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BLOSSOMING TREASURES OF BIODIVERSITY



## 57. Marijuana – unsustainable, unecological and unnecessary cultivation in energy-hog greenhouses

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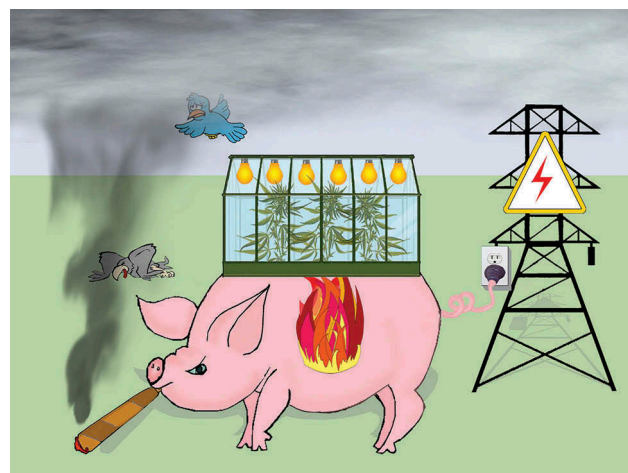
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### Introduction

Unsustainable agriculture, particularly with respect to crops, is the chief threat to planetary resources, including the atmosphere, water, soil, landscapes and biodiversity (DeWitt 2009). For several decades, the cannabis plant (*Cannabis sativa*) has been unrealistically extolled as the potential saviour of habitats, ecosystems and the environment, because of its claimed ecological benefits (Herer 1998). As noted below, this is highly misleading: as fibre and oilseed crops, the plant indeed has admirable environmentally-friendly properties, but as a source of medicinal and recreational drugs, its cultivation is significantly consumptive and polluting. Currently, huge expenditures of energy are associated with growing marijuana plants in high-technology greenhouses (Figure 1) rather than as nature intended: outdoors. While the issue of greenhouse production of marijuana has recently become prominent because of enormous expansion of the legitimate marijuana industries, the ecological justification of greenhouse cultivation in general is very important for the welfare of the planet and its living inhabitants. As discussed in this review, greenhouses can be environmentally benign or unacceptably harmful.

Marijuana represents the most rapidly expanding industry in the Western world (Borchardt 2017), with the potential to generate trillions of dollars of business annually in the near future. Immense fortunes are now being invested in the cultivation of marijuana plants, and much of this is based on growing them in energy-consuming greenhouses which can contribute significantly to atmospheric deterioration and indirectly to endangerment of biodiversity. This contribution examines the ways that cultivation of marijuana plants may be ecologically damaging, with particular emphasis on the role of greenhouses. As detailed elsewhere (Montford and Small 1999a, 1999b; Small and Catling 2009; Small 2015), when grown for fibre or for oilseed,

*C. sativa* is one of the world's most ecologically beneficial crops, and it is perfectly feasible to grow the plant for production of marijuana in an equally sustainable fashion.



**Figure 1.** An energy-hog marijuana greenhouse. Prepared by Brenda Brookes.

### The plants

If ever there was a species that needed no introduction, it is *C. sativa*. Probably no other plant in the world is more recognised, and indeed few people are unable to identify a marijuana leaf.

### A primer on nomenclature of *Cannabis sativa*

Only one species of *Cannabis*, *C. sativa*, is commonly recognised, although sometimes it is split into several alleged species (Small 2015, 2017). *Cannabis sativa* has been employed for thousands of years, primarily as a source of a stem fibre (both the plant and the fibre termed 'hemp'), an edible oilseed (termed 'hempseed') and a resinous intoxicant (the plant and its drug preparations

commonly termed ‘marijuana’) used for euphoric inebriants and therapeutic drugs. Non-italicised, ‘cannabis’ is a generic abstraction, widely used as a noun and adjective, and commonly (often loosely) used both for cannabis plants and any or all of the products made from them.

### *A primer on chemistry of Cannabis sativa*

*Cannabis sativa* contains an unusual class of terpenophenolic secondary metabolites, defined as ‘cannabinoids’. Delta-9-tetrahydrocannabinol ( $\Delta^9$ -THC, or simply THC) is the principal cannabinoid of intoxicating forms of *C. sativa*, while cannabidiol (CBD) is the principal cannabinoid of almost all non-intoxicant biotypes. Plants that have been selected for fibre and oilseed characteristics almost always produce limited amounts of THC, but high amounts of CBD. In contrast, plants that have been selected for intoxication are high in THC, and for practical purposes this (and cannabinol, a degeneration product of THC) are the only cannabinoids of significant euphoriant potential. In the living plant the cannabinoids exist predominantly in the form of carboxylic acids (i.e. a  $-\text{COOH}$  radicle is attached to the molecule). These decarboxylate into their neutral counterparts (the molecules lose the acidic  $-\text{COOH}$  moiety, leaving an H atom) under the influence of light, time (such as prolonged storage), alkaline conditions, or when heated. Carboxylated THC (known as THC acid) is only marginally intoxicating (so eating fresh material will not produce a ‘high’). With mild heat (as applied when smoking, vaporising or cooking marijuana),  $\text{THC-COOH}$  decarboxylates to form  $\text{CO}_2$  and THC, which is quite euphoric. For simplicity, the discussion in this paper will refer to THC and CBD, regardless of whether carboxylated or not.

### *The increasing social acceptance and expansion of legal production of marijuana*

For most of the twentieth century, the cultivation of *C. sativa* and possession of any of its products were illegal in most of the world. Since the 1990s, growing non-intoxicant varieties (for production of fibre and oilseed) has been allowed in most countries. The medical use of marijuana has also been authorised in many jurisdictions, and therapeutic applications are rapidly expanding in Western countries. The literature on medical aspects has become extremely voluminous, and by no means is there agreement on the value of cannabis for treating particular conditions. Indeed, there is quite ferocious debate about the wisdom of employing medical marijuana for almost any medical issue. Most of the world continues to prohibit the recreational use of marijuana, but legalisation has occurred in several countries, particularly in the Americas. In democratic countries, there has been a general softening of penalties, or at least of prosecution, coinciding with increasing public tolerance of illicit usage. However, there remains considerable opposition and concern about potential deleterious effects, particularly on the developing brains of children. Nevertheless, legal marijuana is rapidly becoming available in several countries, and this trend seems unstoppable. This review is not intended to evaluate the wisdom of the current huge expansion of legalised marijuana availability and usage; the objective is to evaluate potentially damaging ecological effects associated with greenhouse culture, and how they can be controlled.

### *What is marijuana?*

Marijuana drugs are preparations with the inebriating chemical THC, which is synthesised in tiny



**Figure 2.** Marijuana plants and the principal harvested product, ‘buds’ (female inflorescences, i.e. compact clusters of flowers). (a) Vegetative plant. Photo by Plantlady223 (CC BY SA 4.0). (b) Flowering top of a female plant (the white stigmas of the flowers are evident). Photo by Ankari80 (CC BY 3.0). (c) Dried buds. Photo by Coaster 420 (public domain).

secretory glands located on the epidermis of the leaves and flowering parts. The plant develops foliage for several weeks or months (Figure 2(a)) before producing flowers. Half of the plants produce female flowers only (Figure 2(b)). Males have much less THC than females, and are afforded little respect in the marijuana world. Today, the flowering portion of female plants, which contain much more THC than the foliage, is the principal part of the plant that is harvested. Technically, the flowering parts are termed ‘inflorescences’, but they have come to be known as ‘buds’ (Figure 2(c)). These are simply very compact portions of the branching system bearing flowers. A somewhat purified resinous formulation called ‘hashish’ was once popular, but is now obsolescent. Concentrated preparations of the secretory glands, sometimes called ‘resin powder’, are sometimes made. In addition to these ‘herbal’ forms of drug, solvent extracts high in THC are also available. All of these types of marijuana can be used as social drugs (i.e. simply to become inebriated) or medicinally. However, authorised medical materials, frequently based on extracted cannabinoids, are rarely intended to be employed simply to get high (recommended medical dosages are too low), and must meet stringent quality standards.

### Greenhouses: common misunderstandings

Greenhouses are best defined simply as buildings with a translucent cover (usually glass or plastic) allowing sunlight to enter for plant growth. However, sometimes a clear distinction is not made between greenhouses and ‘protected structures’, which could include lathe houses (with slat-covered roofs) to provide partial shade. In this review, the phrase ‘commercial greenhouse’ is interpreted in the sense of Hanan (1998): ‘greenhouse means a structure covering ground for growing a crop that will return a profit to the owner risking time and capital’. It has been reported that, on a world basis, commercial greenhouses occupy about 500,000 ha or 1,200,000 acres (Dorais and Cull 2017).

‘Indoors’ means inside a building, ‘outdoors’ means outside of buildings. Greenhouses include what are indisputably buildings, but much of the literature dealing with cultivation of marijuana ignorantly employs the word ‘indoor’ to refer only to buildings that exclude entry of natural light (except perhaps for some windows), so when

‘indoor cultivation’ is mentioned, what is actually meant is cultivation in buildings that do not supply natural light for growth, and this excludes greenhouses. As noted later, the phrase ‘plant factories’ is typically employed in literature referring to marijuana cultivation to designate sunless buildings with artificial lighting, although the acronym PFAL (for Plant Factory Artificial Lighting) more precisely designates growth of plants in buildings using electricity to supply lighting, and also controlling other environmental factors including temperature, humidity, and composition of nutrient solutions (for articles by various authors on this topic, see <https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/plant-factory>). Where the term ‘indoor’ is used in this paper, it usually includes both greenhouses and buildings supplying only artificial light, but where cited authors employ the word to mean only sunless cultivation in artificial light, this is made clear.

The phrase ‘greenhouse effect’ is rather misleadingly related to greenhouses. Greenhouses are heat traps, and this aspect is common to both greenhouses and the greenhouse effect. Energy waves from the sun enter through the glass of a greenhouse, and some of this is absorbed as heat within the greenhouse, and some is reflected back up to the glass which reflects it back (this is called ‘re-radiation’ and is the essential aspect of the so-called ‘greenhouse effect’). However, the most important way that greenhouses naturally become hot in the sun is that the glass stops wind from moving interior heat away to the exterior. This greatly reduces heat, absorbed from the sun inside the greenhouse, from being lost to the outside. Most people (indeed most authors) are under the mistaken impression that the chief cause of heat retention in a greenhouse is the greenhouse effect (a phrase which is misleading since the greenhouse effect is of relatively minor significance in greenhouses). However, the greenhouse effect is the chief factor that produces warming of Earth (for more detailed explanations, see Textbox 1).

### Low-tech greenhouses

The simplest greenhouses do not employ conventional energy sources such as fuels or electricity for climate control, but nevertheless reduce stresses of the local climate. The most common greenhouses in



**Textbox 1. What is the Greenhouse Effect? Different concepts apply to greenhouses and the Earth**

When one covers a crop with a structure, very significant changes are made to the internal environment... The single greatest effect, however, is reduction of wind velocity in comparison to that normally found in the field. This is the true 'greenhouse effect'... Although the cover will also markedly influence energy exchange, especially outgoing radiation, this is, in respect to the influence of wind movement, minor – although the popular use of the term 'greenhouse effect' refers to energy transfer through the earth's atmosphere, the atmosphere, in this case, being a transparent cover. The effect of a cover, because of reduced convective energy transfer by wind, is a marked increase in internal temperatures under clear skies.

—Hanan (1998)

The Sun powers Earth's climate, radiating energy at very short wavelengths, predominately in the visible or near-visible (e.g., ultraviolet) part of the spectrum. Roughly one-third of the solar energy that reaches the top of Earth's atmosphere is reflected directly back to space. The remaining two-thirds is absorbed by the surface and, to a lesser extent, by the atmosphere. To balance the absorbed incoming energy, the Earth must, on average, radiate the same amount of energy back to space. Because the Earth is much colder than the Sun, it radiates at much longer wavelengths, primarily in the infrared part of the spectrum. Much of this thermal radiation emitted by the land and ocean is absorbed by the atmosphere, including clouds, and reradiated back to Earth. This is called the greenhouse effect. The glass walls in a greenhouse reduce airflow and increase the temperature of the air inside. Analogously, but through a different physical process, the Earth's greenhouse effect warms the surface of the planet. Without the natural greenhouse effect, the average temperature at Earth's surface would be below the freezing point of water. Thus, Earth's natural greenhouse effect makes life as we know it possible. However, human activities, primarily the burning of fossil fuels and clearing of forests, have greatly intensified the natural greenhouse effect, causing global warming... In the industrial era, human activities have added greenhouse gases to the atmosphere, primarily through the burning of fossil fuels and clearing of forests. Adding more of a greenhouse gas, such as CO<sub>2</sub>, to the atmosphere intensifies the greenhouse effect, thus warming Earth's climate.

—Intergovernmental Panel on Climate Change (2007)

agriculture are simple, more or less temporary tent-like or Quonset-like structures often referred to as 'tunnels'. 'Low tunnels' are typically semi-circular and less than 1.2 m high (Figure 3(a)), and to access the plants inside requires temporarily moving part of



**Figure 3.** Examples of low-tech greenhouses that require virtually no energy expenditures. (a) Low-tunnel greenhouses. Photo (public domain) from Pixabay. (b) A huge but simple greenhouse growing strawberries. Photo by Jonas Janner Hamann, Universidade Federal de Santa Maria, credit: Bugwood.org (CC BY 3.0).

the cover. 'High tunnels' (also called hoop houses) are tall enough to allow farmers to walk inside. Much larger structures are often constructed by simply covering a frame (made of timber or pipe) with a plastic like polyethylene, as shown in Figure 3(b). Such 'low-tech' greenhouses are cheap to build and unheated (occasionally electric lights are installed), but are often more or less temporary, and serve mainly to extend the growing season in early spring and/or late fall by providing warmth. However, they also protect crops from rain, wind, excessive sunlight, and sometimes also pests. The use of unheated greenhouses only in the warmer seasons avoids operations in the cold winter when heating costs are very high and hours of sunlight are limited. Very large areas of low-technology greenhouses, with no or limited heating, are in Italy and Spain (in Spain they consist mostly of shade cloth-covered, not glass-covered production). 'In more southern and arid regions such as Mexico, the southern U.S. states, the Mediterranean and China ... plastic-tunnel horticulture is a booming business' (Korthals Altes and Van Rij 2013).

## High-tech greenhouses



**Figure 4.** Tulips in a high-tech commercial greenhouse. Photo by Found\_a\_attic (CC BY 2.0).

This review is mainly concerned with sophisticated, expensive, permanent greenhouses that currently require considerable heating as they are located in north-temperate areas and are operated year-round. Large areas of high-technology greenhouses are in Europe (especially the Netherlands) and in North America. Horticultural crops commonly grown in such greenhouses include culinary herbs, leafy edible greens, ornamentals (cut flowers and potted plants; [Figure 4](#)), peppers (*Capsicum* species), strawberries, and tomatoes. ‘Nursery stock’ (seedlings and young plants) for outdoor ornamental planting and tree seedlings for forestation are also commonly established in greenhouses, especially in late winter and early spring. Some pharmaceuticals (especially vaccines) produced in genetically modified plants are now being produced indoors because this halves the time of conventional production. Cannabis has recently been added to this list of greenhouse plants, and indeed many advanced commercial greenhouses growing other crops are being converted to produce marijuana (Mesly [2018](#)).

## Energy requirements of high-tech greenhouses

Advanced greenhouses provide for considerable control of environmental variables, such as temperature, humidity, air movement, and light intensity and duration. Sophisticated greenhouses also may furnish water, nutrients and pest control by the use of computerised monitors activating specialised mechanical controllers. The environmental footprint of greenhouses is particularly associated with advanced greenhouses. Because they are primarily in cool and cold climates, heating and lighting are the principal contributors to usage of fossil fuels and generation of greenhouse gases (Vadiee and Martin [2014](#); [Textbox 2](#)).

### Textbox 2. How heating requirements determine the environmental impact of greenhouses

The type of production system used and the producing location determine the environmental footprint of... greenhouse production. Three types of... greenhouse production systems can be considered: a high technology heated/cooled (HT) greenhouses in soil or in growing media (e.g., demarcated beds, containers), and a medium (MT) and low (LT) technology greenhouses in soil... High technology heated and cooled greenhouses of intensive year round production are mainly found in Northern countries, while MT and LT greenhouses are mostly found in southern countries such as the Mediterranean basin, and Asia. However, MT and LT are also found in Central and Northern Europe and North America to extend the growing season. HT greenhouses are defined as high intensive production systems within permanent structures made with galvanized steel and aluminum, concrete floor, thermal screen, CO<sub>2</sub> enrichment and, in some cases, artificial lighting and semi-closed/closed greenhouses. High sophisticated climate and irrigation control systems are used for HT greenhouses, achieving high annual yield... MT (permanent) and LT (semi-permanent) organic plastic greenhouses/high tunnels are less intensive production systems... Low capacity of heating may be used to keep a minimum temperature (e.g. 5–10°C) and control humidity, providing a certain amount of CO<sub>2</sub>... LT greenhouses use, in general, unheated plastic high tunnels made of a galvanized iron frame, without using CO<sub>2</sub> enrichment. Supplemental lighting is not used in both MT and LT systems.... HT greenhouses... environmental footprint is much higher (4 to 64 times higher) than LT greenhouses... This higher environmental impact is mainly related to the gas requirement to heat the greenhouse, which is generally responsible for more than 85% of the total CO<sub>2</sub> emissions. From a life cycle assessment analysis, it has been reported that the climate control system (81–96%), greenhouse structure (2.3–13.5%), and fertilizers (0.6–3.6%) are the main environmental burdens of conventional greenhouse tomato grown in the Netherlands. Similarly, for tomato grown in Quebec (Canada), climate control was the major contributor in all impact environmental categories, accounting for 74–99% of the total burden due to the high energy demand for heating. On the other hand, for a conventional multi-tunnel greenhouse in Spain, the main contributors to the environmental footprint are the structure (30–48%) and fertilizers (9–51%; e.g., 51% eutrophication due to nitrate leaching, 32% global warming, 21% air acidification), as well as substrate and electricity consumption.

—Dorais and Cull ([2017](#))

## Environmental benefits of greenhouses

There are some environmental advantages of growing crops indoors, regardless of whether such production is in simple passive greenhouses or high-tech facilities. Such cultivation is invariably extremely efficient, with a much higher yield per unit area occupied compared to field crops, so this reduces pressure to find agricultural areas in a world that

has almost run out of unused arable land. Greenhouses are also suitable for ‘urban agriculture’, taking advantage of some areas, such as rooftops, that otherwise would go unused. As with all crop cultivation, water (which is scarce) and fertilisers (which tend to pollute) are consumed, and waste materials are generated, but these are relatively easy to control in the confined space of a greenhouse. Pests and diseases always accompany crops, but at least in a greenhouse they are relatively easy to locate and eliminate, especially using non-chemical techniques. Because conditions are easier to control in greenhouses compared to cultivated fields, ‘organic agriculture’ is much more commonly practised.

### Are commercial high-tech greenhouses essential?

‘Locavore’ refers to a consumer who prefers to buy locally produced food. The term was recognised as ‘word of the year’ for 2007 by the New Oxford American Dictionary (Conner et al. 2009). The expression has been attributed to Jessica Prentice, a chef and food writer, who used it on World Environment Day (June 5) in 2005 (Quinn 2013). Among the claimed environmental benefits for buying local food are savings in energy transportation costs, but this contention is often untrue (e.g. Wallgren 2006). Certainly high-value, compact commodities (like marijuana or its extracts) are relatively inexpensive to transport. However, almost all commercial greenhouse plants are much more cheaply produced as conventional seasonal outdoor horticultural crops, and at least when in season this is usually preferred. During the rest of the year, consumers may choose to buy plant products that store well locally (such as potatoes and apples) or imports (many of which are cheaper despite long-distance transport). Because in affluent countries there is year-round demand for certain fresh vegetables and flowers with limited shelf life, local production is economically possible in greenhouses despite very high energy expenditures. Almost all greenhouse crops are simply not essential for human welfare, but society has chosen to allow this mode of plant cultivation because of human preferences. However, as discussed in this review, in the case of cannabis, wiser choices on behalf of both economics and the environment are available.

### Greenhouses in the Netherlands

About 10,000 ha (25,000 acres) of land are dedicated to greenhouse horticulture in the Netherlands, including about 5000 ha for vegetables and 3500 ha for flowers

(Hortileads 2017). Curiously, since the Netherlands is well known for its tolerance of consumption of marijuana, this is not a significant commercial crop in the country, although Dutch greenhouses are being exported to marijuana companies in other countries. Several nations (notably Italy and Spain) have much higher areas of greenhouses, but the Netherlands has developed high-technology greenhouse production to an amazing degree, primarily concentrating on energy efficiency (Lansink and Ondersteijn 2006; De Vries and Yara International 2016; Textbox 3). Greenhouses are

#### Textbox 3. Sustainable greenhouses in the Netherlands

In The Netherlands, only 0.5% of the arable land is used for greenhouses, but the production value of these greenhouses is 22% of The Netherlands’ total agricultural production value. In addition, while agriculture uses 70% of the world’s potable water, and millions of people will have no access to clean water in 2025, the water use efficiency of greenhouse production can be more than ten times higher than that of open-field production... LED technology is rapidly advancing. This technology provides a new array of possibilities, such as controlled light intensity, duration, timing, and spectrum, as well as positioning the lights dynamically in response to the plants’ needs... Reductions in greenhouse energy use of more than 50% have already been obtained in The Netherlands since 1990. These energy-saving measures include: better insulation using energy screens and high-tech covering materials; new growing strategies that take advantage of natural energy sources and off-peak energy costs; development of semi-closed greenhouses, in which solar heat is captured and stored. In the future, greenhouse production without fossil fuels can be achieved by using heat pumps, geothermal heat, waste heat from other industries, and green electricity.

—Marcelis and Hemming (2013)

Greenhouse-based production has long been regarded as incompatible with sustainable development. But this image is changing... According to expectations, Dutch greenhouses will stop being net consumers of energy and become net producers... in the past few decades, energy consumption has been lowered by inter-seasonal energy storage, the use of residual heat, the use of geo-thermal energy, and cogeneration systems that simultaneously generate electricity and useful heat... The image of sustainability has been further enhanced since greenhouses became part of the solution for the carbon dioxide problem. In the Netherlands greenhouses use carbon dioxide from a gasification hydrogen plant... to promote the growth of crops. Secondly, fewer chemical pesticides are being used as the closed greenhouse environment lends itself to the use of insects for pest control. And last but not least, the use of substrates instead of soil is expected to promote the biological control of root disease. In conclusion, greenhouse cultivation is an innovative and increasingly sustainable sector.

—Korthals Altes and van Rij (2013)



one of the largest consumers of fossil fuel in the Netherlands. Nevertheless, the greenhouse industry has become remarkably environmentally friendly and productive, contributing to this small country becoming the world's second leading exporter of vegetables, after the U.S. (Viviano 2017). The strategies adopted to lower energy use include reducing the heat requirement by insulation, using sustainable energy resources where possible, and when fossil energy is required, using it as efficiently as possible (De Gelder et al. 2012). Bakker (2006) wrote 'the Dutch horticultural industry has set the target of the introduction of "fossil fuel free" greenhouses in 2020. . . The basic principle is a completely closed greenhouse from which the heat surplus during the summer is extracted by a cooling system, stored in a long term storage medium, and reused during the winter period for heating the greenhouse itself and neighbouring greenhouses or buildings.'

### Ecologically harmful illicit indoor cultivation of marijuana



**Figure 5.** Police in England raiding an illegal sunless grow-op in a house. Photo by West Midlands Police (CC BY SA 2.0).

Illegal sunless indoor 'grow-ops' (grow operations, also called 'cannabis factories' in the United Kingdom and 'marijuana factories' in the U.S.) are frequently located in residences modified to produce marijuana (Figure 5). Considerable stolen electricity is used to power lighting, ventilation, and irrigation systems. Irresponsible and incompetent power and fuel installations have resulted in electrical shorts and house fires. Excessive moisture frequently has generated very high humidity, encouraging fungi that rot timber framing, deteriorate walls, and generate very high densities of spores that threaten human health. Amateur preparation of solvent extracts of THC by butane extraction has produced explosions (Healy 2015). Rebuilding

destroyed houses and replacing household furnishings is inevitably associated with large expenditures of fossil fuels and water, accumulation of wastes that add to society's garbage disposal problem and generation of greenhouse gases.

### Ecologically harmful illicit outdoor cultivation of marijuana



**Figure 6.** Garbage and debris left at a marijuana grow site in the Shasta-Trinity National Forest in California. Photo (public domain) by U.S. Forest Service.

In North America, illicit outdoor operations are frequently carried out in plots hidden in forested areas. Using public lands is motivated in part by the threat of forfeiting assets that are present when using personal residences for production. Those who establish marijuana gardens and visit them only to maintain and harvest the plants have been called 'guerrilla growers'. The illegal cultivation of cannabis in preserved wildlands is extremely deleterious to biodiversity and its supporting habitats (United States Senate Committee on Agriculture, Nutrition, and Forestry 1988; Montford and Small 1999a, 1999b; Mallery 2011; Miller 2018). Illicit marijuana producers usually have little respect for delicate ecosystems. Garbage is dumped in national parks (Figure 6), and groundwater and creeks are contaminated with pesticides, herbicides and spilled fuel carried to the sites to run diesel generators. Diesel production of electricity produces considerably more greenhouse gases than the relatively low-carbon electricity used conventionally ('diesel dope' is a pejorative phrase descriptive of marijuana produced using diesel energy). In California, rodenticides are often used to prevent small mammals from destroying illegal marijuana plants. Rats consume the poison, and then Northern Spotted Owls, Fishers, Foxes and Bobcats



eat the rats and become sick. Thompson et al. (2014) documented the considerable deleterious effects of rodenticides on Fishers in California as a result of illicit marijuana sites.

An additional negative result of the widespread clandestine cultivation of marijuana is that it stimulates law-enforcement personnel to use chemical eradication at extremely toxic levels so as to ensure that there are no surviving plants (although herbicides are often of limited effectiveness for plants taller than about 60 cm). Law enforcement in some countries has employed paraquat herbicide to control illicit marijuana cultivation, notably in Mexico (Figure 7).



**Figure 7.** Helicopter spraying of Paraquat herbicide on a field in which marijuana plants are hidden among legally grown crops. Photo provided by the U.S. Drug Enforcement Administration.

A recent study of illicit marijuana cultivation in California (Bauer et al. 2015) observed that outdoor plants at a density of about one per square metre were consuming 22.7 L of water per plant per day. So extensive was water withdrawal from rivers in northern California that marijuana cultivation was using up 50% more water than all residents combined in San Francisco. This threatened fish and other aquatic species, particularly federally-listed Salmon and Steelhead Trout, as well as sensitive amphibian species, in the drought-prone state.

### Ecologically harmful legal indoor cultivation of marijuana

*Cannabis sativa* grown for fibre or oilseed is never grown commercially indoors. These are ‘field crops’ – by nature appropriately grown outdoors, typically in very large monocultures. Up until the middle of the twentieth century, Marijuana was also grown as

a field crop – for millennia in the traditional homeland of cultivation in southern Asia, and subsequently in long-season areas of the Americas. Subsequently, with expanding illicit consumption in the Western world and concentrated efforts to interdict international smuggling, clandestine indoor cultivation in basements and sunless rooms became extremely widespread. When the medical use of marijuana began to be accepted in the 1990s, security concerns dictated that cultivation be done in very secure indoor facilities, whether completely sunless or not. Importation of marijuana is generally restricted internationally (except in the European Economic Union), so it has been necessary for countries to produce their own supply, albeit very much cheaper material could be imported from countries climatically more suited to production. These considerations have combined to establish a tradition of marijuana production indoors in fashions that are excessively expensive and wasteful.

### Completely artificial light cultivation



**Figure 8.** Medicinal marijuana production by Bedrocan, the sole authorised national supplier of medical marijuana to the Netherlands government since 2001. This growth room employs only artificial light. Photo courtesy of Bedrocan.

With artificial light, plants can be produced without the benefit of natural sunlight, and indeed researchers commonly employ sunless relatively small ‘growth chambers’ in which plants are grown (at considerable cost) in a rigidly controlled and monitored climate. Glass houses or at least transparent roofs take advantage of natural sunlight, but frequently marijuana ‘grow rooms’ are completely artificially illuminated. Commercially, so-called ‘plant factories’ are artificially illuminated and highly insulated closed growth systems which are usually very large and located near sources of cheap electricity.

Nevertheless, based on lettuce production, Graamans et al. (2018) found that even the most efficient greenhouses required less purchased energy than plant factories, because, of course, ‘they use freely available solar energy for photosynthesis’. Cannabis is grown to a considerable extent in very secure indoor facilities completely illuminated artificially (Figure 8). Such cultivation irresponsibly produces huge amounts of greenhouse gases (Textbox 4).

**Textbox 4. Indoor completely artificially illuminated ‘marijuana farms’ are energy hogs**

Policymakers have failed to address an important area: the marijuana industry’s energy and climate impacts. Although marijuana is a plant, it is not a ‘green’ product when grown indoors... as marijuana businesses become more competitive and specialized, growers are moving their farms indoors to get a more controlled product... Indoor cultivation requires electricity to power high-intensity lights, frequent air exchanges and ventilation, and to maintain consistent temperatures and humidity levels day and night... Experts estimate that a 5,000-square-foot indoor marijuana facility in Colorado consumes six times more electricity per square foot than an average commercial business, and 49 times more than an average residence... nationwide [U.S.], indoor marijuana cultivation accounts for nearly 15 million metric tons of carbon emissions annually—more than the annual energy-related emissions of South Dakota, Delaware, Rhode Island and Vermont, or the District of Columbia.

—Warren (2016)

While energy costs make up about one to four percent of total operating costs in hospitals, for example, they’re a much bigger portion of a cannabis grow operation’s costs, coming in at 20 to 40 percent of total operating costs.

—Cohn (2017)

### Partly artificial light cultivation



**Figure 9.** One of the growth facilities of GW Pharmaceuticals (U.K.), using a combination of natural and artificial lighting, each providing about half of the light energy required (Potter 2014). Reproduced with permission of GW Pharmaceuticals plc.

The expression ‘hybrid greenhouse’ refers to a building, intended to grow plants, with solid side walls and a translucent ceiling (Figure 9). Certainly, unauthorised entry is much more difficult than in greenhouses made almost entirely of glass. An additional benefit is that the crop is hidden from public view, reducing temptation. And, the opaque side walls can be very heavily insulated to reduce heat loss. Hybrid greenhouses, with metal walls, and glass or plastic roofs, have become very popular for marijuana businesses. Of course, the benefits are at the cost of reduced natural light entry and the need to supply supplementary artificial lighting.

## Advantages and disadvantages of greenhouse cultivation of marijuana

### (1) Protection against pollination

As noted previously, male plants are not given much respect in the marijuana industry. Indeed, most of the time they are despised, because the pollen from male plants fertilises the female flowers, causing the female plants to divert much of their energy into producing seeds, which are devoid of the desired cannabinoid chemicals. For thousands of years, marijuana growers have eliminated male plants that develop in a field as soon as they could be recognised, and this is still often practised. There are also breeding techniques that are used to generate seeds that produce mostly female plants. However, most marijuana producers today reproduce elite female plants (known to be superb producers of cannabinoids) by vegetative cuttings, so there is no need to eliminate males. Unfortunately, pollen from hemp fields, illicitly-planted marijuana plants, and wild-growing plants is extremely widespread in the atmosphere, and can pollinate commercially growing marijuana fields, lowering quality because seeds are produced. This is much more easily avoided indoors since greenhouses form a barrier, and pollen can be filtered from ventilation sources.

Breeders, of course, need male plants to generate new cultivated varieties. Producers of pedigreed hemp seeds are usually required to isolate their field plots by 5 km from adjacent sources of cannabis pollen (which would produce undesired genetic combinations), and this is not easily verified because illegally cultivated and wild plants may be difficult to locate. However, as noted above, in greenhouses, where marijuana strains are commonly bred, ambient atmospheric pollen is easily excluded, preventing unwanted genetic contamination.



## (2) Yield and efficiency of production

Caulkins (undated) attempted to assess comparative marijuana yields of indoor and outdoor plants, but the latter figure has not been adequately determined. Indoor yields of ‘bud’ (inflorescence) typically vary between 250 and 500 g/m<sup>2</sup>, with about four harvests expected annually (Small 2016). High planting densities (of the order of 30 or more plants/m<sup>2</sup>) are typical of indoor plantings to maximise productivity of valuable indoor growth area, and height of plants is limited since light intensity is insufficient to penetrate to the lower leaves of tall plants. The density of outdoor marijuana plants is typically much lower, sometimes 1 m<sup>2</sup> for each plant. For harvest of bud material, the yield/area sometimes does not exceed indoor yields, and only one harvest is usually possible, which is quite disadvantageous on a yearly basis. (The ‘Emerald Triangle’ of Northern California, centred in Humboldt County, has been the epicentre of mostly illegal outdoor cultivation in the U.S. Two outdoor crops are possible by extending the season with low-tech greenhouses, as shown in Figure 10.) On the other hand, for harvest of biomass from which cannabinoids can be solvent-extracted, it is probable that outdoor yield significantly exceeds indoor yield, despite only one harvest being possible (the considerable foliage of outdoor plants represents a large source of cannabinoids). Data in Sacirbey (2017) suggest that 1 g of marijuana can be grown for U.S.\$1.32 indoors (artificial light only), \$0.99 in high-tech greenhouses, and \$0.55 in outdoor fields.

For most annual crops, yield/unit area can be greater, indeed sometimes much greater, in a greenhouse. For example, yield/area of tomatoes in greenhouses is typically about 10 times as large as in fields. Nevertheless, the comparative cost of indoor cultivation is hugely greater than field cultivation, which is the simple reason why almost all crops are grown outdoors, indeed usually as annuals harvested at the conclusion of a single season. To justify the cost of greenhouse cultivation, there needs to be special considerations. For example, greenhouse tomatoes (which happen to be the world’s leading greenhouse crop) meet the need for providing, throughout the year, high-quality but tender fruit to prosperous consumers who dislike the cheaper but rubbery field-grown commodity that is tough enough to withstand transportation from poorer nations with longer natural growing seasons. Should plant breeders create luscious, long-lasting tomatoes that can be imported cheaply, it would create economic disaster for the commercial greenhouse industry!

## (3) Security

Poet Robert Frost famously wrote ‘Good fences make good neighbours’. Fences for producing medicinal marijuana outdoors, where permitted, have typically been as well defended as top-secret military sites (Figure 11; compare Figure 17). In the main, to date, both regulators and licensed growers have been comfortable growing medical marijuana indoors, protected by very solid walls, as well as massive safes for storage, security personnel, guard dogs, motion detectors, video recording, and search lights



**Figure 10.** A simple unheated greenhouse employed to grow marijuana (illegally). The plants are being seized by the California Counterdrug Task Force. Photo (public domain) by U.S. Army National Guard/Sgt. Brianne M. Roudebush.





**Figure 11.** High security barriers typically required for field cultivation of marijuana. Prepared by B. Brookes.

to prevent unauthorised entry. Of course, this has added considerably to costs, which have simply been passed on to patients. With recreational marijuana rapidly being added to the marketplace, the price factor is becoming more pressing. Indoor cultivation greatly adds to the expense of production, but is much more secure. The need for such security is examined later.

#### (4) Photoperiodic control of flowering

As noted earlier, high-grade marijuana is made up of the flowering portion of the plant ('bud'), so plants need to develop flowers. Most kinds of *C. sativa* are prompted to develop flowers (and subsequently seeds for hempseed production) by decreasing day length (continuous hours of daylight) in the autumn. Indoors, marijuana growers induce flower development by providing several weeks of short day length (usually 12 h of darkness every day). Outdoors, Mother Nature (and latitude) determine hours of daylight, and this often greatly limits which varieties can be grown in a given location. Indoors, the necessary dark period to bring plants into flower can easily be provided by shade curtains, and so this allows growers to bring plants into flower in less than 3 months. This consideration is a great advantage for indoor growers. However, a few strains of *C. sativa* are indifferent to day length; these are referred to as 'day-neutral' and 'autoflowering', and some come into flower in as little as 2 months. This has the potential to produce two or three crops outdoors, but six crops indoors. Moreover, since such plants do not need a dark period, they can be grown in continuous light, which makes them grown larger. Once again, there is a considerable advantage to indoor growth. However, as noted

elsewhere, outdoor growth produces material much more cheaply and with less damage to the environment.

#### (5) Photosynthetic intensity

Light intensity outdoors can be at least 10 times as high as indoors, allowing a much greater production per unit area occupied. The basis for this is that the more intense light is able to penetrate to lower leaves, so that much taller plants can be grown efficiently outdoors (Small 2018). The much weaker light provided in indoor facilities can only efficiently support short plants, because the light quickly become insufficient at lower foliage levels. The height of greenhouse cannabis plants is controlled (either by choice of naturally short cultivars or by bringing plants into flower by providing short day length before they grow too large), so that the relatively limited foliage of indoor plants receives adequate illumination. Because three to six short cannabis crops can be produced indoors, but often only one tall crop outdoors, annual net production may not be that different in some circumstances.

#### (6) Seasonal limitations, quality and shelf life

As noted elsewhere in this review, a principal benefit of growing edible plants in local greenhouses is that they meet consumer demand for very tender, out-of-season vegetables and fresh flowers that have limited shelf lives, so transportation from far-away warmer climates is not competitive. Many crops simply won't last long enough to be transported to distant markets (this is the case for most tropical fruits). Greenhouse tomatoes are particularly illustrative: they can be much more tender, albeit not as long-lasting, as the tough tomatoes that need to be able to

withstand long-distance transportation. Some delicate vegetables are very susceptible to pest and climatic damage, and their appearance can be enhanced by growth in very protected greenhouses, free of insects and buffering by atmospheric elements such as wind and rain. For some species, a closely controlled environment can produce more uniform and aesthetically more pleasing vegetable and floral crops. However, these are not significant considerations for marijuana, either in the form of dried herbal material or solvent extracts. Marijuana can be preserved very well for years, in refrigerated, light-proof, oxygen-free conditions. Moreover, marijuana and its products are compact, and can be shipped long distances with minimal transportation costs.

### (7) Protection against pests, microorganisms and weeds

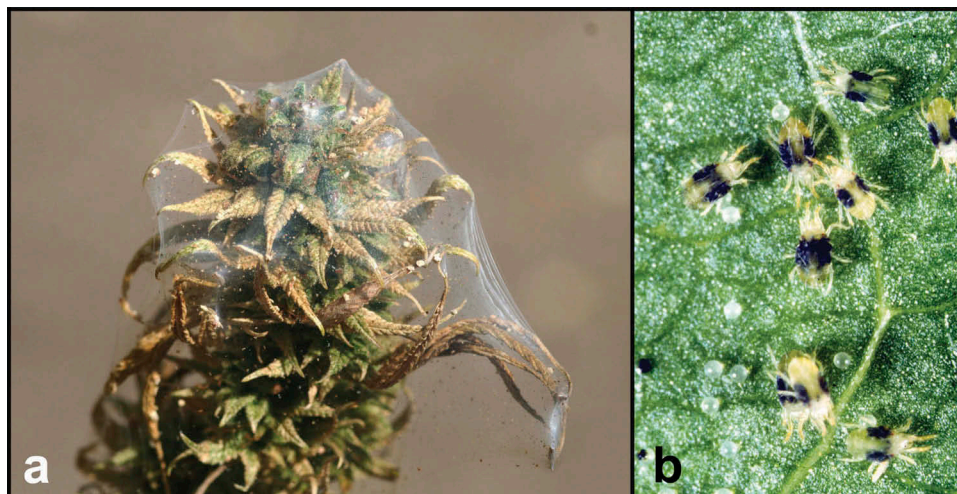
Experienced expert cooks can produce uniformly perfect dishes with nearly 100% fidelity. Experienced expert horticulturalists and farmers cannot always produce perfect crops because Mother Nature deviously furnishes bacteria, fungi, insects, and other forms of biodiversity that sometimes overcome even the best defences of humans. An attack by a pest can easily ruin a greenhouse or a field of material. Several pests are specialists of greenhouses, and in the case of cannabis, spider mites are extremely common (Figure 12). Powdery mildews are also a constant threat (Figure 13). For most commercial crops, there are more serious pests outdoors than indoors. Numerous crops cannot be grown efficiently outdoors without at least occasional application of biocides (particularly pesticides



**Figure 13.** Powdery mildew (*Golovinomyces cichoracearum* = *Erysiphe cichoracearum*) on marijuana plants (Bubba Kush strain) growing in a commercial medicinal cannabis production greenhouse. Photo by S. Sveinson-Dyer, Elmhirst Diagnostics & Research (reproduced with permission).

and fungicides), and some crops can be much more easily grown 'organically' indoors. *Cannabis sativa* is attacked by hundreds of species, but very few are serious, and it is usually possible to grow it both indoors and outdoors without relying on pesticides and fungicides. However, biocides are mostly not needed for *C. sativa*, whether indoors or outdoors, and in general biocides are discouraged for production of marijuana.

The seeds of many crops today are sown in fields that are efficiently cleared using herbicides, and cannabis is no exception (although once established, cannabis plants usually shade out weeds). In



**Figure 12.** (a) Damage to greenhouse-grown plant of *Cannabis sativa* caused by the Twospotted Spider Mite (*Tetranychus urticae*). Spider mites (especially the genus *Tetranychus*) are perhaps the most serious invertebrate pest of indoor *C. sativa*. Photo by Whitney Cranshaw, Colorado State University, Bugwood.org (CC BY 3.0). (b) Adults and eggs of the Twospotted Spider Mite. Photo by CSIRO (CC BY 3.0).

greenhouses, when soils are employed for growing, there is no need to employ herbicides, and this is a clear advantage for ecosystems and their constituent biodiversity.

### (8) Environmental contaminants

The tiny epidermal structures in which the cannabinoids are synthesised are ‘touch-sensitive’ glands, which are protective against small herbivores by explosively releasing a sticky resin, trapping insects, much like fly-paper. Strong winds can agitate the plants and also cause the glands to release their resin. Dust and faeces from passing animals may also be trapped in the sticky material. Such contamination is much more likely to occur outdoors, although in greenhouses, unless gloves and hairnets are worn, some contamination from human handling is also inevitable. While disgusting, it should be remembered that sanitary regulations for food allow for minor contamination by rodents and other unsavoury sources. Regardless, just as many foods are sterilised for sale, authorised marijuana is commonly irradiated.

Some crops are known to accumulate toxic levels of nitrates or heavy metals from the soil, and *C. sativa* is capable of accumulating heavy metals. This is a problem primarily associated with certain soils. However, whether grown indoors or outdoors, producing marijuana commercially requires suitable soils and testing for these elements before sale.

### (9) Harvest

Buds are sometimes individually collected as they mature, and this can be carried out from field plants or from greenhouse plants. Unfortunately, mechanical collection of buds is not well developed. Usually, uprooted plants are dried for several days, and buds are hand-separated, a labour-intensive operation which at least provides considerable employment. For most crops, outdoor cultivation requires much less labour, and is much more easily mechanised, but this is related to the large scale of cultivation. Collection of material for extracts can be carried out very much more efficiently and cheaply outdoors. Working in the very confined, hot quarters of a crowded marijuana greenhouse, with shimmering lights overhead, and while wearing protective gear, is much more demanding than outdoor labour.

### (10) Gene escape

Genetically modified crops are increasingly common, and there is considerable concern about the release of

altered genes (‘transgenes’) to plants in the wild (Lu 2008). Biosafety regulations, depending on jurisdiction, often dictate that trials and even commercial cultivation be confined to secure areas from which pollen, seeds, or plants cannot escape, such as protected greenhouses. For years, allegations have been made that *C. sativa* has been genetically modified (e.g. Anonymous 2018). Unreliable reports have been made that the underworld has been cultivating genetically transformed marijuana in developing nations, and this scenario points to the virtually impossibility of confining such plants, irrespective of whether grown in highly secure indoor quarters or outdoors. Outdoors, either by natural or human means, such plants will inevitably be released to the wild, with unpredictable consequences.

### Energy expenditure: the key criterion for commercial greenhouse cultivation

Energy is the fundamental requirement for growing plants in temperate-region high-tech greenhouses (Textbox 5). Growing cannabis in high-tech greenhouses in most locations requires electricity and/or fuel for artificial lighting, cooling, heating, and dehumidifying. As pointed out by Hassanien et al. (2016), ‘Energy is the largest overhead cost in the production

#### Textbox 5. Energy: the key factor in profitable greenhouse operation

The greenhouse industry is an important user of energy all over the world. Greenhouse growers use a considerable amount of energy (about 8–16 TeraJoule/hectare/year, depending on latitude and weather condition) for maintaining optimal growing conditions (temperature, humidity, CO<sub>2</sub> concentration) to achieve full yield potential. Energy, mainly natural gas or coal, is the second largest cost for protected crop growers. Heating is mainly used at night and during winter to reduce thermal differentials in order to control the environment and boost production. Heating is often combined with ventilation techniques to control humidity and reduce the need for fungicides. Fuel, typically gas, is also burned during the day to produce CO<sub>2</sub>, with the energy stored in large thermal water tanks for use as heating later in the day. Moreover, it is worth noting that the greenhouse area is in continuous expansion, especially in the Mediterranean basin, due to the enlarging demand of vegetables for the export and domestic markets, resulting from economic development. This will prompt growth in energy consumption. From these considerations it is clear that profitability of greenhouse firms is largely dependent on energy costs.

—Ippolito, La Cortiglia, and Petrocelli (2006)



of agricultural greenhouse crops in temperate climates. Moreover, the initial cost of fossil fuels and traditional energy are dramatically increasing.’ Guan and Gao (2010) commented ‘Greenhouse production is one of the most energy intensive branches of agriculture. High energy costs and increasing environmental concerns associated with the greenhouse gas emissions are posing an increasing threat to the industry. To address the emerging challenges, greenhouse growers will have to improve energy efficiency and reduce CO<sub>2</sub> emissions.’ It is particularly wise to link greenhouse culture to renewable power sources, including solar, wind, biomass and geothermal energy.

### ‘Free’ heat sources

The sun is not the only source of free heat. The Earth is also a source of thermal radiation. Deep mines are naturally warm, and in the 1990s Canadian medicinal marijuana was produced in a mine (Figure 14). Heat pumps are able to extract energy from the ground, or indeed even from nearby bodies of water and air, and supply this to any kind of building, including greenhouses. Such energy is available everywhere on the surface of the earth. In the south of Iceland, volcanic activity warms the soil and greenhouses have been located there to take advantage of this natural heat (Figure 15). Some greenhouses are warmed with waste heat produced

from power plants and industrial processes, but such locations are uncommon.

### Environmental costs of sunless indoor production of marijuana

Currently, considerable marijuana (predominantly grown illegally) in the U.S. is produced indoors, without exposure to natural sunlight. Extremely high energy expenditure is required, primarily because of the need for lighting, but also to provide ventilation (to assist temperature control for living plants and for drying harvested marijuana), heating/cooling for climate control, and cool storage (to prevent deterioration of the product). Mills (2012) reported that 1% of the entire energy consumption of the U.S. is dedicated to the production of indoor marijuana, equivalent to \$6 billion annually. Building materials to house marijuana production facilities are expensive to purchase, but are also costly in that energy was required for their construction. All factors considered, a very large expenditure of energy and consequent ‘environmental imprint’ is associated with the indoor cultivation of marijuana.

Indoor production of marijuana is also associated with the production of carbon dioxide, which acts as a greenhouse gas contributing to climate change. Much of the electrical energy utilised results in CO<sub>2</sub> production, and often fuels are burned directly in support of greenhouse operations, releasing



**Figure 14.** Marijuana (*Cannabis sativa*) growing in a mine shaft tunnel for the Canadian medical marijuana program. Growth underground greatly reduces costs of heating, but requires artificial lighting. Photo by E. Small.



**Figure 15.** Geothermally heated greenhouses in Iceland. (a) A simple polyethylene greenhouse, taking advantage of the naturally warmed soil to considerably extend the growing season. Photo by Axel Kristinsson (CC BY 2.0). (b) Tomatoes growing in a greenhouse heated by geothermally warmed water. Photo by Tanya hart (CC BY SA 2.0).

CO<sub>2</sub>. Mills (2012) calculated that 1 kg of marijuana produced indoors is associated with the release of 4600 kg of CO<sub>2</sub> emission to the atmosphere, equivalent to operating 3 million cars for a year. Occasionally, CO<sub>2</sub> is injected into grow rooms to increase photosynthesis and yields, and this also contributes to atmospheric pollution. However, since productivity is increased, the overall carbon footprint of introducing CO<sub>2</sub> may actually decrease negative environmental impacts (O'Hare, Sanchez, and Alstone 2013).

O'Hare, Sanchez, and Alstone (2013) analysed environmental costs of producing marijuana for a legal market in Washington State. Several observations in the report are worth noting. It was pointed out that indoor lighting carried out during the night period is relatively efficient, and would have a smaller deleterious effect on climate than lighting during daylight hours when there is high demand for electricity. It was noted that although the environmental costs of cannabis production are substantial, they are significantly less than associated with other activities such as large-scale agriculture, mining, metallurgy and other industries. As in all indoor plant production requiring lighting with high-intensity discharge bulbs, there is an environmental cost associated with the non-recyclable bulbs containing mercury and other toxins.

### The case for outdoor cultivation of marijuana

This review has laid out in detail the pros and cons of cultivating marijuana in energy-wasting greenhouses. The criterion that has been most responsible for



**Figure 16.** A field of Opium Poppies cultivated for pharmaceuticals in North Dorset, England. Photo by Marilyn Peddle (CC BY 2.0).



**Figure 17.** Field cultivation of marijuana at the U.S. Government production site, University of Mississippi, Oxford. Photo (public domain) by U.S. National Institute of Drug Abuse.

allowing this unnecessary practice is the need for extreme security as perceived by governmental regulators. However, this is a holdover from a century of fear of narcotic drugs and confusion about appropriate management strategies. Curiously, the world's most



evil narcotic plant, Opium poppy (*Papaver somniferum*), is harvested for authorised medicinal purposes from very large outdoor fields (Figure 16). Even the United States government, which continues to be highly opposed to any commercialisation of marijuana, grows its supply of experimental medical material outdoors (Figure 17), and the case in favour of permitting outdoor cultivation in Canada is under consideration (Marcus et al. 2017). In the long term, the fear of cannabis, that still dictates most policies concerning its production, is likely to lessen to the point that the plant will be grown mostly outdoors, as nature intended.

### Believe it or not

- The classical Romans are credited with being the first to exploit transparent enclosures to grow plants out of season. To provide fresh cucumbers for the emperor Tiberius, his servants grew them in a cart which was moved outside in the sun during the day, and was wheeled indoors at night. A sheet of selenite, a transparent crystal, was placed over the cart, transforming it into a miniature greenhouse.
- Under current production methods in North America, the energy needed to produce indoor marijuana for a single joint could power a 100 W light bulb for 25 h, and would generate 1.5 kg (3 lb) of polluting CO<sub>2</sub> emissions (Mills 2012).
- The energy required to produce one marijuana joint is about equal to the requirement to manufacture 8.5 L (18 pints) of beer (Mills 2012). Nevertheless, it is much cheaper for a consumer to become intoxicated by marijuana than by alcohol.

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