designations in California (Stoa 2017) constitute first steps in this direction. By contributing to consumer awareness and providing incentives for growers to produce in sustainable ways, these programs may pave the way for the development of a more sustainable cannabis sector.

In many ways, the question of how to best produce and consume cannabis while protecting the environment echoes 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 such as land sparing vs. land sharing, intensification vs. expansion, technology-driven agriculture vs. agroecology, the role of smallholder farmers vs. industrial-scale facilities. 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 them with a novel combination of increased freedom and institutional capacity to test and evaluate the effectiveness of multiple policy approaches. Ultimately, failures and successes of environmental regulations for cannabis may lead to important lessons-learned for agriculture more broadly.

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Cannabis OR Marijuana AND	Environm* Deforestat* Pollut* Pesticide Rodenticide Ecology Biodivers* Wildlife Water use Air quality Energy use Waste

Table 1. Search terms used for literature retrieval on the Web of Science database (for peer-reviewed publications) and Google (for non-peer-reviewed sources).

Authors	**Year**	**Geographic Focus**	**Cannabis Production**	**Environmental Impact Pathway**	**Methodologies**				**Peer-Reviewed**
					Obs.	**Exp.**	**Surveys**	**Model**	
Bauer et al.	2015	California	b, c, d	Water use	Y			Y	Y
Butsic & Brenner	2016	California	b, c, d	Water use	Y			Y	Y
Dillis et al.	2019a	California	a, b, c	Water use			Y		Y
Dillis et al.	2019b	California	a, b, c	Water use			Y		Y
Grantham et al.	2019	California	NA	Water use				Y	Y
Wilson et al.	2019	California	a, b, c	Water use			Y		Y
Mills et al.	2012	US	a	Energy use				Y	Y
New Frontier Data	2018	US	a	Energy use			Y		N
Butsic et al.	2017	California	b, c, d	Land cover change	Y			Y	Y
Butsic et al.	2018	California	b, c, d	Land cover change	Y			Y	Y
Klassen & Anthony	2019	Western US	d	Land cover change				Y	Y
Koch et al.	2016	Western US	d	Land cover change				Y	Y
Wang et al.	2017	California	b, c, d	Land cover change	Y			Y	Y
Franklin et al.	2018	California	d	Pesticide	Y	Y			Y
Gabriel et al.	2012	California	d	Pesticide	Y	Y			Y
Gabriel et al.	2015	California	d	Pesticide	Y	Y			Y
Gabriel et al.	2018	California	d	Pesticide	Y	Y			Y
Thompson et al.	2013	California	d	Pesticide	Y	Y			N

Wang et al.	2019a	CO	a	Air pollution		Y			Y
Wang et al.	2019b	CO	a	Air pollution		Y			Y
Castiglioni et al. (ed)	2010	EU, UK, US	NA	Water pollution		Y			N
Parolini et al.	2017	Italy	NA	Water pollution		Y			Y
Terzic et al.	2010	Croatia	NA	Water pollution		Y			Y
Thomas et al.	2012	EU	NA	Water pollution		Y			Y
Burgard et al.	2019	US	NA	Water pollution		Y			Y
Zuccato et al.	2008	Italy, UK	NA	Water pollution		Y			Y

Table 2. List of 26 references included in our literature review. Columns provide details regarding: year of publication; geographic focus; environmental impact pathway; relevant cannabis production systems studied (indoor (a), mixed-light (b), outdoor (c) or trespass (d)); whether results were generated through observation (Obs.), experiments (Exp.), self-reported surveys (Surveys), or model-based estimates (Model); and peer-review status. Y/N refers to yes/no.