

Public Health and Safety Consequences of Liberalizing Drug Laws

Insights from Cannabis Legalization

Steven Davenport

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Abstract

Cannabis has been legalized for non-medical purposes in Canada, Uruguay, eleven U.S. states and Washington DC, with others likely to follow. The world's first large corporate cannabis producers and retailers are operating in Canada and the United States – with the potential for continued expansions in scale and efficiency in the case of national legalization in the United States. This accelerated rate of policy change prompts novel topics of cannabis policy research, including evaluating past policy changes and identifying feasible policy responses for contemporary or anticipated issues.

This dissertation includes four papers. Three concern issues related to cannabis, with the last investigating a related issue (intoxicated driving) manifesting in alcohol policy. The first chapter identifies U.S. national-level patterns of cannabis acquisition and use and from 2002 to 2013, roughly the decade of policy liberalization that preceded the first non-medical cannabis regimes. The second chapter investigates a surprising fifteen-year trend in self-report of cannabis use disorder symptoms among daily/near-daily cannabis users, who disproportionately bear many of the consequences of cannabis use. The third chapter analyzes Washington State's recreational cannabis traceability dataset (July 2014-October 2017), documenting emerging trends, e.g. declining prices, cannabinoid profiles, and product forms. The final chapter evaluates an intervention relating to reducing alcohol-involved crashes, some lessons of which can be carried over to analogous questions with cannabis-involved crashes. That study evaluated Uruguay's zero blood-alcohol-concentration (BAC) law, exploiting a novel synthetic controls method to estimate reductions in severe and fatal injury crashes, using Chile as a control.

A central theme is the potential for a rising public health risk among adult cannabis users, and which may or may not meet clinical diagnoses for cannabis use disorder. There remain puzzles to solve. As the political-economic landscape regarding cannabis continues to evolve, public health-oriented policymakers would be wise to invest time and research in monitoring use trends in detail, and refining definitions and measurements of problematic cannabis use. It is the hope of this dissertation to support that line of inquiry.

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When the student is ready the teacher appears

When the student is truly ready the teacher disappears

- Lao Tzu

Introduction

More than five years now after the first openings of state-legal adult-use cannabis markets in the United States, research and debate regarding cannabis policy is becoming increasingly pertinent. The production, distribution, and sale of non-medical cannabis is now legal in Canada, Uruguay, and ten U.S. states (additionally, Vermont has allowed possession and limited cultivation but not sales). Roughly two-thirds of Americans now live in states with either legal adult use cannabis (93 million) or permissive medical cannabis regimes (another 99 million), which generally license retail dispensaries and allow the sale of high-THC cannabis.

Over thirty million Americans self-report using cannabis in the past-month, with one third of those reporting daily or near-daily use, i.e., using more than twenty days over the past thirty (Hasin et al. 2016). Cannabis spending is estimated to be on the order of \$50 billion – equal to one-third of total U.S. spending on major illegal drugs, including on methamphetamine, cocaine, and heroin. Combining both state-legal and fully-illicit sectors, the retail value of the cannabis market is roughly equivalent to the size of the market for heroin in 2016, or the combined size of markets for methamphetamine and cocaine (Midgette et al. 2019).

This dissertation includes four papers, three of which focus on issues related to cannabis, with the last investigating alcohol policy but with close connections to similar issues in cannabis policy. Together, these papers assemble a collection of new research relating to cannabis policy. The first paper reviews trends in cannabis use in the United States over eleven years (2002-2012), during a period of widespread liberalization of cannabis laws. Using data from the National Survey on Drug Use and Health (NSDUH), it examines aggregate patterns of use, including detail on the prevalence of daily/near-daily use, estimated annual spending per user, and socioeconomic disparities across use.

The second paper uses NSDUH data to ask a more focused question: during the same period, what happened to rates of cannabis dependence and/or abuse as assessed based on self-report of problems with that use? The paper shows that though the population prevalence of daily/near-daily use had risen substantially from 2002-2016, the total number of people reporting symptoms that would qualify them for abuse and/or dependence stagnated. The paper focuses on calculating the conditional probability of self-reported dependence given daily/near-daily use, finding it has fallen by nearly half over the period – raising questions about whether use has in fact gotten less harmful, or if instead individuals have merely changed the way they self-identify and attribute their own difficulties in life.

The third paper exploits Washington State's recreational cannabis traceability dataset, which records all retail transactions (and many earlier supply-chain events) in the state's regulated cannabis marketplace. This is a valuable source of data for trends in prices, product variety, and psychoactive content (e.g. THC and CBD test results), and more broadly, how legal, commercial markets may differ from traditional illegal cannabis markets. This study provides quantitative data about rates of price change and product proliferation.

Finally, the fourth paper seeks to evaluate a blood alcohol concentration drunk-driving law in Uruguay. A novel feature of that policy was that the concentration is set to zero – making Uruguay only the thirteenth country to have such a policy, and the first one to be subject to an international evaluation. To investigate these changes, the paper uses a novel synthetic controls method co-developed by the author. Research in the area relating to alcohol-involved driving may be of indirect assistance to policymakers and research related to cannabis, as they may share methodological underpinnings and concern the common phenomenon of substance-impaired driving.

It is generally characteristic of issues in drug policy that the guiding values, intended benefits, and adverse harms span a broad range of domains (R. MacCoun 1998). To provide broad context for the contents of this dissertation, this introduction will discuss evidence relating to the harms and benefits of cannabis use and policy and the range and status of cannabis policy frameworks available in theory, in the United States, and worldwide.

Some key domains are listed below, along with examples of associated types of effects: public health (direct effects to user of cannabis use, e.g. adverse health issues, mental health risks, and changes in alcohol or tobacco use); psychosocial development (cognitive impairment and cannabis use disorder, especially among daily users); public safety (e.g. risk of car crashes, behavior under the influence, and cannabis-related crime); criminal justice and civil liberties (e.g. harms imposed by enforcement actions on individuals and communities); and political economy (e.g. presenting potential revenue streams to illegal actors, legal private actors, government, or targeted populations such as in social equity programs).

The use of cannabis has also been purported to offer users a wide range of subjective benefits, including pleasure, enhancing creativity, fostering relaxation, or allowing access to a usefully different style of thought (Caulkins, Kilmer, and Kleiman 2016).

Quite distinct from cannabis' benefits to consumers as a consumer good, there are many claims that it has medicinal value. Indeed, the number of ailments for which it is claimed to aid is astonishing. The National Academy of Sciences recently reviewed the state of evidence relating to the harms and the therapeutic uses of cannabis or cannabinoids (National Academy of Sciences 2017). To characterize evidence regarding therapeutic applications, an expert committee developed standardized language for the weight of evidence supporting suspected treatment effect, including, e.g. "conclusive", "substantial", "moderate", "limited", or "no or insufficient" evidence of being an effective or ineffective treatment. The committee found conclusive or substantial evidence for cannabinoids to treat chemotherapy-induced nausea and vomiting, chronic pain; and patient-reported spasticity symptoms (but not physician observed spasticity symptoms). There was moderate evidence for treating sleep disorders. Many of these studies use specific molecular isolates, rather than the whole plant, as it is often used by the broader public.

There was also some limited evidence concerning a wide range of ailments supporting treatment of wasting diseases, symptoms of post-traumatic stress disorder, clinician-measured spasticity symptoms, and Tourette syndrome; and limited evidence of a correlation for relief of anxiety symptoms and facilitating recovery from traumatic brain injury. The committee found limited evidence suggesting the *ineffectiveness* of cannabis or cannabinoids to treat dementia symptoms,

depressive symptoms, and intraocular pressure related to glaucoma. It is often the case in the above studies that they concern the use of specific cannabinoids, rather than the whole plant.

The adverse effects of cannabis use can be roughly grouped by domain: e.g. physical health effects borne by the user, mental health and psychosocial effects borne by the user, risk of injury and death borne by the user, and the indirect effects on non-users relating to public health and safety, such as the risk of vehicle crashes or other risky behavior caused by cannabis use.

The National Academy of Sciences committee also assessed the state of evidence relating to statistical associations of cannabis use with adverse health outcomes. Evidence categories include “conclusive”, “substantial”, “moderate”, “limited”, or “no or insufficient” evidence. Evidence is found in relation to a specific association between cannabis use and the health outcome, i.e. whether there is evidence suggesting the phenomena are correlated, or are not correlated; or if there is not sufficient evidence either to support or refute a claim in either direction/

The committee surveyed domains of physical health including cancer; cardiometabolic risk; respiratory disease; immunity; injury and death; and prenatal, perinatal, and neonatal exposure to cannabis. Table I presents a slightly simplified summary of these findings. It does not communicate the findings of the report in totality or the finest level of detail; rather, it is simplified somewhat for readability and input into a table. For existence, some evidence relates only to smoking cannabis, or to its chronic use, or desistance after a long period of use. Another type of variation in the evidence base is the type of cannabis used, e.g. specific isolated molecules versus flower cannabis, which itself may have varying levels of THC concentration, often lower than the THC concentration of cannabis that is widely available to American users. Such details are *not* communicated in the summary table provided below; please refer to the source document for that level of detail.

Table i. Weight of Evidence for Correlations with Use of Cannabis or Cannabinoids (NAS)

Category	Health Issue	Evidence	Relationship
Mental Health	Development of schizophrenia or other psychoses	Substantial	Correlated
	Better cognitive performance (if with psychotic disorders)	Moderate	Correlated
	Symptoms of mania and hypomania (if bipolar)	Moderate	Correlated
	Depressive disorders, increased risk	Moderate	Correlated
	Suicidal ideation and attempts (especially among heavier users)	Moderate	Correlated
	Suicide completion	Moderate	Correlated
	Social anxiety disorder	Moderate	Correlated
	Negative schizophrenia symptoms (with psychotic disorders)	Moderate	Not Correlated
	Positive schizophrenia symptoms (with psychotic disorders)	Limited	Correlated
	Bipolar disorder (especially regular or daily users)	Limited	Correlated
	All anxiety disorders except social anxiety disorder	Limited	Correlated
	Anxiety symptoms (with near-daily use)	Limited	Correlated
	PTSD, symptom severity	Limited	Correlated
	Depressive disorders, changes in course or symptoms	No Evidence	Neither Support nor Refute
	PTSD, development	No Evidence	Neither Support nor Refute
Respiratory	Respiratory symptoms and chronic bronchitis	Substantial	Correlated
	Improved airways (with acute use, but not chronic use)	Moderate	Correlated
	Higher forced vital capacity	Moderate	Correlated
	Respiratory improvements (after cessation of use)	Moderate	Correlated
	Risk of COPD (smoking)	Limited	Correlated
	Hospital admissions for COPD (smoking)	Insufficient	Correlated
	Asthma development or exacerbation (smoking)	Insufficient	Correlated
Prenatal	Lower birth weight	Substantial	Correlated
	Cognitive impairment, e.g. learning, memory, attention	Moderate	Correlated
	Impaired academic achievement and education outcomes	Limited	Correlated
	Unemployment and/or low income	Limited	Correlated
	Impaired social function or engagement	Limited	Correlated
	Cognitive impairment (under sustained abstinence)	Limited	Correlated
	Complications for mother	Limited	Correlated
	Admission of infant to NICU	Limited	Correlated
	Later outcomes in offspring	Insufficient	Correlated
Cardio- metabolic	Ischemic stroke or subarachnoid hemorrhage	Limited	Correlated
	Decreased risk of diabetes and metabolic syndrome	Limited	Correlated
	Increased prediabetes risk	Limited	Correlated
	Acute myocardial infarction (triggering onset)	Limited	Correlated
	Acute myocardial infarction (increased risk)	No Evidence	Neither Support nor Refute
Injury and Death	Risk of motor vehicle crashes	Substantial	Correlated
	Overdose injuries among pediatric populations in legal states	Moderate	Correlated
	All-cause mortality	No Evidence	Neither Support nor Refute
	Occupational accidents or injuries	No Evidence	Neither Support nor Refute
	Death due to cannabis overdose	No Evidence	Neither Support nor Refute
Cancer	Lung cancer	Moderate	Not Correlated
	Head and neck cancer	Moderate	Not Correlated
	Esophageal cancer	Insufficient	Neither Support nor Refute
	Other cancers, e.g., prostate, cervical	Insufficient	Neither Support nor Refute
Immunity	Liver fibrosis or hepatic disease in individuals with Hepatitis C	Limited	Not Correlated
	Decreases in inflammatory cytokines	Limited	Correlated
	HPV incidence	Insufficient	Neither Support nor Refute
	Immune system measures (if infected with HIV)	Insufficient	Neither Support nor Refute

Among psychosocial outcomes, the committee found “moderate” evidence for associations between learning, memory, and attention and sustained cannabis use, and “limited” evidence in the face of acute cannabis use. All other psychosocial outcomes studied were found to have limited evidence of statistical correlation with cannabis use, e.g. impaired academic achievement, low income, impaired social functioning or engagement in developmentally appropriate social roles; and cognitive impairment during periods of sustained abstinence.

Perhaps the single largest public health risk relates to the development of cannabis use disorder or other types of heavy and/or problematic use. Though over thirty million Americans self-report using cannabis in the past-month, with one third of those using more than twenty days over the past thirty (Hasin et al. 2016; National Academy of Sciences 2017). Under the definition provided by the DSM-V, nearly six million adult Americans report symptoms that would qualify them for cannabis use disorder in the past year (Hasin et al. 2016).

Emerging research in several countries identifies that the risks of developing cannabis use disorder and/or admission for psychosis are intensified by higher THC concentrations or higher levels to exposure to THC (Curran et al. 2019; Tom P. Freeman et al. 2018; Hjorthøj et al. 2019; Kraan et al. 2016). Conceptually, exposure to THC can be considered a function of the frequency of use, the cannabis use modality employed, and the THC concentration in that product. Each of these factors in isolation have also been linked to increased risk of developing cannabis use disorder, tolerance, and the onset of psychiatric events such as panic attacks and onset of psychosis.

A developing body of literature points to the risks of consumption of high-THC products and of the different routes of administration (ROAs), such as oil-based vaporizing, dabbing solid concentrate, and consumption of edibles. A recent review of research concluded that ROAs have distinct health impacts, but that a more rigorous high-quality studies are needed before these can be compared systematically (Russell et al. 2018a).

Particularly concerning is the use of high-THC concentrates, especially “dabs” but also edibles and portable vaporizers (Sagar et al. 2018). Dabbing has been associated with increased risk in many aspects of harm from cannabis use, including acute health risks of consumption and risks of developing use disorders (Loflin and Earleywine 2014). Users of cannabis typically report more intense intoxication and more negative effects from dabbing e.g. with use of butane hash oil (BHO) (Chan et al. 2017). In a recent survey of college students, use of BHO was correlated with higher levels of self-reported physical dependence, even after extensive controls such as for cannabis use frequency and sociodemographic factors (Meier 2017).

Cannabis Policy Around the World

Policymakers have a wide range of options for cannabis policy regimes. In addition to the extreme positions of vigorous prohibition and laissez-faire legalization, there are a number of middle-ground supply options which have not yet been widely implemented, such as allowing adults to grow their own cannabis but prohibiting sale; a government-operated supply chain; and allowing production and distribution only to firms of a special class, e.g. communal

organizations, non-profit organizations, or for-benefit corporations (Caulkins et al. 2015). One example is provided by the Netherlands, where laws against the cultivation and wholesale distribution of cannabis are enforced, but there is a policy of non-enforcement for retail sales and possession in small quantities (Government of the Netherlands 2019).

Two major international agreements have set guidelines and constraints for national policy. The 1961 Single Convention on Narcotics has 186 signatory countries, each required to criminalize “cultivation, production, manufacture, extraction, preparation, possession, offering, offering for sale, distribution, purchase, sale, . . . importation and exportation of drugs” contrary to the provisions of the Convention (Single Convention on Narcotic Drugs 2019). Further, the Convention on Psychotropic Substances of 1971 requires parties to impose some restrictions on controlled substances, including policies “for the repression of acts contrary to laws or regulations” adopted pursuant to treaty obligations (United Nations 1971). The combined effect of these agreements amounts to an agreement to prohibit and adequately enforce against the non-medical and non-religious use of certain substances, including cannabis, cocaine, methamphetamine, and heroin.

Medical cannabis regimes are now present in over thirty countries across the world, with recent additions including Asian nations such as South Korea and Thailand (Shao 2019; Williams 2018). Regimes for medical cannabis are in theory allowed under these conventions (Faiola 2018), although there are strong arguments to be made that certain provisions of modern medical cannabis regimes are not compliant with the spirit of the Single Convention, including less stringent controls on how qualify for access to medical cannabis, the allowance of herbal preparations without accurate description of cannabinoid content, and other permissive aspects of regulation (International Narcotics Control Board 2019).

As more nations legalize the production or use of medical cannabis, a nascent international trade has begun to develop. Medical cannabis regimes have positioned some countries as potential centers for research and export. For example, after legalizing medical cannabis in 2016 for domestic use and export, Colombia has become a significant exporter of medical cannabis, developing for export markets such as Germany, Peru, Italy, and Croatia (Faiola 2018). Similarly, Uruguay produced its first medical cannabis crop to export in 2017, separate of its recreational cannabis regime (Uruguay to produce medical marijuana for export 2017). Jamaica is another country that has developed a medical cannabis program with hope to develop an export industry, though the regulated regime there remains in its infancy, with just roughly thirty licenses approved to date (Subramaniam 2019).

Recently, Uruguay and then Canada became the first countries to legalize non-medical cannabis use, production, distribution, and sale. The International Narcotics Control Board cautions that the legalization of the use and supply of cannabis for non-medical purposes may undermine the international legal drug control framework and respect for the rules-based international order, and has written that legalization and regulation of cannabis by Canada for non-medical purposes “cannot be reconciled with the country’s international obligations as a State Party to the drug control conventions” (International Narcotics Control Board 2018).

Canada’s approach to legalizing adult use cannabis works primarily by licensing commercial firms for production and manufacturing, but with substantial local flexibility. Areas

of control are split such that the federal government may establish requirements for cannabis producers and manufacturers, along with industry-wide rules governing the type of products available for sale, traceability systems, marketing, and other aspects of health and safety regulation; while allowing provinces and territories the responsibility to determine additional rules, including those for distribution and sale (Government of Canada. Department of Justice 2019). Each Canadian jurisdiction has chosen to operate either a government-run retail model, a privately-run model, or both. Seven regions currently operate under private and hybrid retail models, accounting for 72% of the Canadian population (Statistics Canada 2019). Local governments are also allowed discretion over brick-and-mortar versus online sales, though in practice most that have allowed online sales have restricted them to government-run retailers, and the vast majority (recently 95%) of legal sales occur at brick-and-mortar retailers (Statistics Canada 2019).

Uruguay's approach to legalization combines commercial licensing with other forms of supply. The regulating agency, Instituto de Regulación y Control del Cannabis (IRCCA), maintains control over more aspects of the marketplace than any comparable agency in Canada or the U.S. Citizens aged 18 and older are allowed to register for one of three modes of access: personal cultivation, membership in a not-for-profit growers' collective, or purchase from a licensed pharmacy. Pharmacies are supplied by licensed commercial firms, but subject to price controls and THC limits set by the IRCCA. Users are limited to purchasing only ten grams weekly, and sales are limited to flower; no edibles or concentrates have been allowed (Cerdá and Kilmer 2017; Maybin 2019). According to a recent IRCCA report, nearly 50,000 Uruguayans had registered to obtain cannabis legally (1.4% of the population) – compared to roughly 200,000 Uruguayans between 15 and 65 years old who report past-month cannabis use in a recent national survey (Nacional de Drogas 2019). Nearly four-in-five Uruguayans who used non-medical cannabis in the past year continued to rely upon only illegal sources (Institute for Regulation and Control of Cannabis (IRCCA) 2019b). While the system in Uruguay allows for three modes of cannabis access (self-cultivation, co-op memberships, and pharmacy purchase), nearly two-thirds of registrations have been for pharmacy purchase (Institute of Regulation and Control of Cannabis (IRCCA) 2020).

In the United States, cannabis remains federally prohibited, classified as a Schedule I substance under the Controlled Substances Act (Controlled Substances Act 1971). Yet, the possession, distribution, and use of cannabis for non-medical purposes for adults is now available in ten U.S. states and Washington DC (except that Washington DC has in place a de facto prohibition on non-medical sales). Additionally Vermont has allowed possession and limited cultivation but retains a prohibition on sale. Most of those jurisdictions have allowed some form of personal cannabis cultivation. Further, an additional twenty-two states and the District of Columbia have approved permissive medical cannabis programs, including many with permissive regulations known to raise concerns for the INCB (National Conference of State Legislatures 2019). Thus, the federal government's administrative-discretionary measures have allowed a growing sphere of grudging tolerance for the growth of commercialized recreational cannabis activity.

The widening discrepancy between federal and state cannabis policy in the United States has been termed the "marijuana policy gap" (Lampe and Attorney 2019). In the face of that contradiction, it remains a matter of legal controversy whether the U.S. is technically in breach

of its international obligations. The United States Supreme Court has held that these treaties are not self-executing, and therefore are not enforceable in the U.S. without accompanying domestic law (Lampe and Attorney 2019). Yet, certainly this position makes the U.S. “vulnerable to censure from members of the international community” (Blumenfeld 2019). Ultimately, it is the responsibility of the International Narcotics Control Board to evaluate whether the U.S. or other countries with non-medical cannabis policies are in compliance with obligations, and that body has yet to issue a direct condemnation aimed at the U.S. government.

U.S. Federal Policy

The environment for federal policymaking is shaped on a fundamental level by national sentiments. Across the United States, public approval for cannabis legalization has continued to rise. A 2019 Gallup poll showed record-high 67% approval for legalizing cannabis use – more than double the 31% recorded in 2000 – and 91% reported support for at least one of medical or adult use cannabis (Daniller 2019). Decomposed by generation, the “silent generation” continues to hold out against legal cannabis (35% approval), despite roughly two-thirds or higher support among baby boomers (63%), generation X (65%), and millennials (76%). Across partisan divides, legalization was favored by a slim majority for respondents identifying as republican or leaning republican (55%), and nearly four-fifths among (leaning) Democrats (78%). It would be interesting to know public sentiment comparing various versions of legal cannabis regimes, but unfortunately national polls rarely provide such options, e.g. allowing licensed for-profit sales versus legalization without commerce.

Federal enforcement policy has evolved gradually over time, across several influential memos from the U.S. Department of Justice. In reaction to the growing scale of state-legal medical cannabis businesses, in 2009 the Ogden Memo announced that businesses in compliance with state law and uninvolved in broader criminal activity would not be prioritized as targets for law enforcement (United States Department of Justice 2009). This did not relieve state-legal businesses of all enforcement activities, nor did it end Federal actions against state-legal cannabis businesses. After the onset of recreational cannabis laws in Washington and Colorado, in August 2013, the Cole memo (United States Department of Justice 2013) established an eight-point set of priority areas that would justify Federal intervention into state-legal medical or recreational cannabis markets, including sales to youth, involvement of criminal drug trafficking organizations or gangs, and trafficking across inter-state lines. A 2018 memo by then-Attorney General Jeff Sessions rescinded the 2013 Cole memo, allowing Federal prosecutors discretion of how to prioritize enforcement of federal cannabis laws (United States Department of Justice 2018).¹ However, even after rescinding the memo, analysis of Department of Justice press releases suggests that prosecutors are generally following Obama-era guidelines; almost all Federal prosecutions involving cannabis involved one of the Cole Memorandum priorities, and those that did not occurred in states with restrictive or absent medical cannabis laws (Firestone 2020).

¹ The memo instructs US Attorneys to “weigh all relevant considerations, including federal law enforcement priorities set by the Attorney General, the seriousness of the crime, the deterrent effect of criminal prosecution, and the cumulative impact of particular crimes on the community.”

The Rohrabacher-Farr amendment is a budget rider that has prevented federal funds from being used to prevent implementation of state medical cannabis laws since being added to the 2014 budget (Kopp 2020). President Trump has expressed inconsistent sentiment about whether he would remove the rider, but whatever is his intent relating to the budget rider, the cooperation of Congress will also be required.

As circumstances and incentives change, notable high-level policymakers have called for a Federal response, including from voices on both sides of the aisle. Former House majority leader John Boehner reversed a long-held opposition to cannabis legalization, calling for Federal recognition of state legalization and re-scheduling (Raymond 2018; Wise 2018), though only after accepting a seat on the board of Acreage Holdings, a cannabis investment firm. Boehner's compensation package as boardmember entitles him as much as \$20 million (Williamson 2019). Attorney General Barr stated that he would prefer to see a uniform Federal policy on cannabis rather than the current approach (C. Hansen 2019).

The STATES Act was introduced in 2018 to the 115th Congress as a compromise bipartisan approach to reconciling the Federal-State conflicts that have enveloped United States cannabis policy (Warren 2018), but did not pass (GovTrack.us 2020c). Under the STATES Act, cannabis would have remained Federally prohibited as a Schedule I substance, but Federal laws would not be enforced against individuals acting in compliance with state cannabis laws. The 116th Congress has seen another attempt, the Marijuana Justice Act, which proposes a more expansive approach to legalizing cannabis (Booker 2019; GovTrack.us 2020a). The bill would legalize cannabis, expunge criminal records, and create a reinvestment fund to aid communities hurt by the "war on drugs". Another bill that appears stalled in the 116th Congress -- the Marijuana Opportunity, Reinvestment, and Expungement (MORE) Act -- aims for Federal decriminalization and a generally more permissive approach -- removing cannabis from the Controlled Substances Act, allowing federal agencies like the Small Business Administration to provide assistance to state-legal cannabis businesses, and incentivizing states to expunge certain cannabis offenses (GovTrack.us 2020b).

Another issue related to cannabis is the treatment of hemp, defined as a cannabis plant containing less than 0.3% THC. Hemp is commonly produced for seed and fiber used mainly for industrial purposes, including some emerging technologies the utility of which has yet to be fully fleshed out (e.g. "hempcrete"). Hemp is also the primary crop for producing cannabidiol, commonly known as CBD (Congressional Research Service 2019). CBD has been marketed to treat a wide range of symptoms, including pain, anxiety, insomnia, depression, low libido, skincare issues, and even diabetes and multiple sclerosis. However, thus far only one CBD-based drug has met the standards for FDA approval: Epidiolex, which has been found to reduce seizures for rare types of child epilepsy. CBD research is at a very early stage. While some popularly purported claims are clearly false, there remains a wide range of potential health benefits for which there is not yet sufficient research (National Academy of Sciences 2017; Rabin 2019).

U.S. State Policy

In recent years in the United States, cannabis policy change has generally been driven by the states. Roughly two-thirds of Americans now live in states with either legal adult use

cannabis (28%, 93 million) or permissive medical cannabis regimes (30%, 99 million), which generally operate dispensaries and allow the sale of high-THC cannabis.

One historical narrative for the spread of liberal state-level cannabis policies in the United States is of a gradual progression from efforts to remove or reduce criminal penalties associated with cannabis possession, to the granting of privileges for a narrow category of medical patients, to a widening of the eligible patient pool and/or expansion of caregiver supply programs, the ensuing fostering of a commercial industry (sometimes unregulated or quasi-legal) involved in producing and selling medical cannabis, and finally, the consideration of adult use cannabis policies.

Decriminalization and depenalization laws passed in about a dozen states beginning in the 1970s, lowering or eliminating fines or criminal penalties associated with possession and/or distribution of small quantities of cannabis (R. J. MacCoun and Reuter 2004)². Later, beginning with California's Proposition 215 in 1996, a series of state-level medical marijuana laws established means for individuals to qualify for the medical use of cannabis, and thereby to obtain protections for them to possess, use, and sometimes grow cannabis (National Conference of State Legislatures 2019). Further, all of the newly-legal adult use states have passed through permissive medical cannabis programs -- generally leading to the some form of merging or reconciliation of parallel programs for cannabis supply.

Washington State and Colorado were the first jurisdictions to legalize the production, distribution, and sale of recreational cannabis, both with voter-approved ballot initiatives in November 2012, and with the first licensed recreational stores opening in 2014. This initiated a series of successful legalization initiatives at the ballot, namely: Alaska, Oregon, and Washington DC in 2014; California, Maine, Massachusetts, and Nevada in 2016; and Michigan in 2018. Adult use stores are operating in each of those states except Washington DC and Maine, where the Office of Marijuana Policy anticipates a summer-2020 opening (Neavling 2019; Putka 2020).

Notably, adult use cannabis legalization has received consideration by an increasing number of state governors and legislatures. Throughout 2018, twenty-one states considered bills that would legalize adult-use cannabis. (National Conference of State Legislatures 2018). Vermont became the first state to legalize non-medical cannabis through the legislature, followed by Illinois in 2019 (McCullum 2018). Illinois adult use stores opened in January 2020 (Marotti, Petrella, and Munks 2019). Vermont is now considering a bill that would set a July 2021 licensing target (A. Martin 2020a). A Virginia legislature committee is studying plans for adult use cannabis legalization, scheduled to report findings by November 2021 (A. Martin 2020b). Rhode Island's governor has attempted to introduce a policy to introduce state-owned distribution of adult use cannabis, with the state taking a much larger cut of revenue (60%) than if feasible in a taxed licensed system, though the plan has been met with substantial resistance in the legislature (Borden 2020).

² Depenalization refers to the reduction of sanctions associated with a crime; decriminalization advances one step further, e.g. lessening cannabis possession from a criminal offense to a civil offense.

Several states appear likely to feature adult use cannabis initiatives on November 2020 ballot, e.g. New Jersey and Arizona. Two months before this writing, the list was longer, but many ballot efforts have been stalled by the coronavirus epidemic, to the obvious frustration of legalization advocates (Zhang 2020). Arizona provides an interesting case study. There the bill has been backed by the state’s medical cannabis industry, and is set to grandfather existing medical licensees into the new adult use system (Penny 2020). The campaign has received over \$1.5 million in funds from the existing medical cannabis industry (Arizona 2019).

Medical cannabis policies also remain an active political frontier, though there is great variation in state-level details. The medical cannabis laws in some states allow broad access to medical cannabis. Less restrictive medical cannabis regimes are generally characterized by three policies: 1) allowing individuals to qualify for medical use based on a long list of qualifying symptoms including some that are widespread and difficult to objectively diagnose such as chronic pain and insomnia, 2) the establishment of dispensaries where patients may purchase medical cannabis, and 3) the allowance of a wide range of product types, rather than only allowing non-smokable products.

The remaining one-third of Americans generally lack state-legal means to obtain high-THC cannabis, concentrated primarily in the U.S. South, great plains, and lower Appalachia. As of 2019, only four states had no allowance for public access to cannabis whatsoever: Kansas, Nebraska, South Dakota, and Idaho (National Conference of State Legislatures 2019). Though the first generation of liberalizing medical cannabis policies appeared largely in politically liberal states, the newest wave of medical cannabis states are emerging from more conservative parts of the nation, such as Missouri, Oklahoma, Utah, and West Virginia (Table ii).

Table ii. State-level cannabis policies, by population and geographic concentration (2019)

Policy	States	Population, Millions (2019)	Population Share %
Legal Adult Use, and Regulated Medical	11	93.1	28%
Comprehensive Medical	22	128.3	39%
CBD/Low THC Program	13	99.3	30%
No Public Access Program	4	7.5	2%

Chapter One. Evolution of the United States Marijuana Market in the Decade of Liberalization Before Full Legalization³

Steven S. Davenport

Pardee RAND Graduate School, Santa Monica, CA

Jonathan P. Caulkins

Carnegie Mellon University, Pittsburgh, PA, USA

Abstract

The past decade has seen a remarkable liberalization of marijuana policies in many parts of the United States. We analyze data from the National Survey on Drug Use and Health (NSDUH) for coinciding changes in the marijuana market from 2002 to 2013, including market size, number and demographics of customers, and varying means of acquiring the drug. Results suggests that (a) the national market has grown, especially in terms of the number of daily users; (b) marijuana users remained economically “downscale” over this period, and in many ways resemble cigarette users; (c) distribution networks appear to be professionalizing in a sense, as fewer users obtain marijuana socially; (d) the typical purchase has gotten smaller by weight but not price paid, suggestive of a trend toward higher potencies; (e) marijuana expenditures vary by user group; and (f) respondents with medical marijuana recommendations differ from other users in systematic ways.

³ This study was published in the Journal of Drug Issues 46(4), August 2016, doi: 10.1177/0022042616659759. This work was carried out largely under Dr. Caulkins’ supervision, some of which while enrolled at Carnegie Mellon’s MSPPM program (though the article was submitted to journals during my first year attending Pardee RAND). The paper was partially supported by funding by GiveWell via BOTEC Analysis.

Introduction

Four states have now legalized commercial production and distribution of marijuana for non-medical use.⁴ About two dozen have legalized marijuana for medical purposes, most now with dispensaries although the particulars vary by state (Pacula and Sevigny 2014). A constitutional amendment (“Issue 3”) that would have legalized an oligopoly for commercial marijuana was defeated in Ohio in November 2015, receiving only 36% of the vote (Ohio Secretary of State 2015). As of March 2016, the Vermont Senate is considering a bill that would enact commercial legalization there by 2018. More states will consider marijuana legalization in 2016 and beyond (Caulkins, Kilmer, and Kleiman 2016; Malone 2016).

When considering alternatives to current policy, one would do well to investigate how key outcomes have been changing in the recent past, as we do here using household survey data from 2002 to 2013. This period saw extensive liberalization in many parts of the United States, leading up to but not including full-scale commercial legalization.

Although the first state medical marijuana (MMJ) law dates to 1996 (in California), the proliferation of brick and mortar dispensaries, formalization of regulatory approval, and spread to other states mostly happened after the turn of the century. Likewise, even though voters in Colorado and Washington approved legalization in the 2012 elections, and individual rights to possess—and in Colorado to grow—took effect shortly thereafter, it took time to set up the regulatory structure for commercial operations; the first stores did not open until in 2014. And Alaska and Oregon did not pass their laws until 2014, alongside Washington, D.C.’s more limited legalization of possession and home growing.

The legalization debate is complex, encompassing not only harms of (heavy) use (Hall 2015; Hall and Degenhardt 2009; Volkow et al. 2014) but also harms generated by the illicit markets and related law enforcement (Kleiman 1992).

Aspects of changing use are well-documented (Burns et al. 2013). The past few decades feature an increasing prevalence and intensity of marijuana use, especially among daily or near-daily (DND) users, who we show have increased sevenfold since 1992 and now account for upward of 75% of reported spending. The demographic profile of users is also changing. Burns et al. (2013) note that in 2002, there were three youthful DND users (17 and under) for every DND user who was 50 or older. By 2013, that ratio had inverted, becoming 1:2.5 (Burns et al. 2013).

Although we analyze some trends in marijuana demand, our primary contribution concerns changes in how users report obtaining marijuana. Historically, ethnographic studies suggested that marijuana markets differ from those for heroin, crack, and cocaine (Curtis and Wendel 2000; Johnson, Golub, and Fagan 1995). Marijuana sellers are more likely to operate independently (outside of organized operation), sell indoors, and sell to people within their social circles, rather than through arm’s length transactions (Office of National Drug Control Policy 2002, 2004).

⁴ As of the date of publication in August 2016.

In 2001, the national household survey added questions asking respondents how they had most recently acquired marijuana. Analysis of that first year of data supported the findings from ethnographic studies: Caulkins and Pacula (Caulkins and Pacula 2006) reported that most respondents obtained marijuana indoors (87%), from a friend or relative (89%), and for free (58%).

Data from subsequent years of this market module have been understudied relative to the use module, despite many reasons to suspect changes in market behavior, including the following:

- By 2014, more than half of Americans (51%) approved of marijuana legalization, twice as many as in 1995 (25%) (Lidya 2014).
- The average potency of marijuana used in the United States increased (Mehmedic et al. 2010) from 5.2% in 2000 to 8.1% in 2010 (Kilmer et al. 2014), partly due to domestic production taking market share away from imports; meanwhile, while simple prices-per-gram appear to have increased, potency-adjusted prices may nonetheless be flat or falling.
- MMJ laws, and especially legally protected dispensaries, which are thought to contribute both to greater potency (Sevigny, Pacula, and Heaton 2014) and lower prices (Mark Anderson, Hansen, and Rees 2013) having proliferated across states.

This article explores changing patterns of marijuana use and access, including (a) aggregate volumes of marijuana use and access activity, (b) the intensity of use habits, (c) demographics of marijuana users relative to cigarette users or to the nation as a whole, (d) the financial burden of marijuana use borne on users, (e) popular modes of access and characteristics of purchases, and (f) the increasing use of MMJ recommendations.

Data

The National Survey on Drug Use and Health (NSDUH) is a nationally representative survey of individuals 12 years and older conducted annually since 2002, when it replaced the National Household Survey on Drug Abuse (NHSDA). In 2001, NHSDA added a Marijuana Purchases module that asked how respondents had most recently acquired marijuana. NSDUH retained the purchases module with no changes to question wording or sequencing within the module, but changes to sampling methodology complicate comparisons between 2001 NHSDA data and later NSDUH data, so this article focuses on the data collected from 2002 to 2013.

NSDUH has limitations. All answers are self-reports, and so may be dishonest or misremembered (Harrison et al. 2007), and NSDUH's sampling frame excludes those who are in the military, incarcerated, or homeless outside of shelters. However, these concerns are smaller for marijuana than they are for other illicit drugs (Harrison 1995; Kilmer et al. 2014; Wright, Gfroerer, and Epstein 1997). The NSDUH survey covers a broad range of aspects of marijuana use and access activity, as described below.

Recency and Intensity of Use

The survey's core component asks how often respondents have used marijuana or hashish in the past month. The answers, after Substance Abuse and Mental Health Services Administration (SAMHSA) statisticians impute for missing values, are recorded in the variable IRMJFM. Following Kilmer et al. (2014), we classify respondents according to the recency of and frequency of their use: "Past-Year" (PY) are those who report using in the past year; "Past-Month" (PM) users report at least one day of use within the past 30 days, including "Daily" users who report using all 30 out of the past 30 days; and "Near-daily" users who report 21 to 29 days of use. We sometimes group Daily users and Near-daily users together (DND), and sometimes treat these groups exclusively, for instance, so as to compare PY-not-PM users against PM users.

Method of Acquisition

The Marijuana Purchases module asks PY users about their *Most Recent Acquisition* (MRA): "Now think about the last time you used marijuana. How did you get this marijuana?" Responses are (a) "You bought it"; (b) "You traded something else for it"; (c) "You got it for free or shared someone else's"; and (d) "You grew it yourself." (Very few respondents report trading, and so we do not analyze them.) Because the module focuses on purchases, all respondents are asked whether they bought marijuana within the past year, even if they recently acquired via some other method—and if so, they are further asked whether their *Most Recent Purchase* (MRP) occurred within the past 30 days. For this article, any user reporting an MRP within the past 30 days is considered a "PM buyer."

Characteristics of Most Recent Acquisitions

PM users are asked details about their MRA, including where it took place, their relationship with the supplier, and whether the user later gave away or sold any portion of that acquisition. Questions are specific to their mode of access. For example, the variables MMBPLACE versus MMFPLACE versus MMTPLACE record where the person most recently *Bought*, obtained for *Free*, or *Traded* to obtain marijuana, respectively. Most users answer only one question track, but users who bought in the past month but accessed their MRA by some other method will answer both.

Weight and Price of MRPs

PM buyers who report purchasing "loose" marijuana are asked about the weight and price of those purchases. (Respondents may instead report buying in "joint" form instead; because few answer this way, our analysis omits those answers.) For weight, users are asked if they would like to report the weight in grams, ounces, or pounds (MMLSUNIT). They then report weight in those units by selecting among ranges—except for "gram" purchases exceeding 10 grams and any purchase reported in pounds, which are solicited as write-in integer values. For amount spent, answers are categorical, ranging from "Less than US\$5," to "US\$5.00 to US\$10.99," "US\$11.00 to US\$20.99," "US\$21.00 to US\$30.99," and so on, up to "more than US\$1,000." To reduce volatility, we often pool adjacent years' responses.

For the analysis herein, these ranges are converted to numerical point estimates by way of the midpoint of each range (with the answer "more than US\$1,000" replaced with US\$2,000). The true distributions of prices paid within these buckets are unknown, despite some evidence

that purchases will cluster near round numbers at the top of many of those buckets (e.g., US\$10, US\$20).

We can test the sensitivity to this parameter by computing estimated spending using the range's maximum rather than its midpoint. For instance, for 2013, we estimate US\$29B in annual marijuana expenditures when using range midpoints but US\$34B when using range maximum; pooling years 2011-2013, midpoints yield US\$104B, compared with US\$124B using range maximums (in both cases, we exclude all purchases that were resold or were over 5 ounces, as in the "Growth in the Marijuana Market" Section).

We further test this with an analysis of data from seizures of marijuana, cocaine, and heroin (to expand sample size) using the DEA STRIDE dataset for years 1988 to 2012. Seizures are surely not perfectly representative of non-seized purchases, but are useful for point of comparison given data limitations. For all price categories, the average of reported seizure prices was higher than the range's midpoint, although usually by less than 10% and frequently by less than 5%. For seizures between US\$5 and US\$10.99, the average price was US\$9.84 compared with a midpoint of US\$8 (23% higher); between US\$11 and US\$20.99, the average price was US\$19.75 versus a midpoint of US\$16 (24% higher).⁵ Therefore, using the midpoint estimates of ranges appears to introduce a downward bias, which could theoretically range as high as 20%, but which seizure data suggests is closer to 10%.

Volume of All Past-Month Purchases and Expenditures

PM buyers are asked on how many days out of the past 30 that they bought marijuana (MMBT30DY). We estimate monthly spending by multiplying purchase frequency by the weight or value of the MRP. MRPs may be atypical for various reasons (Kilmer et al. 2014), although recent evidence from other surveys that ask about multiple purchases suggests that MRPs are typical of other recent purchases (Bond et al. 2014). Similarly, answers about other characteristics of the recent purchase (e.g., location, dealer relationship) are weighted by the frequency of PM purchases to estimate distributions of all PM purchases (not just the MRPs; (Burns et al. 2013).

Redistribution of MRAs

Some respondents are not just consumers but also suppliers, whether as dealers or simply as "social sources" for friends. This complicates efforts to estimate total market size. Adding up the monthly purchase amounts for all users would double-count amounts respondents sell or give to others. Following Caulkins and Pacula (2006), we try to minimize double-counting by omitting purchases that appear likely to be intended for resale. Therefore, users who reported selling a portion of their MRA (variable MMBSELL) are excluded when we are computing market size, as are purchases over one pound (as respondents may be reluctant to admit supplying marijuana and so lie on the MMBSELL question).

⁵ Authors' calculations.

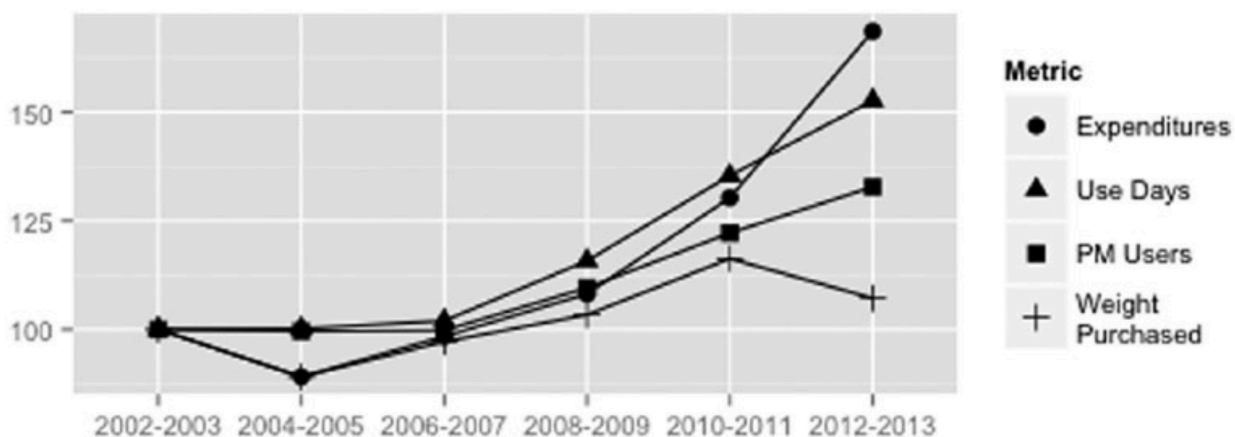
Results

Growth in the Marijuana Market

The marijuana market clearly grew between 2002 and 2013, but the extent of growth depends on the measure of market size. Because we are primarily concerned about intoxication, ideally one might wish to track that directly, for example, with hours of intoxication or the amount of THC (Tetrahydrocannabinol) consumed. Unfortunately NSDUH does not ask users about potency or the number of use sessions per day. However, instead we can track the number of “days of use” reported in the past month, which, though it is an imperfect proxy for THC consumption, at least captures changes in both prevalence and frequency of use (Kilmer et al. 2013; Zeisser et al. 2012). That measure is complemented by three traditional measures—the number of PM users, weight in metric tons (MT), and user expenditures—which, though they are relatively easy to measure and of intuitive meaning, are poor correlates with THC consumption: PM prevalence overlooks changing intensities of use; increasing potency means a gram now contains more THC than in the past; and changes in price can make spending trends depart from trends in use.

Figure 1.1 shows market growth by these four metrics, each indexed to 100, their average value across 2002 and 2003. It can be seen that all metrics have increased, but interpreting those growth rates is subject to some caveats. Some of the increase stems from population growth; the population of age 12 and above increased by 12% over this period. Furthermore, some could be artificial if under-reporting has fallen with increasing public approval, although Cuellar, Caulkins, Haviland, and Seltman (2015) casts doubt on whether that is significant for the household survey data over this period. The absolute values—but not the trends—in weight and spending are sensitive to the cutoff used to exclude purchases as likely being for resale. The ranges of estimates for 2012-2013 obtained when varying that cutoff from 1 ounce up to 5 ounces are 3,900 to 6,200 MT and US\$32 to US\$37 billion. The former is similar to the 4,200 to 8,400 MT range Kilmer et al. (2014) estimated for 2010 in the most recent study in the What America’s Users Spend on Illegal Drugs series, although the current spending estimate is at the lower end of their US\$30 to US\$60 billion range.

Figure 1.1. Market growth (2002-2013, by year pair) in constant 2013 dollars, excluding purchases resold or above 5 ounces.



Note. PM = past-month.

Nonetheless, comparing the relative rates of growth identifies two dominant trends that drive many of our findings: increases (a) in prices and potency per gram and (b) in intensity of use by PM users. Taking the ratio of weight to PM use days suggests that the average number of grams consumed per use-day fell by 39% from 1.14 grams-per-use-day in 2002-2003 to 0.69 in 2012-2013; if we were to assume (perhaps dubiously) that THC-per-use-day remained constant, that would signal a 65% increase in potency—a number not far from the 55% increase in potency (5.2%-8.1%) suggested by other sources (Kilmer et al. 2014; Mehmedic et al. 2010). Similarly, though this method is admittedly imprecise, an increasing in prices per gram can be inferred by taking the ratio of growth in marijuana expenditures to that in weight purchased, and changes in intensity of use by taking the ratio of PM use days to PM users.

DND users have always accounted for a disproportionate share of consumption, but whereas in the early 1990s, only one in nine PM users reported using DND, now it is fully one in three. Their share of the market, regardless of the choice of metrics, has grown steadily over the study period. Table 1.1 reports those shares at the beginning and end of the period, pooling together years to improve precision.

Table 1.1. Past-Month Market Share by Use Frequency

Type	2002-2003				2012-2013			
	Users	Use Days	Grams bought	Dollars spent	Users	Use Days	Grams bought	Dollars spent
Daily	13.4%	32.5%	43.5%	42.0%	20.7%	43.4%	55.7%	40.4%
Near-Daily	12.9%	26.9%	25.3%	24.8%	13.7%	24.9%	21.3%	19.2%
Other PM	73.7%	40.6%	31.1%	33.2%	65.7%	31.7%	23.0%	40.4%

Note. PM = past-month.

Customer Demographics

Although the total amount of marijuana use and market activity has increased, that does not alone reveal trends or rates within certain demographics. To investigate, following Burns et al. (2013), we weight respondents' answers by the amounts they consume or spend. This provides a picture of the typical customer rather than a typical user; that is, these descriptions answer the question "If one could sample purchases or episodes of use randomly, what would the user look like?" rather than having all people who used any at all, however much or little, be equally likely to be sampled.

This distinction is perhaps best illustrated by example. Responses to the 2013 NSDUH indicate that 10 million people reported making a total of 64 million purchases in the past month. Within that total, there were 1.3 million college graduates who reported 4.7 million purchases. As our goal is to understand markets, we are more interested in the fact that college graduates made 7% of the purchases (4.7 million out of 64 million) than that 13% of people who made a purchase had a college degree (1.3 million out of 10 million). From the dealers' perspective, the probability that the customer has a college degree is 7%, not 13%.

Table 1.2 tracks changes in the level of education and household income of marijuana customers between 2002-2003 and 2012-2013, with reference to secular trends for the nation at large. Secular trends make these comparisons difficult: For instance, although the portion of PM users who graduated college increased by 4 percentage points during our study period (from 15% to 19%), that merely reflected the nationwide trend (from 23% to 27%). To account for nationwide trends, the three right-most columns (a) subtract the 2002/2003 PM user shares from the comparable 2012/2013 user share and, from that, (b) subtract away the change in population shares for the United States as a whole. Therefore, they roughly indicate whether that group's activity has increased after adjusting for changing demographics. This reveals that PM marijuana users have fallen further behind national trends with regard to household income and, to a lesser extent, educational outcomes. Notably, the portion of PM users with household incomes below US\$20,000 increased by 4 percentage points in excess of nationwide trends.⁶ With regard to educational attainment, perhaps most obvious is the major decrease in PM use among 12- to 17-year-olds; nonetheless, looking only at adults, the distribution of levels of educational attainment has shifted downward.

Table 1.2. Income and Education of Past-Month Users Versus U.S. Population.

2012-2013				Difference 2012/3 - 2002/3	Percentage Point Change Since 2002-2003, Adjusted for U.S. Trend		
US Pop.	MJ Users	MJ Use Days	No. of Buys	U.S. pop.	Users	Use Days	No. of Buys

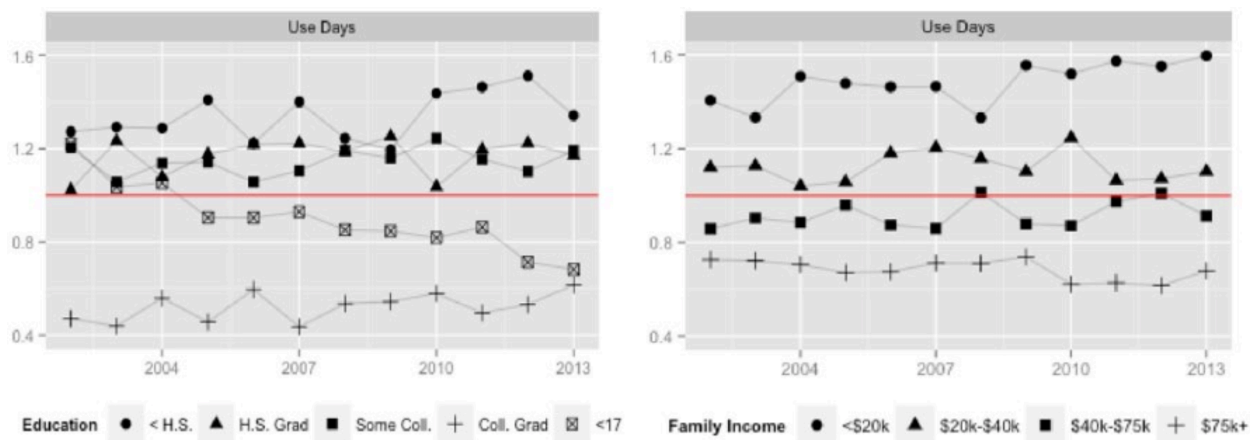
⁶ US\$20,000 approximates the Federal Poverty Line for a three-person family in 2013 (US\$19,530); US\$75,000 approximates the 400% line (US\$78,120).

% Accruing to Income								
Group								
< US \$20k	19%	28%	29%	33%	-1	+4	+4	+6
\$20k - \$39.9k	21%	23%	23%	24%	-4	0	-1	-2
\$40k - \$74.9k	27%	25%	26%	25%	-3	0	+2	+2
\$75k+	33%	25%	21%	19%	+8	-3	-5	-5
% Accruing to Education								
Group								
12 to 17 year olds	10%	9%	7%	10%	-1	-3	-4	-6
Less than HS	13%	16%	18%	24%	-3	+2	+1	+3
HS Graduate	27%	29%	32%	34%	-2	+2	+2	+1
Some College	24%	27%	28%	25%	+2	-1	+1	+3
College graduate	27%	19%	15%	7%	+4	0	0	0

Note. PM = past-month; MJ = Marijuana; HS = high school.

Figure 1.2 examines the same dynamic visually. For any given group (e.g., college grads), we divide the group's share of use days by its share of the national population. For example, as those with incomes below US\$20,000 accounted for 29% of use days but just 19% of the population, their ratio is $0.29 / 0.19 = 1.53$, indicating that they consume 53% more than their numbers would have suggested. We observe that less educated and poorer users consume marijuana at disproportionately high rates, and at roughly constant rates over our study period. (Also evident is the substantial decrease in use days per user under 17 years old.) The parallel figure for number of purchases (not shown) looks similar but more severe, with less advantaged groups even more over-represented with purchasing.

Figure 1.2. Ratios of per capita use days to analogous U.S. population share, 2002-2013.



Note. HS = high school.

Another method by which we may analyze demographic patterns is to take the share of aggregate activity accounted for by a given group. Table 1.3 does this; additionally, it compares the education and income groups' share of marijuana consumption with their corresponding

shares for cigarettes and alcohol use. Marijuana use, like that of cigarettes, is concentrated in lower socio-economic strata, whereas alcohol is a relatively upscale drug. In all, 17% of marijuana use days involved adults with a college degree, slightly more than cigarettes (13%) but much less than alcohol (40%). Likewise, 42.5% of alcohol use days were by users with incomes exceeding US\$75,000, compared with only one fifth of marijuana or cigarette use days. Given the similarities between users of cigarettes and marijuana, one might wonder to what extent these user bases draw from the same population. Pooling years 2012 and 2013, we find that fully half (49%) of DND marijuana users had also reported using cigarettes on more than 20 of the past 30 days, compared with only 13% of respondents without PM marijuana use. On the contrary, only 9% of DND cigarette users reported DND marijuana use; still, that is eight times higher than among those who do not report any PM cigarette use at all.

Table 1.3. Distribution of Days of Use for Alcohol, Marijuana, and Cigarettes, by Household Income and, for Users Over 17, Education (2012-2013).

	Less than HS	HS Graduate	Some College	College Graduate	< US \$20k	< US \$40k	< US \$75k	>= US \$75k
Alcohol	8%	25%	27%	40%	13%	17%	28%	42%
Marijuana	19%	34%	30%	17%	29%	23%	26%	21%
Cigarettes	20%	38%	29%	13%	27%	26%	27%	20%

Note. HS = high school.

The Financial Burden of Marijuana Spending

Most marijuana is consumed by DND users who are not particularly affluent, for whom marijuana purchases absorb an important share of disposable income. Of course the financial burden of marijuana use is still much, much less onerous than would be a daily heroin habit for a stereotypical unemployed street user (Johnson and Golub 1998), but the financial burden of marijuana spending may nonetheless be significant.

One can estimate spending per year by multiplying spending per purchase by purchases per month, and then also multiplying by 12 to approximate annual spending. Furthermore, dividing that figure by respondents' reported household income (taking the midpoint of the range) yields the portion of household income spent on marijuana. The trends over this period are flat, but variations across types of users at any given point in time are interesting.

One finding is that a heavy marijuana user spends roughly the same amount of money on that habit as a pack-a-day smoker spends on cigarettes. Excluding those who resold some of their purchase (i.e., potential dealers), the median PM user self-reports spending US\$1,250 on marijuana per year; for the median DND user, the figure is US\$2,200—very close to the US\$2,274 a pack-a-day smoker paying the national average price of US\$6.23 per pack would pay over the course of a year (Campaign for Tobacco-Free Kids 2015). For DND users, that distribution is skewed right and roughly log-normal, such that the median is close to twice of the first quartile (US\$958) and half of the third quartile (US\$4,031).

As a percentage of income, marijuana spending appears fairly manageable for the most users, but for some, it can be overwhelming. We calculate financial burden by dividing annual marijuana spending by reported household income (again, taking the midpoint of the range, and excluding users who resold or whose MRP was over 5 ounces). Half of use days are accrued by users spending at least 5% of income on marijuana; 30% to users spending at least one tenth; and 15% to users who spend fully one quarter of their income. Marijuana spending is especially burdensome for more frequent users with lower incomes: DND users over 21 years old without college degrees spend on average nearly 9% of household income (Table 1.4). That impact is perhaps underappreciated by Americans who are better-educated and keep non-problematic marijuana habits: as a portion of income, college graduates without signs of abuse or dependence (ABOD) spend only one quarter of that amount.

Table 1.4. Portion of Income Spent on Marijuana by Demographic (2012-2013), Excluding Large (5-Ounce) and Resold Purchases.

Market Segment	No. of users in market segment (M)	Segment's share of use days	Total income of people in market segment (US\$B)	Total MJ spending by people in segment (US\$B)	% of income spent on MJ (ratio of preceding two columns)
Adult (21+), no college, DND	3.5	39%	147	13.8	9
Users under 21	2.9	17%	142	7.9	6
College grad, no ABOD	1.9	11%	124	2.2	2
All other PM	10.2	34%	475	12.9	3
Total	18.7	100%	894	43.3	4.0

Note. MJ = Marijuana; DND = daily or near-daily; ABOD = abuse or dependence; PM = past-month.

The facts that (a) most marijuana is consumed by people who admit spending upward of US\$2,000 per year on the drug and (b) marijuana use is concentrated among those with lower income and educational attainment may help explain why economists find that demand for marijuana is fairly responsive to changes in price (Gallet 2014; Pacula and Lundberg 2014).

Purchase Frequency, Size, and Price

Perhaps unsurprisingly given the increase in the size of the marijuana market, over our study period, the total number of reported marijuana purchases increased substantially (by 48%) to 752 million per year. Coupled with a 20% decline in marijuana arrests since 2002, this produces nearly a halving in the number of arrests per purchase, from one for every 550 marijuana purchases self-reported to the 2001 NHSDA (Caulkins and Pacula 2006) to one arrest for every 1,090 purchases in 2013.³ Not all arrests occur at the time of purchase, but if one conceives of a unit of marijuana use as the collection of activities beginning with purchase and continuing until that supply is exhausted, this decade saw a substantial reduction in arrest risk per unit of use.

Furthermore, not only did the total number of purchases increase, but so did the portion of PM users who acquired their MRA by purchasing, though not by as much (from 52% up to 57%). However, this trend is largely a consequence of increasing use intensity: holding use intensity constant, rates of purchase are largely unchanged. Table 1.5 compares rates for 2002-2003 against 2012-2013; each of those metrics has changed significantly from 2002-2003, with p values under .001.

Table 1.5. Methods of Most Recent Past-Month Acquisitions, 2002-2003 Versus 2012-2013

	By Buying	For Free	By Growing
2002-2003	51.6%	45.7%	1.0%
2012-2013	57.1%	38.4%	2.8%

Data about the characteristics of users' MRP yields more details about relevant trends. Many characteristics of those purchases remain unchanged. For instance, purchasing from a stranger remained relatively rare (only 12% of MRPs), as did purchasing outdoors (15%).

A second observation regard downstream behavior. Self-reports of selling or giving away acquired marijuana have decreased, even if we hold constant use frequency and/or whether the initial acquisition was bought or gotten for free. In 2002/2003, 7% of MRPs were later resold, and 61% later given away; in 2012/2013, comparable figures are 4.5% and 51%.

Third, the typical purchase has gotten lighter over time. The proportion of users who choose to report their purchase weight in grams rather than ounces increased (from 64% to 76%); among respondents who answer in grams, the proportion of respondents who described their MRP as being under 5 grams increased from one in three (32%) to nearly half (49%). However, as THC and price-per-gram was also increasing over this time period, it may not be accurate to say that purchases have gotten "smaller." Table 1.6 shows there was little change in the amount of money spent on MRPs even in nominal dollars, despite inflation over these 10 years totaling 27%.

Table 1.6. Distribution of Past-Month MRPs by Amount Spent, 2002-2003 Versus 2012-2013.

	Less than \$11	\$11 – \$20	\$21 - \$30	\$31 - \$50	\$51 - \$100	\$101 or more
2002-2003	17.8%	17.6%	15.4%	20.7%	15.2%	13.2%
2012-2013	20.1%	20.8%	11.0%	18.3%	16.2%	13.5%

Note. PM = past-month; MRP = most recent purchase.

So have MRPs gotten smaller? If we think of size as "weight," then purchase sizes have shrunk; if we think of size as "price," then any changes are modest. If we think of size as THC content, the data do not speak to the question directly: as THC-per-gram may have increased by something like 50%, one cannot rule out the possibility that the average amount of THC in the typical purchase might have increased.

Taken together, these changes suggest that the market was, to some extent and for lack of a better word, “professionalizing.” Previous analysis of NSDUH data and also ethnographic studies (e.g. Sifaneck et al. 2007) have characterized retail marijuana distribution as being embedded within existing social networks and is sometimes done at cost or as a favor, not just purely for profit. While these traits continue to characterize much of retail marijuana distribution, particularly that the sources were rarely strangers, there is a clear shift from gifting toward selling. In contrast, the markets for cocaine, heroin, and methamphetamine are thought to mostly be supplied by professionals, not in the sense of being licensed by the state, but rather that the dealers derive an important share of their total income from that selling. Although it would be an overstatement to closely compare the marijuana market with those other drugs, the recent observed trend has been in that direction.

Growing and MMJ

Table 1.5 showed that the proportion of PM users who reported getting their MRA “by growing” nearly tripled (to 2.8%) over the decade, albeit from very low initial levels, with most of the increase coming at the end of the period. Although all user types reported increased rates of growing their MRA, the increase is most severe among DND users; while in 2002, only 65,000 reported growing their MRA, by 2013, this increased sevenfold to 460,000. The increase appears closely linked to intensifying use: daily users report growing their MRA 5 times more often than do non-DND PM users.

Why did so many users begin to grow marijuana? Using an online survey promoted primarily via social media and advertising, Potter et al. (2016) surveyed 645 individuals in the United States who had claimed to have grown cannabis at least once. Most said they grew or started to grow because “it’s cheaper than buying” (90%) or “to provide myself with cannabis for medical reasons” (81%). Only one quarter (28%) started growing “so I can sell it”; yet in the past year, 38% reported selling some of their grown marijuana and most (69%) reported giving away or sharing. These rates seem broadly consistent with self-reported NSDUH growers’ (across 2002- 2013) proportions who reported selling (23%) or giving away (68%) some of their MRA, especially given the differences in question wording.

One might wonder how much of the cannabis market home growers could supply. Suppose we take the number of people who reported acquiring most recently from their own growing (roughly 750,000 in the 2013 NSDUH) as indicative of the number of home growers. (This is something of a leap. Some NSDUH respondents might lie about growing even if they report using marijuana; conversely, some survey respondents could be operating large-scale commercial grows. Others could have grown, but nonetheless obtained their MRA in some other way.) Nevertheless, if we multiply that number by the average size of a U.S. grow-operation in Potter et al.’s (2016) study⁷ (a median of 1.9 square meters of cultivation space, interquartile

⁷ Responses in National Survey on Drug Use and Health (NSDUH) suggest there were 752 million purchases per year in 2012-2013. Data from the Uniform Crime Reports (UCR) suggest that in 2013, there were 1.5 million arrests for drug abuse violations, 46% of which pertained to marijuana, for about 690,000 arrests for marijuana (Federal Bureau of Investigation, 2015). These estimates slightly underestimate the total number of marijuana arrests; according to the Hierarchy Rule, the UCR excludes arrests for marijuana in addition to offenses deemed more serious.

range [IQR] = 0.9-9.3), that works out to about 15 million square feet. By way of comparison, as of November 2014, Washington State had licensed over 3 million square feet of cultivation space and set a market-wide cap of 8.5 million, amounts intended to serve only residents of Washington, a state with just over 2% of the nation's population. This suggests that small-scale home growing might supply only a modest share of the nation's marijuana consumption, with the important provisos that people may well under-report the fact that they grow (to NSDUH) and/or the scale of their operations (to Potter et al.'s [2016] survey).

Perhaps the proliferation of MMJ laws, many of which allow patients or caregivers to grow marijuana, has contributed to this phenomenon. Unfortunately, it was not until 2013 that NSDUH began to collect data about medical use; though simple cross-tabs cannot prove causal relations, they suggest at least a strong association. The 2013 survey tagged respondents who lived in a "state where marijuana was approved for medical use before the interview" (variable MDMJST2). In that year, the vast majority of growers (85%) lived in MMJ states, and self-reported growing was much more common in MMJ states (7% of PM users) than in non-MMJ states (just 0.9%). The survey also asked (MEDMJYR), "Was any of your marijuana use in the past 12 months recommended by a doctor or other health care professional?" Those answering yes disproportionately grew their MRA, constituting nearly half (45%) of self-reported growers but only 12% of PM users nationwide.

Within MMJ states, users reporting a medical recommendation were generally older (49% vs. 36% over age 35), Whiter (74% vs. 65%), more frequently female (44% vs. 29%), and more likely to report being in poor health (25% vs. 10%). They disproportionately use on a daily basis (49% vs. 26%), report recently growing marijuana (7% vs. 2%), are less likely to give or share their MRA (35% vs. 56%), and spend more per year (US\$1,850 vs. US\$1,300).

Discussion

Our results herein are necessarily limited by the fact that NSDUH data are only available up to 2013—before any commercial marijuana stores had opened—and on the national level, with the exception of the flag for MMJ states in the 2013 survey. Therefore, our results can in no way be interpreted as evidence toward the successes or failures of marijuana legalization or even MMJ laws, where implemented.

Traditionally, research on marijuana markets has identified important differences relative to the markets for "harder" drugs such as heroin and cocaine. Marijuana distribution appears to primarily take place among known acquaintances rather than strangers, and often for free, indoors, and by freelance dealers independent of larger criminal organization. But, given the rapidly liberalizing popular attitudes and policies toward marijuana over the past decade, one might suspect marijuana use and markets to have changed in important ways. Twelve consecutive years of NSDUH data suggest that patterns of marijuana use and access *have* changed, but perhaps not as radically as one might have expected.

Key Findings

The key findings herein can be loosely grouped into trends regarding three areas: (a) aggregate market outcomes, (b) characteristics of access and distribution, and (c) user demographics. Taking the market as a whole, we find that market has continued to grow,

especially in terms of dollar expenditures, use days, and PM users, but less so in terms of weight; furthermore, the “typical” PM user consumes more frequently than before: a greater portion of PM users now report using at least 20 days per month (34%) than in 2002-2003 (11%).

The criminal risk per marijuana transaction has fallen by half, such that now there is only one marijuana arrest per every 1,100 transactions. Perhaps as a consequence, there are indications that the operations of marijuana access and distribution are, for lack of a better word, “professionalizing”: fewer PM users are reporting getting their MRA for free, and fewer report giving away or selling their MRA. Furthermore, among MRPs by PM users, the trend is toward lighter purchases by weight, though roughly the same by dollar price tag, yielding an ambiguous trend regarding total THC content (as discussed in section “Purchase Frequency, Size, and Price”). Finally, the portion of PM users who report growing their MRA has tripled, albeit from a low base, and that trend has accelerated in recent years. Many of the above trends are closely linked to intensifying use habits, and at the individual level can be partially or largely “explained away” by adjusting for changes in the number of use days per month. Taken together, these trends suggest that the marijuana market is becoming increasingly characterized (a) by users habituated to buying marijuana (or growing it) rather than getting it for free and (b) by “professional” dealers outside of the NSDUH sampling frame.

A related trend is toward increasing utilization of MMJ recommendations. Respondents who reported having a medical recommendation for at least some of their marijuana use showed patterns indicative of heavier use and also a more middle-of-the-road demographics. In states that had MMJ laws, nearly half of users with recommendations (a) used on a daily basis, (b) were 35 years or older, or (c) were female.

Despite the popular stereotypes of marijuana users as well-off and well-educated, we find that with respect to educational attainment and household income, they lag behind national averages; nearly three in 10 use days accrue to users with US\$20,000 or less of reported household income, and half accrue to users with only a high school degree or less. That discrepancy is larger than in years past, especially with regard to income.

In fact, with respect to education and income, marijuana users bear close resemblance to users of cigarettes. The amount of money that users spend on their substance of choice is also comparable: the median DND marijuana user (reporting at least 20 days of use per month) is estimated to spend US\$2,200 per year on marijuana, approximately equal to what the average pack-a-day cigarette smoker spends on cigarettes.

The financial burden of marijuana habits bears more heavily on some users than others. For instance, DND users above 21 years old without any college education whatsoever are estimated to spend nearly 8% of their household income on marijuana—nearly triple the portion paid by adult users in college without ABOD (2.6%) and twice the national average (4%). That is not a negligible slice of the population: DND users above 21 years old without any college education make up 4.5 million people (25% of all PM users) and account for roughly 45% of all PM use days.

Changes to NSDUH Methodology

The NSDUH survey itself could yield more useful information regarding marijuana use and market activity; in some cases, that involves re-thinking the conventional methods of measuring marijuana use. Although it is clear that marijuana use is increasing, the speed of that growth depends upon along which dimension it is measured. According to the “traditional” epidemiological framework, use is tracked in terms of prevalence of PM or PY users. But focusing only on prevalence rates misses the important fact that recent increases in marijuana use has been driven primarily by changes in the intensity of use *within* PM users. One possible response is to simply “tweak” the epidemiological framework as to measure the prevalence of Daily and Near Daily users as well. But a more elegant solution is to track “days of use” instead, which does not require selecting multiple arbitrary cutoffs to distinguish users of different types.

Complementing this would be a change in terminology. In contrast to epidemiologists, economists speak of “intensive” versus “extensive” margins. We suggest adopting that framework, where “extensive” margins pertain to the number of agents participating in an activity (e.g., number of PM users), and “intensive” margin refers to the level of activity per agent (e.g., use days per user).

Illicit drug activity has commonly been measured in terms of gross weight. For instance, for cocaine (but not heroin), weight is a relatively stable measure of price and intoxicative effect. The same is not true for marijuana: THC concentration is steadily increasing nationwide and varies wildly from one user to another in unclear but systematic ways. Knowing the annual weight of purchased marijuana is almost meaningless without also knowing trends in potency, which are difficult to measure given that most marijuana traded in the United States remains in the black market, where potency labeling is rare and, if provided, unreliable. That complication is compounded by the rising popularity of edibles and concentrates, which clearly are incomparable with herbal product on the basis of weight, though some researchers have tried to establish “equivalency” formulas (Orens et al. 2015).

We suggest researchers make greater effort to directly measure THC content. NSDUH could ask users about the THC percentage of their recent purchase (or, where legal, take a small sample of their personal supply). Alternately, researchers may wish to complement data on weight with data on price. For one, price is inherently interesting as it is a major determinant of access. Second, data from the past decade suggests that prices have been a convenient and relatively stable proxy for THC content. But even that approach might only be useful in the short term, as potency-adjusted prices are likely to drop as the licit marijuana industry continues to develop in scale and efficiency.

Keeping Apace With Market Trends

Other changes to the NSDUH survey are needed to keep pace with the changing landscape of marijuana use and policy. For one, marijuana dispensaries (and legal commercial stores) are proliferating within and across states. But currently, NSDUH respondents are never directly asked whether they recently purchased from a dispensary, and though MMBPLOS2 allows respondents to report that via write-in answer, it appears that the majority of dispensary

buyers are never given that opportunity due to skip patterns pertaining to MMBPLACE.⁸ The 2013 survey’s new questions pertaining to MMJ recommendations (i.e., MEDMJYR, MEDMJST2) are a helpful addition, but each have shortcomings. MEDMJYR would perhaps be more useful if it linked MMJ recommendations to methods of access (e.g., growing under a medical recommendation or buying from a dispensary) rather than to use. Instead of reporting only a simple binary indicator for whether the respondent’s state has MMJ laws (MEDMJST2), it would be insightful to also tag whether a state has allowed MMJ dispensaries—and going forward, whether it has legalized marijuana in full. Another intriguing modification would be, when asking respondents who provided their MRA (e.g., MMBUYWHO), to allow respondents to answer in greater detail, for instance, “(A) dispensary; (B) friend who only sells occasionally; (C) dealer who is also a friend; (D) dealer; (E) family.”

The variety of available marijuana products has changed dramatically. The term *marijuana-infused product* has taken to include a wide range of non-herbal products, including “shatter,” edibles, beverages, and oils, none of which are specifically asked about on the current NSDUH survey (though technically the NSDUH questions pertain to “marijuana or hashish”). Yet there are clear concerns about the health impacts of different modes of use, particularly an increased risk for acute overdose, especially when oils are flash-vaporized (“dabbing”) or edibles are either poorly labeled or consumed recklessly. Washington State and Colorado already have in place comprehensive track-and-trace systems that monitor and record data about the products produced and sold in their supply chains; as a result, they have produced two useful and open datasets capable of tracking the proliferation of those product varieties throughout the state-legal marijuana systems. However, data on the rest of the country remain dark; the NSDUH survey could fill that void.

As marijuana markets continue to professionalize, one might expect to observe certain patterns characteristic of well-capitalized licit markets. For instance, marijuana stores may offer buyers a wider range of choice of quality and affordability, just as liquor stores offer high- and low-shelf liquor. If so, it seems likely that price-sensitive users (e.g., younger users, the poor, and heavy users) choose to buy marijuana that is cheaper-per-THC but lower quality in other regard (e.g., aesthetics, freshness, name brand). To date, however, our results do not suggest meaningful splits in price-paid-per-gram versus use frequency or income—although that may be due to limitations of our data. Going forward, it seems reasonable to expect that those trends will occur first in states with liberal marijuana policies, substantial investment from the industry, large cannabis farming operations, and a proliferation of marijuana stores.

⁸ No question asks directly about purchasing at a dispensary, but 51 respondents reported their purchase location as “some other place” and then wrote in “medical marijuana dispensary/club.” These 51 represent only 2% of Past-Month (PM) buyers, and almost surely do not include all people who bought at dispensaries, as other dispensary buyers might have selected the “inside a public building” option. Nevertheless, it is interesting to note that relative to all Past-Year (PY) users, these 51 were less likely to report selling (1.3% vs. 4.5%) or giving away (32.5% vs. 52.4%) some of their *Most Recent Acquisition* (MRA), and bought slightly less (10.5 vs. 14.5 grams) but paid more per gram (US\$9.26 vs. US\$6.93).

We conclude with a statement about the policy decisions currently facing voters in a handful of states expected to vote on marijuana legalization in 2016 and years to come. Although these debates often appeal to voters on the basis of “ending the drug war,” that issue seems somewhat exaggerated: marijuana use and possession is already decriminalized in 18 states and the District of Columbia as of January 2016, and nationwide, it carries very low risks per incident of use (Caulkins and Pacula 2006; Nguyen and Reuter 2012), which we show have continued to drop. Rather, we expect that the principal effect of such initiatives, if passed, would be to create a legal channel for production and distribution—in turn catalyzing dramatic reductions in price (Kilmer et al. 2010). Were that to occur, it seems likely that many of the patterns identified herein would continue to trend (and perhaps accelerate) in the current direction; on the contrary, it might trigger a fundamental shift in how marijuana is used, accessed, and distributed today.

Chapter Two. Falling rates of marijuana dependence among heavy users⁹

Steven S. Davenport

Pardee RAND Graduate School, Santa Monica, CA

Abstract

Aim. Marijuana use has become increasingly popular in the United States since the turn of the century, and typical use patterns among past-month marijuana users have intensified, raising concerns for an increase in cannabis use disorders (CUDs). Yet the population prevalence of CUDs has mostly remained flat. We analyzed trends in DSM-IV marijuana dependence among Daily/Near-Daily (DND) users, both overall and by age and gender, and considered potential explanations. **Methods.** Using data assembled from the National Survey on Drug Use and Health (2002-2016), rates of self-reported dependence and constituent symptoms are calculated for DND marijuana users; logistic regressions with pre- and post- periods (2002-2004, 2014-2016) and a Cochrane-Armitage trend test are applied to describe temporal changes. **Results.** Dependence among DND users fell by 39% (26.5%-16.1%; $p < 0.001$), with significant trend. No significant change is detected at the population level. Sub-group analysis shows a steep gradient for age but not for gender. Declines are robust to sub-group analysis, except for users over 50 years old. Among dependence symptoms, most showed significant declines: reducing important activities ($p < 0.001$); use despite emotional, mental, or physical problems ($p < 0.001$); failing attempts to cutback ($p < 0.001$); lots of time getting, using, or getting over marijuana ($p < 0.01$); and failing to keep limits set on use ($p < .05$). Reported tolerance showed no significant change. **Conclusions.** Though it is unclear why, the risk of dependence formation among heavy marijuana users appear to have declined since 2002. Further research is warranted regarding explanations related to state marijuana policies, product forms, or social context.

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Introduction

Since the turn of the century, the United States has seen dramatic changes in marijuana policy, use, and social context. Eight states and Washington DC have legalized possession, use, production, and sale of marijuana for non-medical use; more than thirty states have legalized some form of medical marijuana, often with dispensaries. Perceptions of the marijuana's risks have been falling (Pacek, Mauro, and Martins 2015), and approval for legalization is now nearly two-thirds (Gallup 2017). Marijuana use has also changed in other ways, e.g., increasing THC potency, an increasing acceptance and availability of marijuana for medical use, and rising popularity of alternative forms of consumption such as edibles, portable vaporizers, and “dabbing” solid concentrates (Davenport and Caulkins 2016; Kilmer et al. 2014).

Marijuana use has been on an upward trend since roughly the mid-1990s, and intensifying since 2007 (Carliner et al. 2017). The portion of Americans 12 years or older reporting past-month marijuana use rose from 6.2% in 2002 to 8.9% in 2016 (Center for Behavioral Health Statistics and Quality 2017a). Even among past-month marijuana users, use habits have intensified, for instance as measured by the portion of past-month users reporting daily or near-daily (“DND”) use, i.e., use on more than 20 of the past 30 days, which tripled from one-in-nine in 1994 to one-in-three in 2014. DND users dominate the marijuana market, accounting for 68% of use days and 60% of expenditures in 2012-2013. In total, the number of days of marijuana use reported to NSDUH increased by more than half from 2002-2003 to 2012-2013 (Davenport and Caulkins 2016).

Use disorders are an important risk of marijuana use. The Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (DSM-IV) provides definitions of marijuana abuse and dependence, with diagnostic criteria including spending a great time using or getting marijuana, increasing tolerance, continued use despite physical or mental problems, and reduced time spent on important activities; with the notable exclusion of withdrawal symptoms, due to a lack of evidence at the time of publication (American Psychiatric Association 2000; Hasin et al. 2013). Questions corresponding to these criteria have been asked by the National Survey on Drug Use and Health (NSDUH) for decades, allowing for the calculation of prevalence of cannabis abuse and/or dependence based on self-reported symptoms.

Though the NSDUH questionnaire remains unchanged, the DSM-V has since introduced changes relating to cannabis use disorders (American Psychiatric Association 2013; Center for Behavioral Health Statistics and Quality 2016). First, the DSM-V changed the diagnostic threshold for cannabis use disorder, merging cannabis abuse and dependence and changing some criteria: namely, dropping the criterion relating to legality, citing limited information gained for diagnosis and amid doubts about its use as a clinical indicator, and adding a criterion relating to cravings (Peer et al. 2013). Second, reflecting new research, the DSM-V recognized symptoms for cannabis withdrawal, based on feelings of irritability, anger, anxiety, disturbed sleep, decreased appetite, mood, and/or energy, and at least one physical symptom causing significant discomfort, e.g., abdominal pain, tremors, fever, or headache (Hasin et al. 2008). Comparisons suggest these changes have had little effect on the measured prevalence of cannabis use disorders (Mewton, Slade, and Teesson 2013; Peer et al. 2013).

NSDUH data suggest four million Americans suffer from DSM-IV marijuana dependence (Center for Behavioral Health Statistics and Quality 2017a); and as a percent of the general population, marijuana abuse and dependence have remained relatively stable from 2002-2014 at 1.5% (Compton et al. 2016). (The National Epidemiologic Survey on Alcohol and Related Conditions records a much larger increase, from 1.5% to 2.9% (Hasin et al. 2015), due largely to changes in NESARC methodology.) (Gruza et al. 2016)

One might have expected the population prevalence of marijuana dependence to have increased proportionally to the substantial increase in prevalence of marijuana use. That this did not occur presents a puzzle, which this paper seeks to elaborate. Using National Survey of Drug Use and Health (NSDUH) data, we seek to measure levels and changes in marijuana dependence and its symptomatic criteria among the heaviest users, and consider potential causes at hand.

Methods

Data

Questions corresponding to the DSM-IV diagnostic criteria have been asked by NSDUH since 2002, providing a consistent data source for tracking trends in the reporting of marijuana dependence diagnoses and their constituent symptomatic criteria. NSDUH is a household survey, representative of the U.S. household population aged 12 and older, with over 60,000 respondents per year. NSDUH asks respondents a range of health-related questions, including recent use of drugs; for marijuana, respondents reporting past-year use are asked follow-up items about recent use, including a battery corresponding to DSM-IV diagnostic criteria for marijuana abuse and dependence. (NSDUH has not announced changes to its question battery or re-coded variables to incorporate DSM-V criteria.) We assemble these data from 2002 to 2016.

Measures

Our main outcomes are marijuana dependence and its symptomatic criteria, as indicated by the Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (DSM-IV). In accordance with SAMHSA practices following those guidelines, dependence was coded as yes if respondent met at least 3 of the 6 indicated criteria, presented here along with the coded variable(s) in NSDUH: 1) Spent a great deal of time over a period of a month getting, using, or getting over a substance's effects (MRJLOTTM=1 or MRJGTOVR=1); 2) Unable to keep set limits on substance use or used more often than intended (MRJLIMIT=1 or 2, and MRJKPLMT=2); 3) Needed to use more to get desired effects or noticed lesser effect from the same amount (MRJNDMOR=1 or MRJLSEFX=1); 4) Unable to cut down or stop using at every attempt or desire (MRJCUTDN=1 or 2, and MRJCUTEV=2); 5) Continued to use despite it causing problems with emotions, nerves, mental health, or physical health (MRJEMCTD=1 or MRJPHCTD=1); and 6) Reduced or stopped participation in important activities due to substance use (MRJLSACT=1) (Center for Behavioral Health Statistics and Quality 2017b).

Analyses

Data were weighted to reflect NSDUH's sampling design, assembled from individual years into an omnibus dataset, and analyzed in R (3.4.2). (Substance Abuse and Mental Health Services Administration 2018) The prevalence among DND users of DSM-IV dependence is

calculated for each year of available data, first across all DND users and then by age group (12-17, 18-25, 26-34, 35+) and gender. To provide broader context, levels and changes in DND prevalence are compared to prevalence among past-year marijuana users and among the general population, but detailed results from analyses of non-DND user groups is omitted for brevity. DND prevalence is plotted without alteration, but for sub-group analyses, smoothing is applied in order to reduce year-to-year variation driven by small sample sizes. A simple 5-year moving average is applied (e.g., 2008 = average for 2006-2010) where possible; to conserve data points for plotting, years near the sample's edge are presented unsmoothed (e.g. 2002, 2016) or partially but symmetrically smoothed (e.g., 2003 = average for 2002-2004). To summarize changes over the study period, data are divided into three-year pre-/post- time periods (2002-2004 and 2014-2016), and fit with a quasi-binomial regression predicting self-reported DSM-IV dependence as a function of age, race, education, gender, and time period. Statistical significance is tested by the p-value on the time dummy coefficient. Change is presented in absolute and relative terms.

Likewise, the prevalence of individual DSM-IV Marijuana Dependence criteria among DND users are calculated, plotted, and tested for statistical significance. No sub-group analysis is undertaken here, for simplicity.

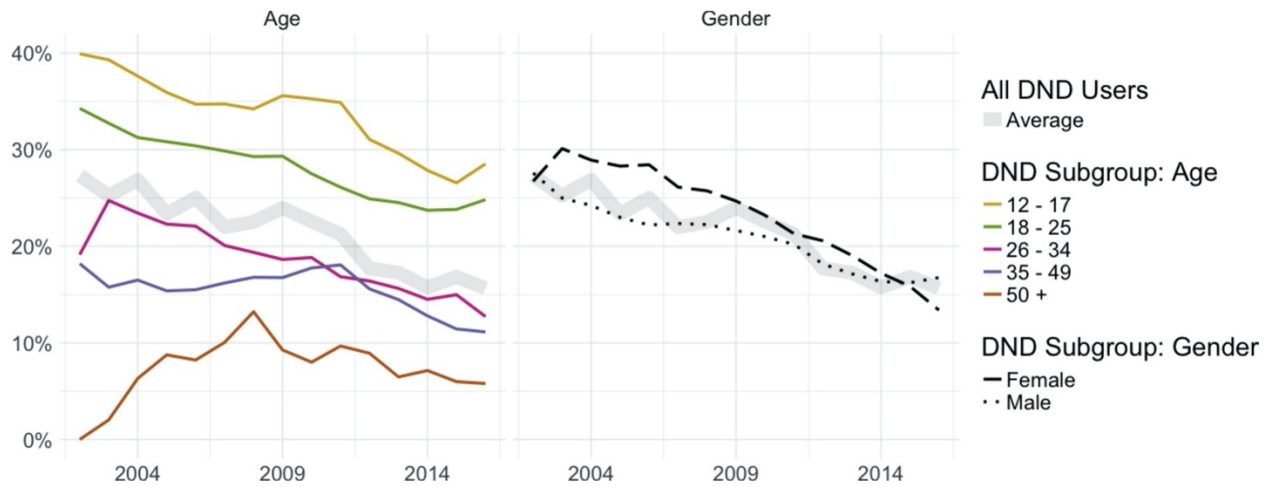
Results

Marijuana Dependence

Rates of marijuana dependence among DND users fell throughout the study period, from a high of 27.3% in 2002 (26.5%, pooling 2002-2004) to a low of 15.8% in 2014 (16.1% for 2014-2016). Among all past-year users, we observe a decline that is similar in relative terms (from 13.8% to 8.5%). Logistic regression confirms the reduction in DND dependence from 2002-2004 to 2014-2016 is statistically significant ($p < .001$). A similar model run on all NSDUH respondents, estimating the population-level prevalence, shows no significant change. From 2002-2004, 4,461 respondents reported daily/near-daily use and so were asked questions about DSM-IV dependence, and 6,190 in 2014-2016.

Figure 2.1 shows DND (thick semi-transparent line) and sub-group dependence rates by age group (dashed- and dotted-lines) and gender (shaped points). Sub-group analyses show declines among all age and gender groups, except for adults over 50 years old, among whom dependence has fallen only since 2007, but was increasing beforehand. Dependence rates show a steep age gradient, with adolescent rates roughly doubling those among 26-49 year-olds, which in turn double older users'. Rates among females are persistently higher than male rates until crossing in 2015.

Figure 2.1. Rates of DSM-IV Dependence Among DND Users and Subgroups



Symptom Criterion

Among DND users, five of six DSM-IV marijuana dependence symptoms showed significant declines in prevalence. The biggest relative declines are in criterion related to health and lifestyle, e.g., stopping important activities and continued use despite emotional, mental, or physical problems. Reported tolerance (“needed more for the same effect”) showed no significant change.

Table 2.1. DND Prevalence of Dependence and Symptom Criterion

Condition / Symptom	2002-4	2014-6	P-value	Difference	Change (%)
DSM-IV MJ Dependence	26.5	16.1	<0.001 ***	-10.4	-39.2
Reduced or Gave Up Important Activities	17.9	9.9	<0.001 ***	-8	-44.7
Emotional, Mental, or Physical Problems and Continued Use	15.1	8.1	<0.001 ***	-7	-46.4
Attempted to Reduce Use but Failed	15.1	10	<0.001 ***	-5.1	-33.8
Lots of Time Getting, Using, or Getting Over Marijuana	73.9	63.1	0.004 ***	-10.8	-14.6
Set Limits on Use but Failed to Keep Them	13.2	10.4	0.015 **	-2.8	-21.2
Needed More for Same Effect	44.8	40.3	0.519	-4.5	-10

Conclusions

Findings from this paper emphasize that during a period of liberalizing cannabis policy, increases in past-month prevalence, and the intensification of typical use habits, there has been a marked reduction in self-reported rates of marijuana dependence among DND users, from roughly one-in-four to one-in-six. A similar decline in relative terms was observed among past-year users (13.8% to 8.5%). The net effect of these declines, along with increases in prevalence, has yielded stable rates of dependence in the broader population. Declines are robust to subgroup analysis by age and gender, with the exception of adults over 50, who show mixed trends. Conditioning on DND use offers a fresh perspective, essentially treating prevalence as a confounder. Dependence manifests differently in men and women (Agrawal and Lynskey 2007), and though men show lower non-conditional dependence (Chou et al. 2015), our results reveal women had long faced higher rates of conditional dependence, until recent years.

What may be driving these trends is not entirely clear. The truth lies between two alternative extreme interpretations. One approach takes trends at face value, inferring a genuine drop in the dependence risk of marijuana use. Perhaps increasing social approval of marijuana use has helped DND users to integrate their marijuana use habits with their other commitments, causing fewer to report giving up important activities and fewer problems with family, friends, and co-workers; perhaps as marijuana has become more widely available, DND users are spending less time seeking marijuana; perhaps the spread of less harmful modes of consumption (e.g. vaporizers) or use with the intent to tread health-related issues has led to fewer emotional, mental, or physical problems. Conversely, perhaps the only change has been in users' propensity to detect problems, attribute them to their cannabis use, and report them – but the underlying risks remain the same. A potential third option concerns a confounder: as marijuana use has spread and normalized, this has driven changes in the composition of the user base (Burns et al. 2013) – perhaps also in characteristics that are not captured in survey data, e.g., users' general capacity for self-control or deference to social norms.

The spread of new ways to consume marijuana, namely vaporization, “dabbing”, and edibles, also likely play a role, particularly where medical and recreational marijuana laws have driven sales of these products. (Flower has dropped to only 66% of Washington State's legal marijuana sales by dollar value by mid-2016 (Rosanna Smart et al. 2017).)

As U.S. marijuana policies liberalize, it is especially important that researchers, policymakers, and voters understand the harms of marijuana use – and further, to appreciate these harms may be changing, driven by policy decisions, product characteristics, and social context. The issue merits further research studying how different state marijuana policies or the use of different marijuana products may affect risks of dependence and other health harms. Policy stakes are high, including not only whether marijuana legalization continues to spread to more jurisdictions, but also how harmful aspects of marijuana are perceived and managed within legalized environments.

Chapter Three. Price and Product Variation in Washington's Recreational Cannabis Market¹⁰

Steven S. Davenport

Pardee RAND Graduate School, Santa Monica, CA

Abstract

Background. Ten U.S. states, Canada, and Uruguay have passed laws to legalize the production and sale of cannabis for non-medical purposes. Available research has documented rapidly falling prices and changing product mixes, but many details are not well understood: particularly, the popularity, prices, and product characteristics of different cannabis edibles and extract-based products – each offering different ways to consume cannabis, with unclear health consequences. **Methods.** This paper analyzes data from Washington's recreational cannabis market, which has recorded over 110 million retail item-transactions from July 2014 to October 2017. Previous research on price and product trends has focused mostly on herbal cannabis, which accounts for the majority, but a decreasing share, of sales. This paper applies advanced text-analytic methods to provide new insights, including A) estimating potency data for edibles and B) identifying extract sub-types. Patterns and trends are described, across product types, regarding THC and CBD profiles and price per THC. **Results.** Extracts accounted for 28.5% of sales in October 2017. Of extracts categorized to subtype, nearly half were identified as “dabs”, and another half “cartridges”. In October 2017, price per 10mg THC was roughly \$3 among edibles, 70 cents among extract cartridges, and 30 to 40 cents for other flower and other extracts; solid concentrates offered the lowest priced THC among extract products. Price declines continue but have slowed. High-CBD chemovars are becoming more common, but still are almost non-existent in flower marijuana and rare (1% of sales) among extract products. **Conclusion.** As Washington's recreational cannabis market has developed over three and a half years, trends identified in that market may serve as an early indication of potential issues in other states. Legislators and regulators in other jurisdictions with commercial non-medical cannabis markets may wish to establish policies responsive to these trends in product popularity, price, and potency.

Introduction

The last five years have seen landmark changes in cannabis policy, with ten U.S. states, Washington DC, Canada, and Uruguay having legalized cannabis for non-medical uses. In

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Canada and the United States (except for Washington, DC and Vermont), this has included licensing for-profit commercial firms to produce, distribute, and retail cannabis products (National Conference of State Legislatures 2018). For-profit non-medical or “recreational” cannabis markets have now been operating in the United States in Washington and Colorado for over four years, since January 2014 in Colorado and July 2014 in Washington State. The involvement of commercial firms has raised concerns of a potential collapse in cannabis prices and the proliferation of new and potentially more harmful products. But the unprecedented nature of these developments limits the utility of *a priori* theory and rewards a careful analysis of new outcomes.

Cannabis use, product characteristics, and markets have complex implications for public health. Generically, cannabis use carries a number of risks, e.g., of dependence, cognitive impairment, adverse educational outcomes, and schizophrenia (Hall 2015; Volkow et al. 2014, 2016). High-potency cannabis flower raises additional concerns. Among cannabis flower seized by law enforcement in the U.S., THC concentration tripled over two decades to 12% in 2014, alongside falling CBD concentrations (ElSohly et al. 2016). In response to rising THC concentrations, a mixed evidence based suggests that cannabis users “titrate” their THC consumption, adjusting the amount of flower consumed as to hold total THC content constant – but only partially, such that higher THC concentrations generally lead to higher amounts of THC consumed. (T P Freeman and Winstock 2015; Van Der Pol et al. 2013) Perhaps as a result, use of high-potency cannabis, especially daily use, has been associated with additional risks of schizophrenia (Di Forti et al. 2015; T P Freeman and Winstock 2015).

Additional health concerns have been raised by the spread of new ways to consume cannabis, e.g., edibles, “dabs”, and vaporizers, often provided by a medical dispensary or state-legal marijuana store (Russell et al. 2018b; Rosanna Smart et al. 2017). Each have their own harms. Particular to cannabis edibles is the risk of accidental consumption and/or overdose, mainly due to delayed onset of intoxication and inaccurate labeling (Raber, Elzinga, and Kaplan 2015). A recent phenomenon, “dabbing” is defined by the rapid intake of cannabinoids. To use a dab “rig”, a blowtorch is applied to a hot plate of metal (“nail”), with solidified cannabis concentrate placed on top. A single “hit” is often sufficient for intoxication (Loflin and Earleywine 2014). Literature on its health effects is admittedly slim (Loflin and Earleywine 2014; J. M. Stogner and Miller 2015), but there is evidence of associations with cannabis-induced psychosis, higher rates of withdrawal and tolerance, self-reports of anxiety and depression, and use of other illicit drugs. (Chan et al. 2017; Loflin and Earleywine 2014; Pierre, Gandal, and Son 2016).

New products may also offer ways to reduce harms associated with use. Cannabis vaporizers, usually portable and able to discretely vaporize pre-packaged oil cartridges and/or dried flower, have been characterized as a user-friendly and potentially safer method for consuming cannabis (Malouff, Rooke, and Copeland 2014), and perhaps even a means to reduce frequency of use (Varlet et al. 2016). Unlike the one-hit “dab”, vaporizers deliver a slower, steadier stream of cannabinoids, and therefore a less intense effect, even when holding constant the product’s THC concentration. Moreover, compared to dried cannabis flower, use of cannabis e-cigarettes is not as well statistically correlated with nicotine use (Agrawal, Budney, and Lynskey 2013; Lynskey, Hindocha, and Freeman 2016; Malouff, Rooke, and Copeland 2014). On the other hand, others consider vaporizers a harm reduction “double-edged sword”, by

making cannabis use more convenient, which encourages further use (Budney, Sargent, and Lee 2015).

Washington State legalized cannabis by voter initiative in 2012 (Initiative 502), to be regulated by the Liquor and Cannabis Board (“LCB”, formerly the Liquor Control Board). The law stipulated a three-tiered licensing structure (producer, processor, retailer) and a set of certified labs for testing. Unlike in Colorado, vertical integration to retail was prohibited. Originally, a 25% tax was imposed at each point as product moved from producer to processor to retailer, but this tax was replaced in July 2015 with a single 37% excise tax at the point of retail sale.

The recreational cannabis market has been shaped in part by Washington’s pre-existing medical cannabis laws. As of 1998, qualifying medical patients had been afforded affirmative defense under Washington State law for the cultivation, possession, and use of certain quantities of cannabis (Initiative 692), but distribution remained illegal. The first dispensaries were legalized in 2011, with the partial veto of SB 5073, which established a system of “collective gardens” allowed to operate quasi-commercially, unregulated and untaxed. Over the following years, collective gardens would proliferate across the state, reaching at least 273 but likely substantially more during its peak (O’Connor et al. 2016). In the early days of the recreational cannabis market, stores competed openly with unregulated and untaxed medical dispensaries. This confusing situation was resolved with a 2016 law to merge the medical and recreational markets. Collective gardens were required to acquire an I-502 license in order to continue operating, as of July 2016, and several hundred additional retail licenses were allocated to facilitate that transition. More than 90% of Washington’s regulated cannabis stores have acquired a “medical marijuana endorsement” allowing them to sell to medical cannabis patients; medical transactions are charged 37% excise tax, but unlike recreational transactions, are exempt from state sales tax (6.5% statewide, and up to 10.4% in some areas). Medical cannabis products may contain as much as 500mg THC per package, instead of only 100mg THC allowed in the recreational market (Young 2016).

Aim

Washington State has maintained a seed-to-sale, tracking all retail sales of recreational cannabis and many events within the supply chain (Washington State Liquor and Cannabis Board 2017). This dataset provides an excellent window into a quickly changing but opaque market. Though other U.S. states maintain similar databases, only Washington State has made their data public. Previous research using this dataset has identified substantial declines in cannabis prices, high typical THC concentrations in flower marijuana, and a proliferation of cannabis-derived products (R. Smart et al. 2017). But studies have generally been limited by the problematic nature of the dataset. In this study we attempt to overcome two limitations: 1) Data on potency characteristics is unreliable for some product types; and 2) Products are grouped into non-intuitive categories. We introduce methods for cleaning and modeling data to address these deficiencies, before using the new dataset to further describe key trends in the market. We confine analysis to products belonging to one of eight groups identified from the data: 1) dried flower (“usable marijuana”/“marijuana mix”), 2) infused flower, e.g. joints enriched with kief; 3) liquid edibles, 4) solid edibles; 5) dabs; 6) vaporizers; 7) hash/kief; and 8) other concentrates; less popular products such as capsules and tinctures are not analyzed. In addition to introducing

methodological improvements relating to data cleaning and inference, the paper seeks to shed light on several questions:

- How has the range of products offered on the market shifted?
- How can the growing share of extract-based products be disaggregated into sub-types, and in particular, across rapid-intake products (i.e. dabs) versus slow-release products (i.e. vaporizer cartridges)?
- How have potency levels and cannabinoid profiles changed over time and across different types of products?
- How has the price-per-intoxication changed over time and across different types of products?

Methods

Data

Licensed cannabis businesses are required to report certain events to the state’s “seed-to-sale” inventory tracking system, which is publicly available by request. Events are recorded throughout the supply chain, including the locations and movements of plants; harvests; processing events; test results; and the sale of wholesale and retail products. As this study focuses on characteristics of retail products, the database has been merged and cleaned to prepare a retail-level analytical dataset that encompasses the universe of licensed retail cannabis sales in Washington State.

Data Cleaning

The dataset is quite raw, composed directly from licensee reports, which may be inaccurate for a number of reasons, including dishonesty, neglect, honest mistakes, and software glitches; the database design itself can present additional difficulties for data retrieval and analysis, especially given the lack of an official codebook. Moreover, the study period elapses many changes in regulations, business practices, and database rules. As such, extensive data cleaning is required to generate sensible results.

Because potency and contaminant testing are required of all retail cannabis products, all retail items in the database can be linked to an ancestor(s) from which a sample has been taken and sent to a lab, yielding data on cannabinoid content, and purity from contaminants, which may be extrapolated to the retail product. All tests yield results for THC, THC-A, and CBD; and, as of March 2016, also CBD-A. To represent the expected weight after decarboxylation, i.e., when CBD-A/THC-A has been transformed to CBD/THC, Washington State regulations calculate “Total” THC or CBD as $d9\text{THC} + 0.877 * d9\text{THCA}$ or $d9\text{CBD} + 0.877 * d9\text{CBD}$ (Washington State Administrative Code. Quality assurance testing 314-55-102 n.d.). As the “Totals” values in the dataset do not consistently follow that formula, we apply those formula to the raw THC/THCA/CBD/CBA values to calculate new values TotalTHC, TotalCBD, and Total (TotalTHC + TotalCBD, representing combined decarboxylated weight of THC and CBD). This

leads to a slightly underestimation of CBD content in the early days of the market, when CBDA was not reported.

The vast majority of products may be linked to a single ancestor that was submitted for testing (via the variable “inventoryparentID”). Roughly four million item-transactions (3.5% of all) descend from multiple ancestors; unfortunately, irregularities in the database design prevent convenient use of these data points, yielding invalid missing THC or CBD values. Next, we flag observations for missing, zero, or negative values for price, quantity, or THC or CBD content. We also flag observations with extreme values for item price, price-per-unit, or THC or CBD content. Extreme values are defined as in the top or bottom 1% among item-transaction for that year-month-product type. THC or CBD scores were considered invalid if total cannabinoid values exceeded 100 for product types where cannabinoids are denominated in percent, or 500 where denominated in milligrams (marking the maximum packaged THC content for medical products). Flagged observations are removed from the dataset before analysis (see Table 3.1).

Table 3.1. Number of Item-Transactions Removed by Data Condition and Dataset Summary

	2014	2015	2016	2017	Total
Price <=0 or Missing	787	28,330	111,924	170,002	311,043
Quantity <=0 or Missing	-	8,722	32	7	8,761
THC/CBD <= 0 or Missing	21,100	356,508	1,994,965	2,241,908	4,614,481
THC/CBD Invalid	370	6,442	74,609	168,319	249,740
Price Extreme	15,202	253,435	647,136	833,308	1,749,081
THC/CBD Extreme	6,428	143,047	458,848	619,355	1,227,678
Price/Gram Extreme	11,834	167,585	569,685	622,319	1,371,423
Total Items Removed	43,887	796,492	3,287,646	4,036,329	8,164,354
Items (Original)	886,505	15,289,587	42,278,597	54,709,354	113,164,043
Items (Cleaned)	842,618	14,493,095	38,990,951	50,673,025	104,999,689
%	95.0%	94.8%	92.2%	92.6%	92.8%
Sales (Original) (\$1000s)	43,775	441,467	969,431	1,056,420	2,511,094
Sales (Cleaned) (\$1000s)	41,156	416,013	894,804	965,174	2,317,147
%	94.0%	94.2%	92.3%	91.4%	92.3%

From July 2014 to October 2017, in raw form, the traceability dataset includes 113,164,043 retail item-transactions, accounting for \$2,511,093,939 in total sales (inclusive of excise tax). Post-data cleaning, 104,999,689 retail item-transactions (for \$2,317,147,123 in sales) remain in the analytical dataset. The data cleaning procedure retained 92.8% of all transactions. Even after data cleaning, the dataset suffers two key limitations: 1) poor quality of potency data, particularly for edible products; and 2) an overly broad “extracts for inhalation” product category, which inhibits closer study examination of the fastest growing share of the market. We introduce two methods below to mitigate these limitations.

Identifying Product Subtypes

To describe changes in extract products, we first decompose the product type “extract for inhalation”, which is somewhat of a catch-all term, into four subgroups: 1) hash or “kief”, 2) solid extracts for “dabbing”; 3) liquid extracts enclosed in vaporizer cartridges for vaporizing, and 4) non-cartridge liquid extracts. What these extract products share in common is that they contain high concentrations of cannabinoids extracted from the cannabis plant. They differ on a number of dimensions, including extraction method (e.g., dry, water-based, solvent-based, or liquid gas-based) and associated risks of residual chemical solvents; texture and/or viscosity; speed of cannabinoid intake from the predominant method of use (from the delayed effects of oral ingestion, to slow-release vaporization, to smoking, to the ultra-fast “dabbing”); and typical cannabinoid concentrations and THC:CBD ratios (Raber, Elzinga, and Kaplan 2015).

To distinguish each of those four extract sub-types, we again parse the label field (“productname”). An iterative methodology was deployed to generate a list of search criteria used for classification: first, items are grouped by THC content and reviewed for common “productname” text that uniquely accompanies cartridges; then, these phrases are used to classify products, and the first step repeated only with items remaining unclassified; this process is repeated until there no longer remains phrases that appear associated uniquely with cartridges. Likewise, a parallel process searches for text indicative of certain non-cartridge product types, namely (“oral extracts” generally intended to be consumed orally but are not packaged within cartridges, “smoked extracts” representing solid concentrates and others intended to be smoked, vaporized, or dabbed; and finally, “kief” or “hash”). This process identified nine terms associated with cartridges (e.g. “cart”, “vap(orizer)?”, “pen”, “vc”, “refill”, “e(-)?joint”, “atomizer”, “disposable”, “juju”), twelve with oral extracts, nearly two dozen associated with smoked extracts, and two with kief/hash. After classification, to validate the results, we then compute basic characteristics (i.e. number, sales volume, and typical price and potency), of each subtype. This method was able to generate a classification for 74.5% of sales of extract products. Of those, 49% were identified as dabs, 44.4% as cartridges, 4.8% as oral extracts, and 1.5% as hash/kief. Among the remaining one-quarter of unclassified sales, by inspecting the percent of cannabinoids decarboxylated, THC content, and price-per-THC, we may roughly infer a fifty-fifty split between cartridges and solid concentrates, though it is difficult to distinguish which at the individual level.

Estimating Potency Content of Edible Products

Cannabinoid content is provided for all observations in the dataset, but data quality ranges by product type. Potency data accompanying edible products appears to be denominated in milligrams, while the other major product types appear in percentage by weight (excluding packaging, e.g., for vaporize cartridges, the percentage weight of content inside the cartridge, including solvents). Moreover, a close inspection of the data reveals the potency content of many edibles is reported in terms of serving size (limited at 10 milligrams in Washington State) rather than total package contents.

In order to rescue potency data for edibles, we apply text analytic methods to a field containing a brief free text product description (“productname”), but for many observations this

field is either empty or does not contain information about product potency. Nonetheless, we apply the method where it is feasible and then check for systematic differences in observable characteristics across labeled and unlabeled products, as to infer whether the characteristics can be extrapolated outside the sample. The text analytic program uses regular expressions to find numbers preceding “grams”, “g”, or “mg”, extract those numbers, and convert to milligrams as appropriate. As some “productname” fields describe content both of the serving size and of the package (e.g., “10mg brownies 6pk”), if multiple matches are made, the largest number is extracted.

Estimated THC potency is extracted for edible products from the labeled text. By sales volume, 5% of observations showed empty labels; another 57% had labels that could not be parsed for potency data; therefore, potency estimates were yielded for the remaining 39% of liquid edibles and 38% for solid edibles. (However, the classifier’s performance improves over time: among 2017 observations, matches were generated for 43% of solid edibles and 53% of liquid edibles.) Since THC estimates were produced for only 39% of the data, it is reasonable to worry that this sample may not be representative of all edible products sold. This possibility can be investigated by comparing observable characteristics of those products that were classified versus those that were not. We do not find significant differences among solid edibles, but liquid edibles with parse-able labels cost roughly half as much per unit as those that were not, i.e., the algorithm had better success with cheaper products.

Analyses

Before analysis, observations are sorted into one of eight groups or otherwise discarded. Four groups represent different values for the “inventorytype” variable: 1) dried flower (called “usable marijuana” or “marijuana mix” in the dataset), 2) infused flower, e.g. joints enriched with kief; 3) liquid edibles, and 4) solid edibles. We add four subgroups of the “extracts for inhalation” variable based on text analysis: vaporizers and/or cartridges; solid concentrates for dabbing (e.g. wax/shatter); kief/hash for smoking and/or vaporizing; and oil concentrates sold outside of cartridges. The roughly one-quarter of extracts that remained unclassified were obscured for these comparisons. Further, for analyses involving THC concentration or price-per-THC, we drop data from sales of edibles where potency information could not be assigned from label text. We may also identify cannabis products as one of three chemotypes based on their THC:CBD ratio (Hillig and Mahlberg 2004). Following Jikomes and Zoorob (2018), we identify transactions as either high THC (at least 5:1 THC:CBD ratio), low THC (< 1:5 THC:CBD), or otherwise balanced.

Along these dimensions, we describe several key trends: 1) the composition of the market by product type, 2) average labeled THC and CBD concentrations by product; 3) the prevalence and changing content of cannabis chemovars per product type; and 4) levels and rates of change in the price per intoxication, measured as the price per labeled 10mg THC. When comparing changes in cannabinoid content over time, when computing simple averages we consider the data on a monthly basis, but when reviewing statistical distributions, we compare two snapshots in time (July 2015 versus October 2017). October 2017 is chosen because it is the last full month in the dataset; July 2015 is chosen to provide an earlier point of comparison, at a point after the

market had settled from its early turbulent periods in 2014, and it is also the first month after the imposition of the 37% excise tax.

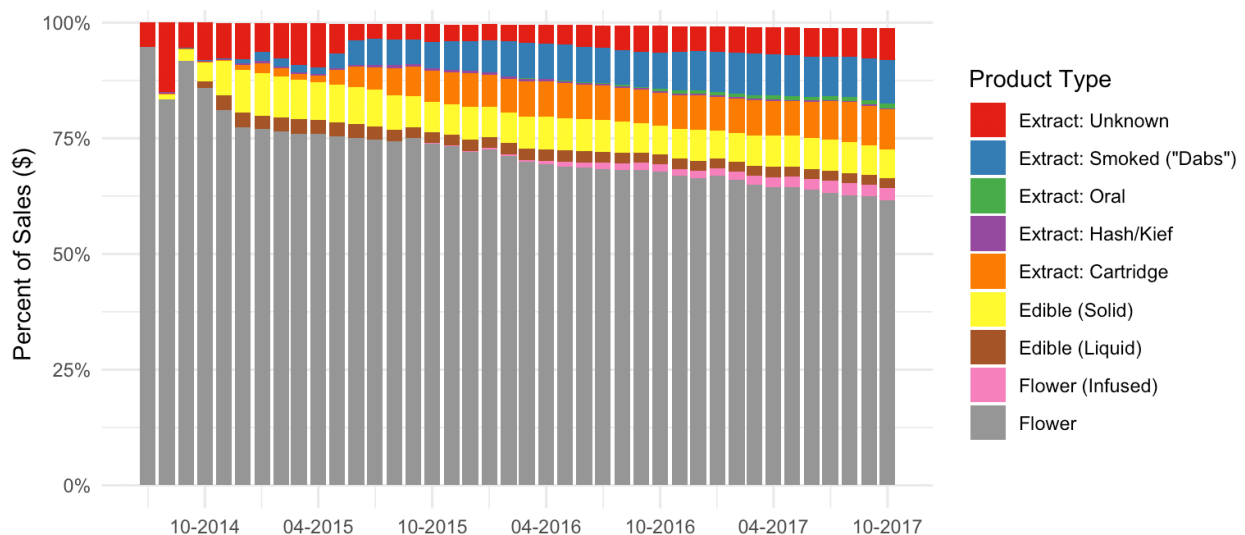
Amid allegations and some statistical evidence of cannabinoid inflation, the reliability of THC potency results reported from Washington cannabis labs has come under question (Black 2017; Jikomes and Zoorob 2018). This potentially confounds potency-based analyses in a way that is difficult to correct. As a means to control for the changing market share of various labs, for estimates of price-per-THC, we complement the analysis with prices estimated by a log-linear regression-based model, including fixed effects for year-quarter and testing laboratory. The model generates predictions of price-per-THC with quantity fixed at one gram (except for edibles, where purchase size is not held fixed by the model) and laboratory set to “Anatek Labs” (arbitrarily, but which has no known scandals regarding its testing performance). For all other analyses, we simply analyze reported THC or CBD values. To facilitate runtime, this model is run on a sample of 5% of the sales data.

Results

Proliferating Product Types

Dried flower marijuana accounts for the majority (59.5%) of sales by dollar value, but its share is slipping as non-traditional products popularize (Figure 3.1). Extracts were the second-largest category (28.5%), followed by solid edibles (6.6%), infused marijuana mix (2.8%), liquid edibles (1.7%), and topicals (0.8%). In dollars, extracts sold for \$27 million in October 2017. The share of sales attributed to extracts has been rising steadily over time, e.g., during the months of October from 2015 to 2017, growing from 8.6% to 16.8% to 26.2%; simultaneously, the share of sales accruing to “usable marijuana” or “marijuana mix package” has been falling away, from 85.9% to 73.9% to 61.6%.

Figure 3.1. Share of Retail Sales by Identifiable Subtype



Cannabinoid Content and Chemotypes

Cannabinoid content ranges widely by product type and over time. Among flower marijuana, average THC concentration has risen to above 21% but the most pronounced increases in potency have occurred among cartridge extracts, perhaps enabled by advances in vaporization technology such that less solvent is required to be mixed with cannabinoid extracts (Figure 3.2). Non-kief extracts averaged 70% THC in the last quarter of data. CBD remains rare, averaging less than 0.5% in flower marijuana, but appears in higher concentrations in solid extracts (2%), cartridges (3%), and non-cartridge liquid extracts (e.g. Rick Simpson’s Oil, Phoenix Tears, “live resin”, at 7% in 2017). Edible products have been excluded from this chart, as they cannot be meaningfully measured with cannabinoid concentration by weight.

Figure 3.2. Average Labeled THC and CBD Content by Product (July 2014 – October 2017)

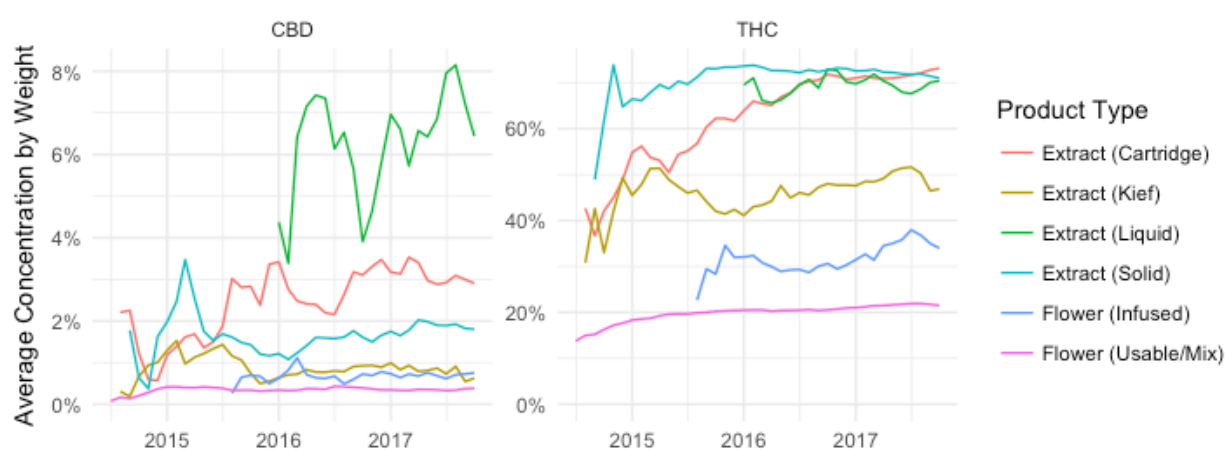


Table 3.2 displays the percentage of sales that each cannabinoid chemotype accounted for, by identifiable product type, in July 2015 and October 2017. In both time periods, high-THC chemotypes dominate the market, accounting for over 99% of flower sales. By October 2017 there are signs of increasing prevalence of high-CBD products in terms of growing sales among product categories that are generally high in CBD (namely, topicals, suppositories, capsules, tinctures, and oral extracts), and also among edible products a shifting composition of chemotypes towards “Balanced” and “High CBD” varieties.

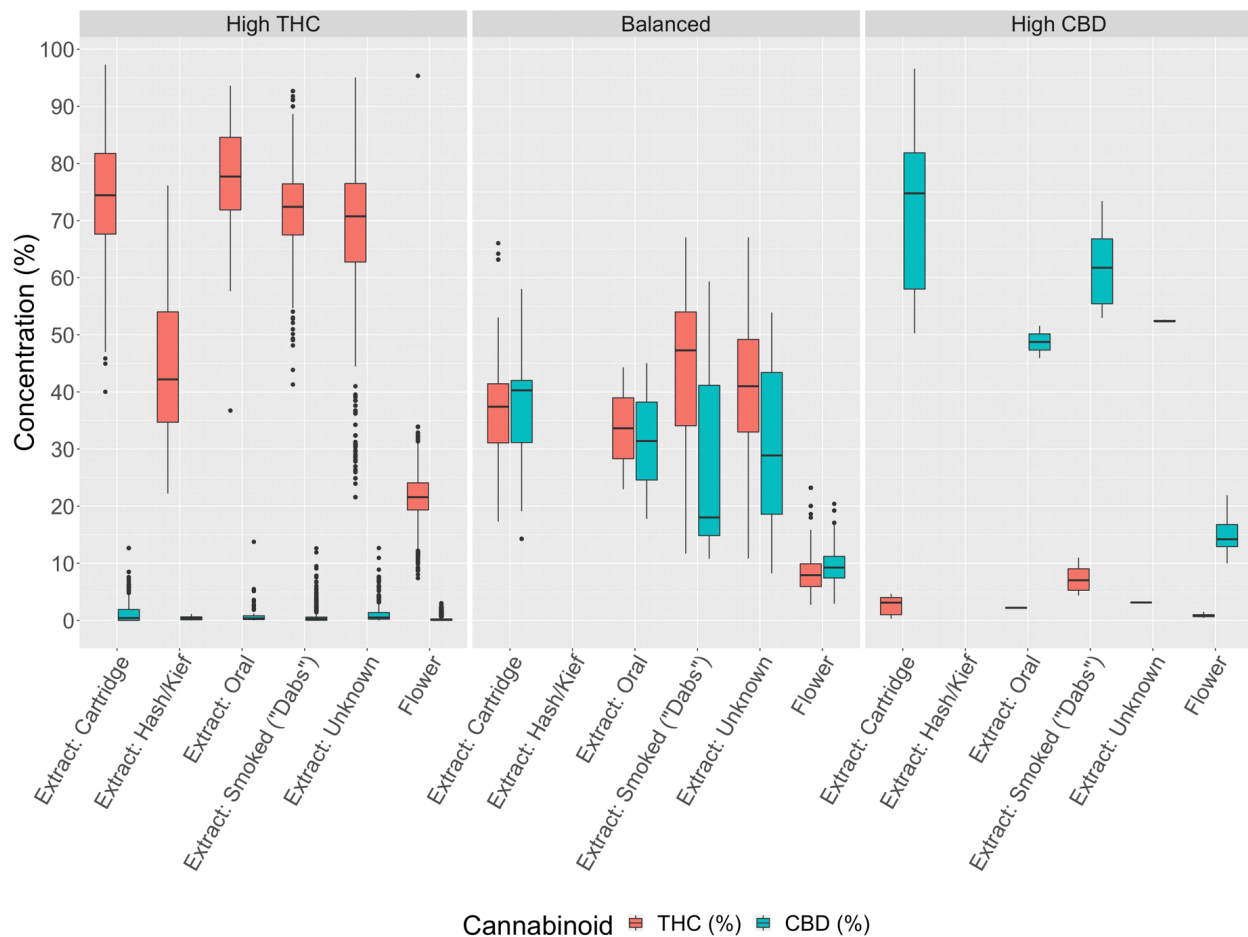
Table 3.2. Prevalence of THC:CBD chemotypes by product type, over time

Product	July 2015			October 2017		
	High THC	Balanced	High CBD	High THC	Balanced	High CBD
Edible (Liquid)	89%	11%	0%	52%	27%	21%
Edible (Solid)	94%	6%	0%	80%	14%	6%
Extract: Cartridge	97%	3%	0%	95%	4%	1%
Extract: Hash/Kief	97%	2%	1%	99%	1%	0%
Extract: Oral	NA	NA	NA	82%	7%	11%

Extract: Smoked ("Dabs")	98%	1%	0%	97%	2%	1%
Extract: Unknown	97%	3%	0%	96%	3%	1%
Flower	99%	1%	0%	99%	1%	0%

For products where THC and CBD content is denominated in percent concentration by weight (i.e., flower and extract products but not edibles), we produce boxplots of THC and CBD concentration among each product-chemotype from the October 2017 data (Figure 3.3). Box borders represent first and third quartiles; whisker tips show the observation nearest to the quartile within 1.5 IQR. This better identifies the THC/CBD content of small but distinct product-chemotype combinations. For instance, 95% of identified cartridge products in October 2017 were high-THC (IQR 68%-82% THC by weight, with almost no CBD), but a non-negligible 4% were “Balanced” (with THC and CBD concentrations commonly ranging between 30% and 40%), and a small but distinct 1% featuring THC levels below 5% and CBD ranging from 58% to 82%.

Figure 3.3. Labeled THC/CBD Concentration by Product Type, Chemotype (October 2017)



Price per Labeled THC

Price per THC varies substantially by product type. When price per THC is computed by simply summing up THC sold and dividing by the sum of retail value, we find that in October 2017, edibles delivered THC in just under \$3 per dose; cartridges were the most expensive form of extract-based product (\$0.69), markedly higher than solid concentrates (\$0.29); and flower delivered THC at by far the cheapest rate (\$0.32) (Table 3.3A). To attempt to control for potential confounders in the form of shifting market shares among labs each with their own testing biases, we generate an additional set of estimates from a log-linear regression with fixed effects for the year-quarter and laboratory, predicting price-per-dose when quantity is held constant at one gram (except for edibles, where purchase size is not held constant; see Figure 3.4, Table 3.3B). As an example of the output of these models, Table 3.4 provides a summary of results for the model to predict among flower cannabis.

Figure 3.4. Regression-based Estimates for Price per THC by Product over time

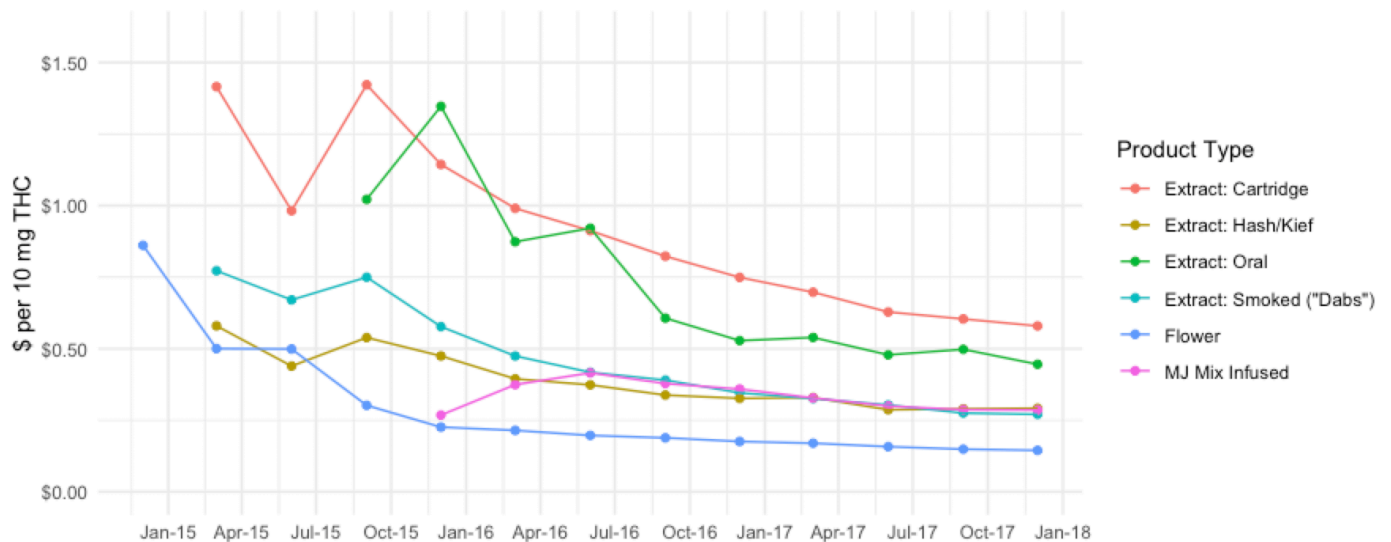


Table 3.3A. Analytic-Based Estimates for Price per 10mg THC

Year-Quarter	Edible (Liquid)	Edible (Solid)	Extract: Cartridge	Extract: Hash/Kief	Extract: Oral	Extract: Smoked ("Dabs")	Flower	MJ Mix Infused
2014-4	40.38	7.73	NaN	NaN	NA	NaN	0.63	NaN
2015-1	11.49	10.25	NaN	NaN	NaN	NaN	0.49	NaN
2015-2	5.96	10.79	1.52	NaN	NA	NaN	0.46	0.27
2015-3	5.77	6.81	1.38	0.63	4.35	0.64	0.46	0.68
2015-4	5.27	5.69	1.27	0.57	1.09	0.52	0.43	0.61
2016-1	4.44	4.86	1.12	0.52	0.63	0.41	0.40	0.53
2016-2	4.02	4.24	0.99	0.48	0.69	0.36	0.37	0.47
2016-3	3.79	4.23	0.89	0.43	0.44	0.34	0.36	0.45
2016-4	3.28	3.83	0.85	0.49	0.47	0.36	0.37	0.46

2017-1	3.09	3.45	0.82	0.44	0.46	0.34	0.36	0.42
2017-2	3.17	3.01	0.76	0.39	0.41	0.32	0.34	0.41
2017-3	3.08	2.91	0.73	0.38	0.43	0.30	0.32	0.40
2017-4	2.94	2.77	0.69	0.40	0.37	0.29	0.32	0.38

Table 3.3B. Model-Based Estimates for Price per 10mg THC

Year-Quarter	Edible (Liquid)	Edible (Solid)	Extract: Cartridge	Extract: Hash / Kief	Extract: Oral	Extract: Smoked ("Dabs")	Flower	MJ Mix Infused
2014-4	NA	NA	NA	NA	NA	NA	1.09	NA
2015-1	16.05	11.92	NA	NA	NA	NA	0.80	NA
2015-2	6.34	10.59	NA	NA	NA	NA	0.69	NA
2015-3	5.64	7.33	1.11	NA	NA	NA	0.67	NA
2015-4	5.17	6.09	0.93	0.70	0.92	0.59	0.62	0.79
2016-1	4.41	5.42	0.83	0.68	0.71	0.50	0.58	0.57
2016-2	4.11	4.82	0.76	0.63	0.76	0.47	0.55	0.50
2016-3	3.73	4.67	0.69	0.58	0.65	0.46	0.53	0.47
2016-4	3.17	4.34	0.66	0.57	0.59	0.43	0.54	0.45
2017-1	2.95	4.06	0.62	0.57	0.59	0.41	0.52	0.41
2017-2	2.99	3.54	0.56	0.49	0.53	0.38	0.50	0.36
2017-3	3.14	3.36	0.54	0.47	0.57	0.36	0.48	0.33
2017-4	3.05	3.23	0.52	0.48	0.48	0.35	0.47	0.34

Table 3.4. Summary of Flower Price Model with Lab Fixed Effects

	<i>Dependent variable:</i>
	log(mgTHC_price)
yrq2014 4	-0.358 ^{***} (0.008)
yrq2015 1	-0.665 ^{***} (0.008)
yrq2015 2	-0.825 ^{***} (0.007)
yrq2015 3	-0.853 ^{***} (0.007)
yrq2015 4	-0.928 ^{***} (0.007)
yrq2016 1	-0.986 ^{***} (0.007)
yrq2016 2	-1.054 ^{***} (0.007)
yrq2016 3	-1.077 ^{***} (0.007)
yrq2016 4	-1.065 ^{***} (0.007)
yrq2017 1	-1.101 ^{***} (0.007)
yrq2017 2	-1.146 ^{***} (0.007)
yrq2017 3	-1.187 ^{***} (0.007)
yrq2017 4	-1.198 ^{***} (0.007)
lab_nameAnatek Labs	-0.114 ^{***} (0.004)
lab_nameCannaSafe Analytics	-0.031 ^{***} (0.008)
lab_nameCAPITOL ANALYSIS	-0.111 ^{***} (0.005)
lab_nameConfidence Analytics	0.042 ^{***} (0.002)
lab_nameDragon Analytical Laboratory	-0.117 ^{***} (0.010)
lab_nameFloraLabs Inc	-0.034 ^{***} (0.012)
lab_nameG.O.A.T. Labs	-0.040 ^{***} (0.004)
lab_nameGreen Grower Labs	-0.111 ^{***} (0.003)
lab_nameHD Analytics	0.026 ^{***} (0.010)
lab_nameIntegrity Labs	-0.038 ^{***} (0.003)
lab_nameLander Robinson Labs	-0.071 ^{**} (0.036)
lab_nameMedicine Creek Analytics	0.004 (0.007)
lab_nameMOLECULAR TESTING LABS	0.054 (0.066)
lab_namePeak Analytics Laboratory Testing Services	-0.143 ^{***} (0.003)
lab_namePhytalab	-0.146 ^{***} (0.010)
lab_nameSteep Hill Labs	0.203 ^{***} (0.006)
lab_nameTesting Technologies	-0.137 ^{***} (0.003)
lab_nameThe Werc Shop	0.224 ^{***} (0.013)
lab_nameTrace Analytics	-0.006 (0.006)
lab_nameTrue Northwest, Inc.	-0.161 ^{***} (0.003)
usableweight	-0.047 ^{***} (0.0001)
Constant	-1.850 ^{***} (0.007)
Observations	738,798
R ²	0.257
Adjusted R ²	0.257
Residual Std. Error	2.033 (df = 738763)
F Statistic	7,511.006 ^{***} (df = 34; 738763)
Note:	$p < 0.1$; $p < 0.05$; $p < 0.01$

Conclusion

Washington State's traceability dataset provides ample data for a granular analysis of patterns and trends in products, potencies, and prices. One contribution of these data is to monitor changes in product variety. The biggest shift is away from flower (59% of sales in October 2017) and towards extracts (28.5%), with the remainder accounted for primarily by edibles (8.3%) alongside miscellaneous extracts such as infused flower, tinctures, topicals, capsules, and suppositories. Among extract products, our analysis identifies that 35% were determined to be solid extracts usable for dabbing, and another 35% were determined oil-containing cartridges, roughly 5% kief or other oil extracts, and the remaining one-quarter unclassified. It is likely that sales of solid concentrates exceeded \$10 million in October 2017. Sales of solid concentrates and cartridges continue to rise, perhaps partially driven by its low price per THC, which may give rise to concerns given the risks associated with dabbing.

Regulatory decisions and events have helped to shape the products and prices offered in the regulated cannabis market. Notably, during the first two years of the recreational cannabis market, it existed alongside an unregulated medical market; sales data from those medical dispensaries was not recorded in any database, and therefore hidden from our analysis. By July 2016, when medical cannabis businesses were required to obtain recreational licenses to continue operation, the entirety of this commercial activity had been shifted into the regulated system and therefore began to appear in the traceability data (with the exception of illegal, unlicensed activity, which nonetheless continues at an unknown scale throughout the study period). It is possible that this has helped to account for some changes observed in the market, e.g., the modest growth in high-CBD products, but without detailed study of what products were sold among unregulated medical cannabis dispensaries, the claim is difficult to evaluate.

That said, a key limitation to this study concerns the reliability of potency data. Laboratory-provided cannabis testing results are often viewed with suspicion; studies of products sold in medical cannabis dispensaries show the THC and CBD content of products are often mislabeled, tending to overstate the actual contents (Bonn-Miller et al. 2017; Vandrey et al. 2015). Washington's cannabis testing laboratories have been accused of improper practices, including inflating potency scores in order to attract business from cannabis producers (Black 2017). Two laboratories have had their licenses suspended by the LCB for poor testing practices, including the state's largest lab (Peake 2017). Indeed, analysis of Washington's cannabis testing data shows evidence of "cannabinoid inflation", and systematic differences in THC and CBD results that persist even after controlling for external factors (Jikomes and Zoorob 2018). The magnitude of these differences is not insignificant. Jikomes & Zoorob (2018) studied reported THC concentrations for high-THC cannabis flower and extracts among six laboratories, and after controlling for plausible confounds, lab-average scores ranged from 18% to 23% for high-THC flower and 65-75% for high-THC concentrates. We have attempted to partially control for these influences with a regression-based price model with fixed effects for testing laboratory, but this cannot alone fully correct for noise generated by poor testing practices; as such, our analysis is best interpreted as describing *labeled* THC content, which may not necessarily reflect its actual values.

The potential application of CBD-rich cannabis products for medical or therapeutic purposes has received substantial coverage in the media and rhetoric, but CBD-rich products

remain a very small share of Washington’s legal cannabis market. In October 2017, 99% of flower cannabis was classified as a high-THC chemovar, along with over 95% of most other extract product types, 80% of solid edibles, and half of liquid edibles. Nonetheless, high-CBD or “balanced” chemovars have become somewhat more common among solid concentrates and vaporizer cartridges, with CBD content typically ranging from 15 to 80%; further, there has been the arrival of new product types, e.g., non-cartridge oil extracts, tinctures, topicals, and suppositories, though these carry very small market shares. Monitoring growth of such CBD-rich products may be useful to pragmatically measure changing practices of using cannabis for health-related reasons.

Another benefit is to evaluate prior hypotheses regarding price. Many experts predicted the decline in cannabis prices that has been recorded in Washington and Colorado. Economic models suggest that large-scale commercial production of cannabis could support very low prices, in the absence of taxation and other regulatory costs. Although many naïve users are often not very sensitive to changes in price, regular users are more price sensitive, as are youth at risk of developing habits. Given that a 10mg “serving size” of labeled THC in usable marijuana form costs only 32 cents, estimating the public health impact of potential price changes requires considering for how long prices will continue to fall, and how changes in prices will affect levels of initiation of cannabis use among non-users and the intensity of use by current regular users.

Since THC is the primary intoxicating ingredient in cannabis, and cannabis is purchased mainly for its intoxicative effects, one might have expected a smaller range in prices per THC across different product types. However, consumers may also wish to pay more for products that offer greater convenience, appear more healthful, or have a certain experiential quality. Further, some modes of use deliver THC to the bloodstream and produce intoxication more efficiently than others. When cannabis is smoked or vaporized, a certain amount of THC is lost to side stream smoke or vapor. When THC is consumed via eating or drinking, one estimate that each mg THC is 5.7 times more effective than when consumed via smoking or vaporization (Orens et al. 2015). Attempting to account for these different rates of efficiency would generate a different set of price-per-THC-intoxication estimates, e.g., estimates for price-per-THC among edibles, after dividing by 5.7, would look much more similar to prices observed in other products.

Further analysis of this kind is limited by the availability of data. Researchers are fortunate that Washington State has made its seed-to-sale data available and could benefit further if granted access to similar traceability datasets from other states. Even then, Washington traceability data has stopped being publicly available in October 2017, due to changes in state data contractors; resumption of this dataset is key to further analysis. Database design and the quality of information in data fields is also important. The Washington State database is suboptimal in that potency information is not consistently recorded for edible products, and that many discrete “extract for inhalation” products are grouped together into the same category. Further, some fields like the free-text “productname” are helpful to analysts looking to better describe the data, but licensees often leave them empty or fill them with mysterious codes and abbreviations. To expedite analysis of these data, regulators should consider providing some data monitoring and data cleaning services in-house, before release to researchers or the public, and also to encourage licensees to provide data in clear and consistent ways.

Chapter Four. Associations Between a Zero Tolerance BAC Law and Traffic Crashes and Fatalities: Insights from a Novel Synthetic Control Method¹¹

Steven S. Davenport, Pardee RAND Graduate School

Michael Robbins, RAND Corporation

Magdalena Cerda, NYU School of Medicine, Dept. Population Health, Center for Opioid Epidemiology and Policy

Ariadne Rivera-Aguirre, NYU School of Medicine, Population Health

Beau Kilmer, RAND Corporation, Drug Policy Research Center

Abstract

Background and Aims: Debates about lowering the blood alcohol concentration (BAC) limit for drivers are intensifying in the United States and other countries, and the World Health Organization recommends the limit for adults should be 0.05%. In January 2016, Uruguay implemented a zero-tolerance law that reduced the BAC limit for all drivers—not just youth—to 0.00%. This paper examines the effect of this policy change on traffic crashes and fatalities.

Methods: To evaluate the effect of this legal change, we use quasi-experimental methods that match Uruguay with a control country, Chile. Population and vehicle crash data were obtained for Chile and Uruguay and transformed into a locality-month panel dataset covering 2013 to 2017. Estimates were generated with a synthetic control method (“microsynth”) that constructs a synthetic control consisting of local areas in Chile as the counterfactual for outcomes in

Uruguay, matched across pre-intervention period outcomes and covariates. **Results:** Synthetic control results suggest a substantial reduction in fatal crashes at 12 months (20.9%; p-value=0.024); the estimated effect at 24 months was somewhat smaller and less precise (14%; p-value=0.058). The estimated effect on crashes with more than mild injuries is negative but imprecise. **Conclusions:** This is the first quasi-experimental evaluation of a national general population zero-BAC policy. Using data from Chile to compute the counterfactual, we find evidence suggesting that Uruguay’s zero tolerance BAC law reduced roadway fatalities immediately after the law was implemented. Whether these reductions persist and whether they can be replicated in other jurisdictions are questions ripe for future research.

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Introduction

Worldwide, traffic crashes account for over 1.3 million deaths and nearly 50 million injuries annually. They are the leading cause of death for individuals aged 5-29 years and the eighth largest cause of death for all age groups (World Health Organization 2018b). These rates are expected to grow, led by rapidly urbanizing developing countries (World Health Organization 2018b). Alcohol-impaired driving is a significant contributor, accounting for more than one-fifth of road deaths and one-tenth of serious injuries worldwide (International Traffic Safety Data and Analysis Group 2017). As part of a broader strategy to reduce automobile crashes and their consequences, many countries have lowered the maximum blood alcohol concentration (BAC) limit for drivers (World Health Organization 2004). The World Health Organization recommends the limit for adults should be 0.5 grams of alcohol per liter of blood, which is commonly referred to as 0.5g/L or 0.05% (World Health Organization 2004).

The evidence on the effectiveness of BAC limits draws on several sources. Even at low BACs (e.g., 0.01%), clinical studies demonstrate measurable impairment, and epidemiological studies show increased at-fault crash risk (Phillips, Sousa, and Moshfegh 2015). Quasi-experimental evaluations are valuable but have disproportionately concerned limits of 0.05% or higher in the developed world, e.g., Canada (Blais et al. 2015), Scotland (Haghpanahan et al. 2019; Hamnett and Poulsen 2018), New Zealand (Hamnett and Poulsen 2018), the Netherlands, France, Austria, and Australia (J. C. Fell and Voas 2006). These generally find reductions in crashes, especially fatal crashes, though varying in magnitude and decreasing over time.

Evaluations of lower BACs are rare. Fourteen countries have national zero-BAC laws, and to our knowledge, none appear to have been evaluated. Of the twenty seven other countries with limits below 0.03% (World Health Organization 2018a), evaluations have been conducted only in Chile (Nistal-Nuño 2017; Otero and Rau 2017a), Japan (Desapriya et al. 2007), Brazil (Andreuccetti et al. 2011; Volpe, Ladeira, and Fantoni 2017), Sweden (Norstrom and Laurell 1997; Ross and Klette 1995), and Norway (Assum 2010; Ross and Klette 1995). Both Chilean studies found reductions in crash injuries, diminishing over time. In Brazil, Andreuccetti et al. found reductions in traffic fatalities and injuries, with larger effects on fatalities and in areas suspected to have more enforcement.

Studies of laws targeting young and/or novice drivers, whose driving appears particularly sensitive to alcohol (Peck et al. 2008), provides additional quasi-experimental evidence on zero-BAC policies, but tend to concern higher income countries, e.g., Ontario (Byrne et al. 2016) and U.S. states (Blomberg 1992; Carpenter 2004; Carpenter and Harris 2005; J. Fell et al. 2007; Lacey, Jones, and Wiliszowski 2000; Liang and Huang 2008; S. Martin and Andreasson 2006; Voas, Tippetts, and Fell 2003; Wagenaar, Malley, and Lafond 2001). Results have been mixed and vary based on study design, but many found reductions in drunk driving among the affected age range (Blomberg 1992; J. Fell et al. 2007; Lacey, Jones, and Wiliszowski 2000; S. Martin and Andreasson 2006; Voas, Tippetts, and Fell 2003).

We contribute to this literature by applying a new synthetic controls method and evaluating Uruguay's 2016 zero-BAC law. The novel synthetic controls method ("microsynth") allows construction of a synthetic Chile matched to Uruguay at small-scale geographies, as to improve treatment-control matching and capture within-nation heterogeneity (M. W. Robbins

and Davenport 2019; Michael W. Robbins, Saunders, and Kilmer 2017). To evaluate Uruguay's policy, we exploit five years of individual-level crash data (2013-2017) in both countries, estimating effects on traffic crashes involving fatalities or severe injuries. We conduct sensitivity analysis, investigating differential effects on nights and weekends, by type of crash (fatal, non-fatal, all), study timeframe, and using an alternate quasi-experimental approach (difference-in-differences). This study is the first quasi-experimental evaluation of a national general population zero-BAC policy, and the first application of the novel synthetic control method to evaluate a BAC law.

Background in Chile and Uruguay

Pursuant to a law signed in December 2015 and effective January 9, 2016, Uruguay became the fifteenth country to prohibit driving with any detectable level of alcohol (World Health Organization 2018a). Previously, a 2007 law mandated incrementally reducing limits from 0.8 g/L to 0.3 g/L within three years, leading to reductions to 0.5 g/L (November 2008) and 0.3 g/L (March 2009). Penalties escalate for each violation, from a six-month license suspension on first offense, to license revocation on the second, and referral to rehabilitation services on the third; importantly, refusal to comply with impairment tests is treated as admission of guilt (Pechansky and Chandran 2012).

Chile passed major traffic legislation in 2005 and 2012. The 2005 law was a comprehensive reform of traffic rules, and is credited with major reductions in traffic fatalities and injuries, especially where paired with increased enforcement (Nazif-Munoz, Quesnel-Vallée, and Van Den Berg 2015; Nazif-Muñoz, Quesnel-Vallée, and Van den Berg 2014). A March 2012 law reduced BAC thresholds under Chile's two-tiered structure separating "impaired" and "intoxicated" driving, from 1.0/0.5 g/L respectively to 0.8/0.3; evaluations show mixed results, including reductions in injury crashes but diminishing over time (Nistal-Nuño 2017; Otero and Rau 2017b). These policies contributed to large (9.5% annual) declines in per capita traffic fatalities from 2006 to 2015 (Nistal-Nuño 2018). We chose Chile as comparison due to data availability; similar GDP per capita; overlapping latitude; and having a blood alcohol policy (0.3 g/L) identical to Uruguay's during the pre-intervention period, which was held constant throughout the study period without substantial policy change.

Data & Methods

Data

Census population data were obtained for the most recent years and lowest levels of aggregation available in Chile (2002) and Uruguay (2011). Population counts in Chile are provided across 186 geographic units, each containing one or several communes (so-called "census commune-groups"). For each of Uruguay's nineteen departments, we obtain population counts in a) each city with 1,000 people or more, b) smaller cities, and c) rural areas.

Individual-level crash data were acquired throughout the evaluation period (2013-2017) from Uruguay's National Unit of Road Safety (UNASEV) and Chile's National Traffic Safety Commission (CONASET) (CONASET 2019; UNASEV 2019). Observations included crash date, time, location, and occurrence of injuries of various severities, including death. The grain of location data varies by each country's administrative subdivisions. Chile is divided

hierarchically into 16 regions, 56 provinces, and 346 communes – the lowest-level unit, consisting of either: subdivisions of large cities; individual medium-sized cities; or groups of small cities and/or rural areas (Government of Chile 2019). Uruguay contains 19 departments, each containing rural area and one of 298 localities, comprising small cities or groups of small towns, but excluding rural areas (Uruguay Military Geographic Organization 2019; Uruguay National Institute of Statistics 2019). Chilean crash data include region and commune, while Uruguayan crashes track department, locality, address, and geocoordinates.

The severity of injuries is reported differently for each country: Chile categorizes injuries as mild, moderate, or severe; Uruguay uses only mild and severe designations. To reconcile designations, we classify crashes as fatal or non-mild (for the latter, that means combining moderate and severe for Chile). (See appendix for additional detail.)

Crash and population data are merged using string-matching methods, designating each crash to a Chilean census commune-group or Uruguayan city or department-rural-area. For a small number of the crashes (0% for Chile and 2% for Uruguay), we could not complete the merge (see appendix for additional information). To facilitate cross-country comparisons, we aggregate low-population Uruguayan areas to groups of at least 20,000 in population.

Synthetic Control Methods

The fundamental difficulty underpinning quasi-experimental evaluation is the potential for unobserved confounding to bias estimated effects. This is accounted for differently in different procedures.

The classic differences-in-differences model compares pre- and post-intervention outcomes across a single treated and single control unit (Angrist and Pischke 2009). Post-intervention outcomes in the control unit can be treated as the treated unit’s counterfactual outcome (i.e., what would have been observed in the absence of treatment) by invoking the “parallel trends” assumption, i.e. the absence of differential confounding trends across units during the study period. This is inherently untestable but can be partially validated by comparing observable trends in the data. This approach may be extended to settings involving additional data units and time periods, which yields several analytical benefits, including the ability to quantify uncertainty (see Donohue and Ho (Donohue III and Ho 2007) among others).

Building on the classic synthetic controls setting of Abadie and Gardeazabal (Abadie and Gardeazabal 2003) and Abadie et al. (Abadie, Diamond, and Hainmueller 2010), we consider a method by Robbins et al (Michael W. Robbins, Saunders, and Kilmer 2017) designed for disaggregated data where multiple cases collectively compose the treated area. This brings several advantages: 1) taking advantage of the small-scale geographic grain of the crash data, 2) modeling multiple outcomes simultaneously, and 3) generating a permutation-based placebo estimator of uncertainty.

Weights are selected to satisfy three sets of constraints. Notionally, we assume there are J_0 and $J - J_0$ pre- and post-intervention regions, respectively, and there are T_0 and $T - T_0$ pre- and post-intervention time periods, respectively. Specifically, letting w_j denote the nonnegative weight assigned to (untreated) region j in Chile, we impose first

$$\sum_{j=1}^{J_0} w_j = J_0 - J$$

such that weights sum to the number of regions in Uruguay. Likewise, letting \mathbf{R}_j indicate a vector of time-invariant covariates for region j , we impose

$$\sum_{j=1}^{J_0} w_j \mathbf{R}_j = \sum_{j=J_0+1}^J \mathbf{R}_j$$

such that the synthetic control matches Uruguay across all covariates. Letting Y_{ijt} indicate the value of outcome i in region j at time t , we enforce

$$\sum_{j=1}^{J_0} w_j Y_{ijt} = \sum_{j=J_0+1}^J Y_{ijt}$$

for each outcome i and each pre-intervention time t for $1 \leq t \leq T_0$. These constraints ensure synthetic Uruguay maximally matches Uruguay across outcomes and covariates across all pre-intervention time points. After finding a satisfactory set of weights w_j for each untreated case j , the term $\sum_{j=1}^{J_0} w_j Y_{ijt}$ for $t > T_0$ estimates the cumulative value of outcome i that would have been observed in Uruguay in the absence of policy change. We therefore estimate the effect of the law on outcome i , aggregated across all post-intervention times, as follows:

$$\hat{\alpha}_i = \sum_{t=T_0+1}^T \left(\sum_{j=J_0+1}^J Y_{ijt} - \sum_{j=1}^{J_0} w_j Y_{ijt} \right).$$

Effects are calculated as percent change from counterfactual, i.e., $100\hat{\alpha}_i / \sum_{t=T_0+1}^T \sum_{j=1}^{J_0} w_j Y_{ijt}$. If outcomes are modeled jointly, this generates a single set of weights incorporating all outcome-constraints but reports separate estimates for each outcome.

This approach is implemented with the `microsynth` package in R (M. W. Robbins and Davenport 2019). If `microsynth` cannot identify nonnegative weights w_j that exactly satisfy each constraint, then a quadratic programming method finds nonnegative weights that satisfy constraints as closely as possible. Uncertainty is modeled with a permutation approach with 1000 permutation groups.

Models

In our primary models, weights are fit jointly to two outcome variables (fatal and non-mild-injury crashes) and a single time-invariant covariate (population). Effects are estimated for three distinct post-intervention time periods. All time frames begin in 2013, one year after implementation of Chile's 2012 traffic reform, and feature the first post-intervention observation on January 2016, the month the Uruguayan law became effective (January 9). Intervention endpoints vary: 1) December 2016 (first year post-intervention), 2) June 2017 (before the first Uruguayan cannabis pharmacy sale on July 19), and 3) December 2017 (two years post-intervention).

Crashes ending with only mild or no injury were not entered into models for several reasons. First, adding additional outcome variables to the model introduces additional constraints and therefore can impede the closeness of treatment-control match on matched variables; second, these variables show higher variation over time, potentially suggesting changes in reporting or measurement practices; and finally, they are of lesser consequence from a public health perspective.

Sensitivity Analysis

Sensitivity tests explore differential effects and sensitivity to modeling choices. To investigate differential effects on crashes suspected to involve drunk drivers, we create proxy measures for crashes occurring at times where drunk driving is common, i.e., nighttime (after midnight but before 6am) or weekends (between 9PM Friday and 6AM Monday), and re-run models with these as outcome variables. These proxies for alcohol-involved crashes have been used in earlier studies (Assum 2010; Voas, Romano, and Peck 2009).

Effects are also estimated with a negative binomial difference-in-differences model. Difference-in-difference models are specified as negative binomial with a log-scale outcome, and unlike the primary synthetic controls models, difference-in-differences models are fit separately to each outcome (Venables and Ripley 2002). The appropriate model uses fixed effects to control for the data unit and time-period:

$$\log(\mu_{jt}) = \beta_t + \gamma_j + \alpha D_{jt}$$

Where μ_{jt} is the expected outcome value for region j at time t ; β_t are fixed effects for time t ; γ_j is a fixed effect for region j ; α is the law's effect; and D_{jt} is an indicator variable equaling one if region j is in Uruguay and t is post-intervention, but otherwise is zero.

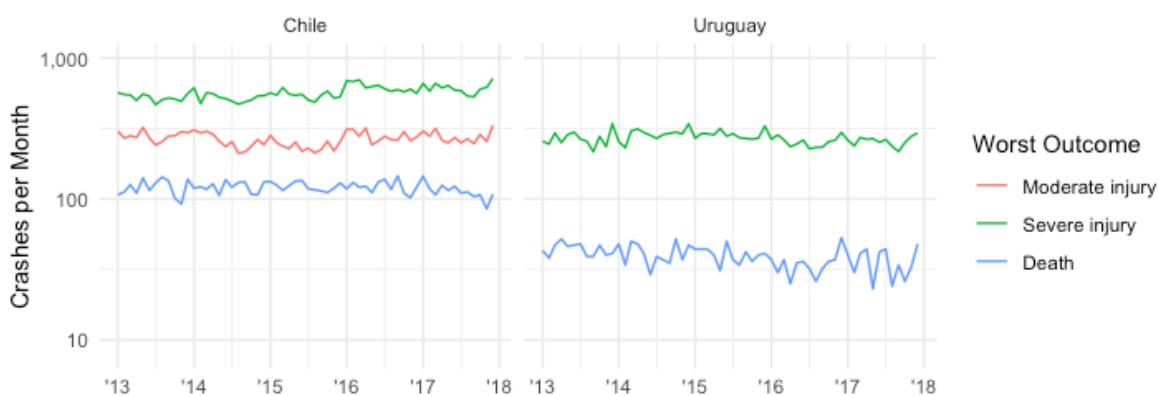
Results

Table 4.1 tabulates crashes by outcome, and Figure 4.1 shows the number of crashes (axis transformed log base 10) for these outcomes by country-month. (See appendix for expanded detail.)

Table 4.1. Raw Crash Counts by Injury Severity in Chile and Uruguay, 2013-2017

Country	Moderate Injury	Severe Injury	Death
Chile	16,023	33,971	7,212
Uruguay	NA	16,269	2,352

Figure 4.1. Reported Crashes by Worst Outcome, Chile and Uruguay, 2013-2017



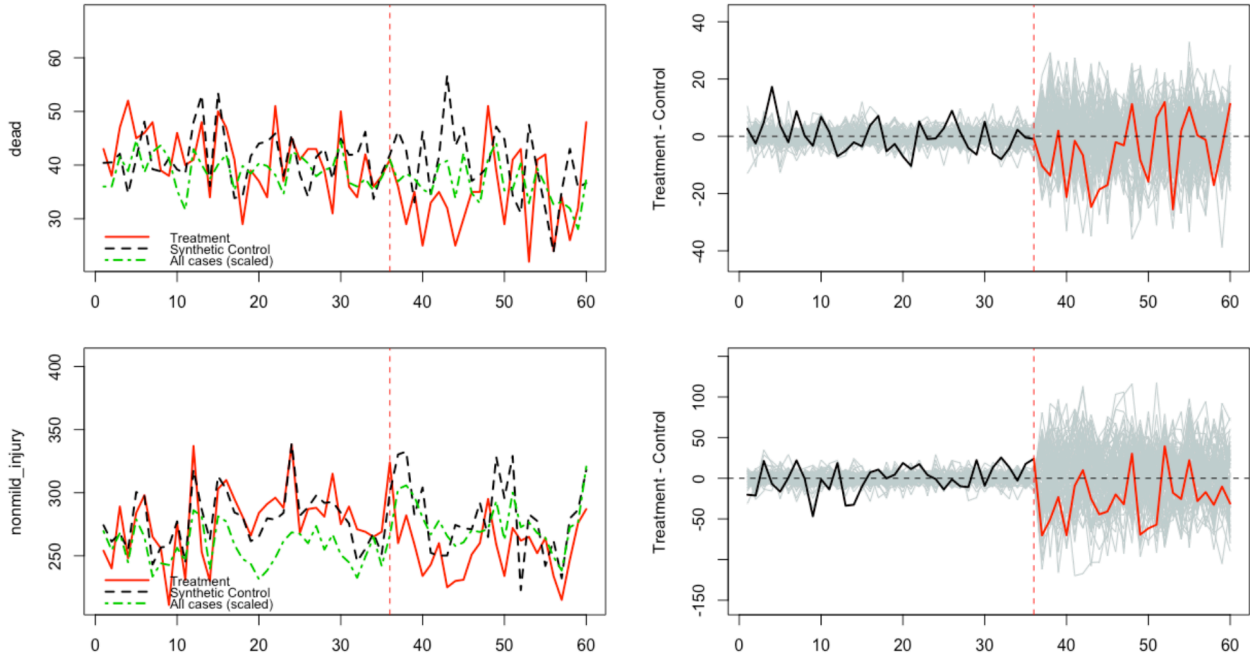
Primary synthetic control models show substantial reductions in deaths and smaller decreases in non-mild injuries. Table 4.2 shows results from the main models for each time period (rows indicate different time periods, each fit jointly on the two outcomes).

Table 4.2. Results from Microsynth Models: Percent Change (Permutation-based p-value) by Crash Worst Outcome

Evaluation End Date	Non-Mild Injury	Death
Dec 2016	-10.2% (0.342)	-20.9% (0.024)
June 2017	-10.5% (0.260)	-17.9% (0.020)
Dec 2017	-9.4% (0.270)	-14.1% (0.058)

Figure 4.2 displays time series plots comparing treatment-synthetic control outcomes before and after the implementation, as estimated with December 2017 as the evaluation end-date. To visualize uncertainty, treatment-control differences are plotted for permutation groups as well. Models suggest large reductions in the aftermath of the policy (20.9% reduction in fatal crashes after 12 months) with diminishing effects over time, though reductions among moderate/severe injury crashes have low statistical precision.

Figure 4.2. Time series plots from Microsynth model (Post-Period: Jan 2016 – Dec 2017)



Sensitivity Analysis

All models estimated reductions in rates for each crash type(s), though statistical precision was only achieved when fatal crashes were modeled individually, or jointly along with non-mild injury crashes. Table 4.3 displays results of additional microsynth models, each deployed on different time periods and different isolations and combinations of crash types and recoding options. Each row represents a different model run, with specifications according to columns; where outcome variables are empty (“-”), that variable was omitted from the model. Evaluation periods begin January 2017, with the 12-month evaluation window ending December 2017.

Table 4.3. Sensitivity Analysis

Scenario	Months After Intervention	Death	Non-Mild Injury	Severe Injury
Main results from Table 4.2	12	-20.9% **	-10.2%	-
	18	-17.9% **	-10.5%	-
	24	-14.1% *	-9.4%	-
If we drop moderate injuries from Chile	12	-22.4%	-	-16.2%
	18	-15.0%	-	-9.6%
	24	-9.7%	-	-16.8%
Nights only	12	-20.5%	-12.7%	-
	18	-12.8%	-9.0%	-

	24	-4.7%	-4.6%	-
	12	-29.6% ***	-12.3%	-
Weekend only	18	-28.8% ***	-11.0%	-
	24	-26.0% ***	-10.2%	-

Notes: Coefficients are provided for the number of fatal crashes, non-mild injury crashes, and severe-injury crashes for each outcome included in the model. Permutation-based p-value thresholds are indicated with *, **, or *** for p-values < 0.1, < 0.05, and < 0.01, respectively.

Results are sensitive to how injury definitions are reconciled across countries, in part because changes to the matching variables can lead to a re-calculation of synthetic control weights. We implemented two alternatives: 1) matching jointly on fatal crashes and severe injury crashes; and 2) matching jointly on fatal crashes and non-mild injury crashes (combining moderate and severe). The latter approach is preferred because it generates a closer treatment-control match pre-intervention (measured by mean squared error) and smaller design effect.¹²

Drivers are much more likely to be drunk at night or on weekends, so one would expect models to show larger reductions when restricted to these crash times. This is the case for weekend crashes (Friday 9PM – Monday 6AM), but not night-time crashes (midnight – 6AM). By the end of the second year, in one model, night-time crash reductions shrink to as far as 4.7%. This discrepancy is counter-intuitive, and may reflect low statistical precision related to a smaller dataset due to the time restriction (in these data, night-time crashes account for 19% of all crashes ending in death).

Difference-in-difference models show similar but more precise results. Table 4.4 combines results from several models, varying the sole dependent variable (crash injury-outcome) and data subset (crash time). Time-generic models found 14% reductions in fatal crashes, 17% for severe injuries, and 19% for non-mild injuries. Estimated reductions were larger when restricted to weekend or night-time crashes, as one might expect given that night-time and weekend crashes are more likely to be alcohol-related, except for fatal crashes occurring at night, among which there was estimated almost no change (-1.3%).

Table 4.4. Differences-in-Differences Results (Evaluation Period: Jan 2016 – Dec 2017)

Crash type	Any time		Weekend Only		Nights Only	
	% Change	p-Value	% Change	p-Value	% Change	p-Value
Dead	-14.4%	0.002	-17.6%	0.014	-1.30%	0.912
Severe Injury	-17.0%	0.000	-22.0%	0.000	-27.0%	0.000
Non-Mild Injury	-19.3%	0.000	-23.7%	0.000	-30.6%	0.000

¹² MSE was 169 for the preferred model versus 4,533; design effect was 1.46 versus 13.53.

Discussion

Using data from Chile to estimate the counterfactual, we find evidence suggesting that Uruguay's zero tolerance BAC law reduced roadway fatalities immediately after the law was implemented. Synthetic control results suggest a substantial reduction in fatal crashes at 12 months (20.9%; p -value=0.024); the estimated effect at 24 months was somewhat smaller and less precise (14%; p -value=0.058). The estimated effect on crashes with more than mild injuries is negative but imprecise.

These results provide additional evidence supporting low-to-no BAC driving limits, at lower levels than the 0.5g/L adult limit recommended by the World Health Organization (World Health Organization 2004). Changes in BAC laws are most effective as part of a multi-faceted strategy, e.g. along with policies targeting motorcycle helmets, child restraint systems, seat belts, speed limits, safety standards for roads and vehicles, and post-crash healthcare (World Health Organization 2004), and alcohol prices and tax structure (Elder et al. 2010). Our challenges comparing injury rates across countries emphasizes the value of cross-country harmonization of definitions of alcohol-related road casualties across countries, e.g., with the Maximum Abbreviated Injury Scale (MAIS) (International Traffic Safety Data and Analysis Group 2017; World Health Organization 2018b).

Quasi-experimental studies are generally vulnerable to confounding by unobservable factors. One potential confounder is Uruguay's legalization of cannabis in December 2013, establishing three ways for individuals to register to acquire cannabis: self-production, membership in a growers' club, or purchase from a pharmacy. Registrations for home-cultivation started August 2014, and for clubs in October 2014 (Cerdá and Kilmer 2017; Institute for Regulation and Control of Cannabis (IRCCA) 2019a). At the time of the first pharmacy sale in July 19, 2017, only 7,000 people had registered to home-cultivate, and fewer than 2,500 for membership in clubs (Institute for Regulation and Control of Cannabis (IRCCA) 2018). In the first month of sales, registrations to purchase increased from 4,900 to 13,000 (Hudak, Ramsey, and Walsh 2018). Even then, strains sold at pharmacies were limited to very low levels of THC (2%) until the introduction of a more potent (9%) strain in late 2017 (Hudak, Ramsey, and Walsh 2018). However, sensitivity tests that evaluated effects only through June 2017 (before pharmacy sales) show similar (even modestly larger) effects to models ending December 2017.

Another potential confounder is intensity of law enforcement. Several studies have found larger reductions in crashes in high-enforcement areas (Andreuccetti et al. 2011; Nazif-Muñoz, Quesnel-Vallée, and Van den Berg 2014), and inadequate traffic enforcement is common among South American countries (Pechansky and Chandran 2012). The WHO rates Chile as 6/10 in intensity of enforcement of drunk driving laws, compared to 9/10 in Uruguay (World Health Organization 2018b) – if there occurred changes in the intensity of enforcement during our study period, those may have been partially responsible for observed differences in crash outcomes.

Whereas many comparable studies examine only pre- and post- outcomes for a single country, ours uses an international control group composed of areas within Chile – another South American country, with similar drunk driving policies to Uruguay before the intervention, and no significant relevant policy changes afterward. This helps control for secular trends across both countries for which we do not have observable data, e.g. changes in technology and climate.

Another strength is the introduction of the micro-level synthetic controls method (M. W. Robbins and Davenport 2019; Michael W. Robbins, Saunders, and Kilmer 2017) into research on alcohol policy. This procedure is capable of constructing a synthetic control from multiple untreated and treated units aggregate to low-level data, modeling outcomes jointly, and providing measurements of uncertainty with permutation placebo tests. By doing so we hope to generate evidence of its utility for similar quasi-experimental studies with low-level data aggregations and multiple outcomes of concern.

This study is the first of its kind to evaluate the impact of a zero BAC law, providing evidence that shifting from a low (0.3 g/L) to zero blood alcohol driving limit can reduce roadway injuries and deaths. The results suggest promise for shifting international standards to lower BAC levels, further below the 0.5g/L currently recommended by the World Health Organization (World Health Organization 2004). Due to potential issues of external validity and undetectable confounders, this study warrants replication in other countries, with other study designs, and for longer time periods.

Chapter 4 Appendix

Data Reporting

Table A4.1 shows the number of crashes in the original dataset, before any data was removed in the data cleaning process.

Table A4.1. Number of Crashes by Country, Before Data Cleaning

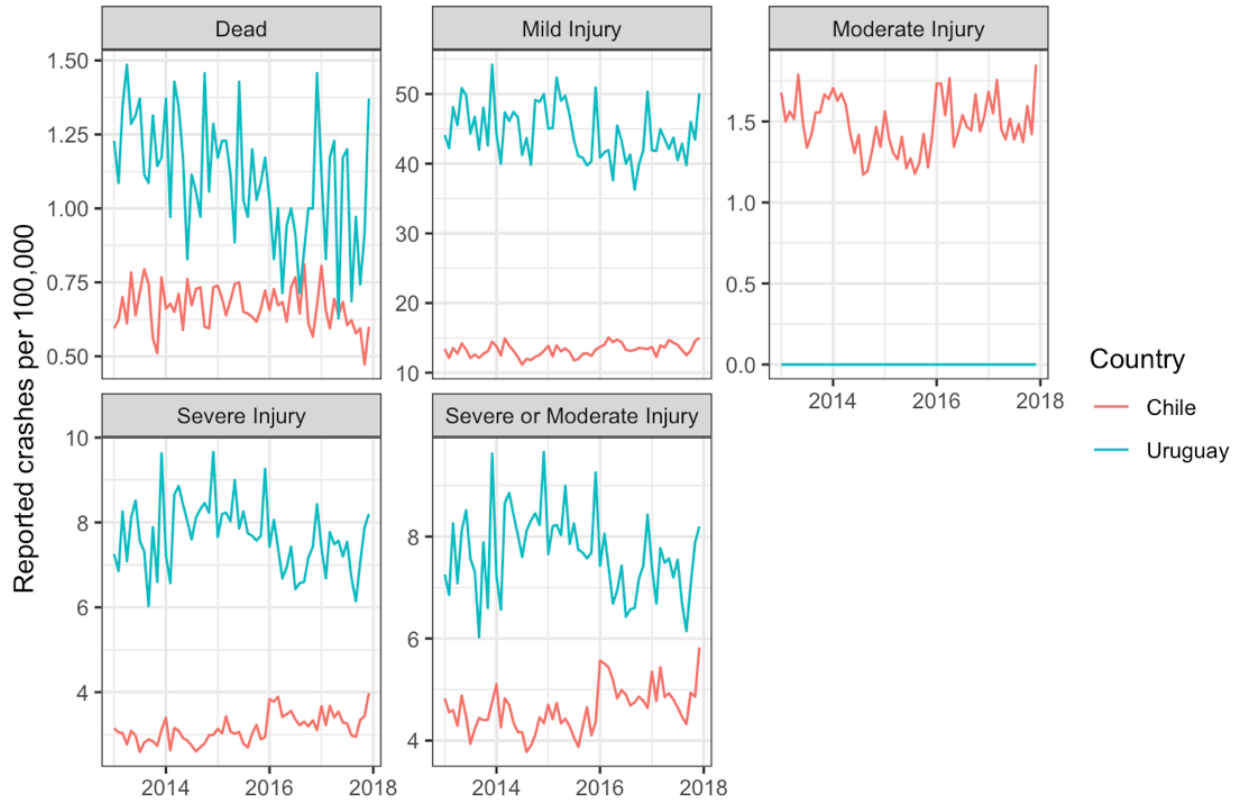
Country	Time Period	No Injuries	Mild Injury	Non-mild Injury	Death
Uruguay	Pre-intervention	21,057	58,102	10,113	1,507
Chile	Pre-intervention	115,075	83,648	28,495	4,383
Uruguay	Post-intervention	15,683	35,995	6,156	845
Chile	Post-intervention	102,551	59,711	21,499	2,829

Table A4.2 shows the number of crashes in the panel dataset after data cleaning steps.

Table A4.2. Number of crashes in panel dataset

Year	Country	Death	Severe Injury	Moderate Injury
2013	Uruguay	523	3189	NA
2014	Uruguay	492	3435	NA
2015	Uruguay	474	3401	NA
2016	Uruguay	401	3030	NA
2017	Uruguay	421	3067	NA
2013	Chile	1448	6313	3369
2014	Chile	1460	6282	3104
2015	Chile	1473	6542	2860
2016	Chile	1469	7469	3354
2017	Chile	1358	7337	3322

Figure A4.1. Raw data relating to crash reports by type by country



Assigning geographic territories to Crash Reports

To merge crash and population data, in Chile, string-matching methods were used to map crashes to commune; in Uruguay, string-matching and reverse-geocoding were used to locate the city where the crash occurred, or if it instead appeared to occur in a rural area or a city smaller than 1,000 people, to designate the crash as occurring somewhere in a “small city or rural area” for that department. However, attempts to merge crash and population data were complicated by inconsistencies across the two datasets and low-quality crash location data.

Crashes in Chile were mapped to census population units by string-matching “locality” from the crash data to the census data, with some manual validation and correction for spelling inconsistencies. Almost all the Chilean crashes were successfully mapped in this way -- except for four fatal and 42 severe injury crashes in “Chol Chol” (a commune which was created in 2004, so not in the 2002 census data) or Alto Bio Bio, which is listed as being in the “bio bio” region, which is missing from our census dataset for an unknown reason, likely related to some recordkeeping or definitional change or procedure.

Geo-mapping in Uruguay was further complicated by missing data and additional data quality issues. A substantial number (24,877 or 16.6%) of crash reports are missing value for the “locality” field; however, all observations include X/Y coordinates encoded in the UTM format. For all observations, X/Y coordinates were converted to latitude/longitude (via earthpoint.us), then reverse-geocoded (via geocode.xyz), which returned three new location fields (the

consistency of these fields vary but are roughly interpretable as town/city, city/region, and department, e.g., Juanico; Los Cerrillos; Canelones). Labeled and geocoded locations almost always matched at the department level (98%) but with more disagreement at the lower levels (the exact rate is hard to measure due to dirty data and string-matching issues, discussed below).

To map crash data to population region, we use an iterative search process. First, the algorithm checks for the “locality” in the by-department list of cities with population of 1,000 or more. If the locality is missing or cannot be found in that list, then it will turn to using alternative location data obtained via reverse geo-coding, repeating this process for the geocoded “city” field, and if that did not produce a match, then the geocoded “region” field. If no matches can be found by any of these methods, then we infer that the crash occurred in a rural area or a city smaller than 1,000 people, and therefore map it to the “small city or rural area” of that department (e.g., “Canelones: small city or rural”). This “label-first, geocoded-second” order is important when there are disagreements across labeled and reverse-coded location data. For example, for a crash reported to occur in Neptunia but was located via reverse-geocoding in Pando (“town/city”), Salinas (“city/region”), we will locate the crash in “Neptunia” rather than “Pando”. In some observations (e.g. 90 fatal crashes), this caused a mismatch of the low-level (“city”) and high-level (“department”) units due to disagreement between the labeled and reverse-geocoded data. Via manual inspection, some of these observations were corrected manually by over-riding the “department” value as to enforce the department to match the lower-level unit. Overall this method identified exact matches for 2144 fatal crashes (91%), inferred 167 as rural or small city (7%), and dropped the remaining 41 fatal crashes (2%) from the dataset.

We also tested alternative means of geo-mapping crash observations, e.g., by relying only on the labeled locality, or only on the reverse-geocoded, or checking the reverse-geocoded data first and using the labeled information as a backup. The “label-first, geocoded-second” showed the highest rate of geo-mapping crashes, and resulted in a distribution of crashes across Uruguay’s departments in a pattern roughly comparable to the distribution of population; e.g., 8.5% of Uruguay’s population lives in rural areas or in cities with under 1,000 residents; in the same area this algorithm located 7.1% of crashes. Table A4.3 shows how many crashes in Uruguay were matched exactly, inferred to be rural or small-city, or were dropped from the dataset, grouped by crash worst outcome.

Table A4.3. Geo-Mapping Uruguayan Crashes, Diagnostics by Outcome

Merge Outcome	No Injuries	Mild Injury	Non-Mild Injury	Dead
Assumed Rural	1,564	2,138	553	167
Exact Match	34,672	91,274	15,569	2,144
No Merge, Dropped	504	685	147	41

Aggregating Units in Uruguay

Across the census dataset we obtained, the lowest level geographic units for Uruguay tend to be much smaller in population than comparable units in Chile. The smallest Chilean commune contains about 20,000 people, which is larger than 85% of the Uruguayan localities. If not corrected for, this leads to problems when feeding into a synthetic control model, as the

optimization method has difficulty simultaneously matching on population count and number of units when there are large disparities in people-per-unit across the treated and untreated units.

Therefore, after constructing the panel dataset but before modeling, we re-aggregate observations occurring in Uruguayan areas with population under 20,000. We aggregate Uruguayan units as needed until total population per group exceeds 20,000 (aggregation occurs such that units are usually added to groups within the same department, unless that department is already “full”, i.e., has no aggregations with fewer than 20,000 people). This reduces 181 units to just 60 units. Aggregating Uruguayan units changes the average population from 18,028 to 53,492, which is closer to the average in Chile (80,885).

Policy Implications

This dissertation includes three papers exploring changes in cannabis products, use patterns, and the public health effects of various policies, and one paper evaluating an intervention targeting alcohol-involved driving. The first two investigated national-level patterns and trends in self-reported cannabis use, acquisition, and use disorder symptoms. The third paper documented falling prices and the proliferation of new products in Washington State’s recreational cannabis market. The fourth estimated the effect of a zero-blood-alcohol-concentration driving law in Uruguay in terms of traffic injuries and fatalities. It spotlights an issue (intoxicated driving) that is rising in prominence generally and in cannabis policy. Together, these studies provide policymakers and other interested stakeholders a number of lessons:

- 1. Informed cannabis policy decision-making requires understanding the long-term effects of cannabis use; however, the levels of cannabinoid consumption estimated of many of today’s cannabis users are so high as to be unprecedented, shrouding potential long-term risks in uncertainty.**

Chapters 1 and 3 contribute evidence suggesting that today’s cannabis users nationwide and especially in legal cannabis states typically 1) use on more days of the month, 2) are using dried flower cannabis with higher THC than observed previously, and 3) are increasingly using high-cannabinoid concentrates rather than dried flower cannabis.

Firstly, Chapter 1 documented the increasing prevalence of daily/near-daily cannabis use habits. In 2018 over one-in-three past-month cannabis users reported using on more than twenty days in the past thirty, thrice the rate in 1994. Second, the types of cannabis in popular use tend to have higher concentrations of cannabinoids. Chapter 3 explored emerging cannabis product trends in Washington State, one of the nation’s first recreational cannabis markets. There, dried flower cannabis averaged 21% in THC concentration. That is markedly higher than the average flower THC reported in cannabis seized throughout the country by the DEA, which averaged only 4% in 1995 and 12% in 2014 (ElSohly et al. 2016).¹³

Third, the emergence of high-cannabinoid concentrate products has introduced the potential for increased cannabinoid consumption during a single session, and potentially helped transform within-day cannabis use patterns. Chapter 3 documented that in Washington State, novel concentrate products such as solid and oil-based concentrates often contained 70 to 85% THC by October 2017; further, these products rose to over one-quarter the market, shrinking cannabis flower sales to just 62% of sales by dollar value.

The spread of “dabbing” contributes to the potential for massively higher cannabinoid consumption (John M. Stogner and Miller 2015). When dabbing solid concentrates, users typically flash-vaporize a dose in a single hit; heavy users commonly reporting dabbing one gram or half-gram at a time. At the cannabinoid levels documented in Washington State, a one-

¹³ Further, from 1995-2014, the average THC:CBD ratio of seized cannabis products increased from 14:1 to 80:1.

gram dab may contain 750 mg THC, roughly equivalent to 3.5 grams (one eighth of an ounce) of dried flower. Web surveys identify that regular concentrate users are more likely to use cannabis on a daily basis; further, when consuming flower cannabis, they consume strains with higher-THC concentrations than do infrequent- or never-concentrate users (Cinnamon Bidwell et al. 2018), suggesting they may have developed higher tolerance or preferences for a more intense high.

Together, the likely net effect is an increase in cannabinoid consumption, including both on a daily basis and cumulatively over a lifetime. However, the actual magnitude of this increase is unknown, and so are the associated potential additional long-term health and behavioral consequences. The contemporary profile of cannabis use includes a higher volume of cannabinoid consumption than in previous eras, potentially suggesting that the understanding of the harms of cannabis use that have accumulated from prior research and experience may no longer be appropriate. Under these circumstances, policymakers may be wise to approach consequences of cannabis use with precaution – for example by crafting policies to discourage daily use or use of high-cannabinoid use methods – until this issue is better understood.

2. Cannabis use disorders represent one of the chief public health threats of liberalizing cannabis policies; however, theory and some recent evidence about its changing prevalence are in conflict and not easily reconciled.

Many of the recently emerging trends in cannabis purchase and consumption behavior have been linked to increased risk of developing intensive cannabis use habits and/or use (Budney and Borodovsky 2017; Budney, Sofis, and Borodovsky 2019), including broader availability of retail stores (Everson et al. 2019; Mair et al. 2015), increased use of high-THC herbal cannabis (T. P. Freeman and Winstock 2015), lower prices (Pacula and Lundberg 2014), and broader use of concentrates (Meier 2017). Therefore, from the period of 2002-2016, one might have expected rates of cannabis use disorder to be on the rise.

Yet, exploiting data from the National Survey on Drug Use and Health (NSDUH), Chapter 2 reported that daily/near-daily cannabis users showed a 39% decline in rates of self-report of symptoms qualifying for DSM-IV dependence, and declines in five of six of contributing DSM-IV dependence symptoms.

This creates an apparent contradiction, and the truth may be somewhere in the middle. One factor in favor of the relatively low NSDUH-informed estimate is the overwhelming clarity of the survey results: the downward trend is robust across sociodemographic groups, and is also detectable among the larger pool of past-month cannabis users. Moreover, the same cultural factors that helped motivate changes in cannabis policy (higher social acceptance and lower perceived risks) may also mitigate some consequences, e.g., if cultural attitudes become more accepting to cannabis use, users may more easily integrate use habits with their lifestyle. Some of the consequences of liberalizing cannabis policy might have also contributed, e.g. the increased availability of non-smokable products and a public that is more willing to discuss the benefits, harms, and experiential aspects of cannabis use.

On the other hand, known issues with self-reported behavioral data suggest that it may be foolish to rely entirely upon the data. Certainly, researchers cannot rely fully on individuals' capacities for wise and honest insights into their mental states and behaviors, or to causally attribute any changes in their mental states or lifestyles to their cannabis use. Further, Keith Humphreys notes that people's willingness to self-report feelings of addiction towards a substance or activity is strongly determined by the relevant cultural attitudes (Humphreys 2017). Such a change in moral perception may therefore be responsible for changes in symptoms related to cannabis use disorder, even if the actual behavior and consequences were to have remained the same.

This presents opportunities for further research regarding cannabis use disorder today. One way to fill this gap would be to combine self-reported survey data with diagnosis from a trained mental health professional – for example, with a three-part study that 1) asks respondents about the DSM-V cannabis use disorder symptoms, 2) offers select respondents an opportunity to follow-up with a clinic diagnosis, and 3) reconciles the pairs of diagnoses using statistical methods to detect false positive/negative rates and improve calibration of survey instruments. This is the type of research that would have been useful decades ago, but nonetheless remains a useful idea, even though the opportunity to collect earlier baseline measures is lost.

Since it is difficult to offer such diagnoses retrospectively, as well as the potential harms of widespread increases in cannabis use disorders, this research activity is urgent and could quickly bring benefits to policymakers.

3. Policymakers have demonstrated interest in crafting policies to shift consumption towards lower levels and/or less harmful means, but both efforts are constrained by a lack of granular data about cannabis use patterns.

Many medical cannabis states have responded by temporary or permanent bans targeting different product types for different reasons, e.g. concentrates for fear of high-THC products, edibles to mitigate risks of acute overdose, herbal cannabis to prevent smoke inhalation, or products above a certain THC concentration to reduce risks of use disorders;¹⁴ some adult use states have also had temporary product restrictions (for example with use edibles during the first months of Oregon and Canada's adult use market).

Under pressure from the cannabis lobby and for fear of pushing demand into the illicit market, and as cannabis concentrates become more popular, states have shown a developing interest in using more modest policies to shift cannabis consumption patterns, for instance with tax policies designed to shift purchasing behavior towards products deemed to be of lower risk. Illinois is unique in U.S. states for its potency-based excise tax, setting separate rates for edibles and low- and high-THC cannabis products. Potency-based excise taxes have recently received in-depth study in economic journals (B. Hansen, Miller, and Weber 2020), popular news outlets, and also from governments in California and Washington (Kerstein and Kerstein 2019; Washington State Liquor and Cannabis Board 2019).

¹⁴ For example, the current prohibition in Hawaii on medical cannabis edibles, as well as their prohibition until mid-2018 of concentrate products intended for vaporization.

However, researchers and policymakers alike have voiced concerns that the extant body of literature relating to product-specific harms is insufficient for the design and justification of such policies (Kumar et al. 2019; Washington State Liquor and Cannabis Board 2019). In particular, there is a need for measurement of cannabis preferences and use patterns at a level that is more granular than what is captured by the current fleet of national surveys, such as NSDUH, Monitoring the Future (MTF), and National Epidemiologic Survey on Alcohol and Related Conditions (NESARC) (Kumar et al. 2019).

Recognizing this, Chapters 1 and 2 of this dissertation analyzed the NSDUH survey in detail, studying time trends and patterns relating to cannabis use prevalence and use disorders. Chapter 3 mined Washington State's traceability data for trends in product characteristics, prices, and sales volumes – as well as enhancing the dataset by introducing a method to differentiate sales of solid concentrates from oils for vaporization, two products which in the original dataset had received the same product code (“marijuana concentrate for inhalation”). This distinction is commonly neglected in studies of cannabis use, even among surveys that are quite detailed and targeted at concentrates (see Cavazos-Rehg et al. 2018).

The relatively few studies that have been designed to study such details have generated findings that help illustrate fine details of prevailing use patterns. For example, a number of studies have offered refined estimates for the average size of a joint (Ridgeway and Kilmer 2016) and how that it may vary when using high- versus low-THC cannabis (Tom P. Freeman et al. 2014; Van Der Pol et al. 2013). Another study reported a sample of daily cannabis users reported dramatically higher average daily amounts of cannabis consumption than near-daily users using between 21-29 days per month (Caulkins, Pardo, and Kilmer 2020). One particularly rich study analyzed data from the Global Drugs Survey, which asks about issue such as quantities of cannabis use, time spent intoxicated, time of the first and last use sessions in the day, symptoms relating to use disorders, and the use of and preferences for different cannabis products and cannabinoid profiles. Analysis found respondents reported a median of four hours stoned per day of use; that 22% of past-year users reported consuming a joint within one hour after waking; and half consumed a joint one to two hours before bed (Kumar et al. 2019). Another web survey-based study found additional risks faced by frequent concentrate users, who reported more symptoms of cannabis use disorder than never- or seldom-using concentrate users, and even when using dried flower cannabis tended to report higher THC levels (Miller, Stogner, and Miller 2016).

As more evidence accumulates, it will help paint a higher-resolution and more colorful picture of cannabis use profiles, including how various cannabis products and cannabinoid characteristics affect users' risk of developing use disorders or more intense use patterns. Currently, too many details remain precariously uncertain, such as the typical size of a “dab” hit, rates of development of tolerance, patterns of THC-titration among users of cannabis concentrates, and the typical ranges of daily cannabinoid consumption across different product types. Promising data sources for this research include targeted web surveys; customer use and purchase data collected by private-sector retailers, software providers, or manufacturers of “smart” vaporizers; and purchase data from state-run cannabis traceability systems. However, the high prevalence of multi-mode cannabis use complicates the task of making causal inferences, so careful design of surveys and experiments and the use of appropriate statistical methods will be important to

attempts to isolate clear patterns, let alone arrows of causation between cannabis use decisions and health outcomes. Yet gradually, with each additional study, policymakers and users alike will become better positioned to mitigate the risks of cannabis use, and to act now rather than in a more distant future.

4. Novel synthetic control methods may be useful for better understanding causal relationships in cannabis policy, especially when working with quasi-experiments with small-grained and high dimensional data.

Many pressing policy questions refer to issues of causation, e.g., relating to cannabis, “would legalizing cannabis affect the total number of traffic crashes?” In the absence of genuine experiments, answers are elusive, with researchers resorting to evaluating “natural” experiments such as policy changes implemented in one of several comparable jurisdictions. But those can be rare to come by – limited by the incidence of the targeted policy change and the availability of data from similar jurisdictions that may be treated as potential comparisons.

Chapter 4 provides an example of how novel synthetic control methods such as “microsynth” offer another tool to researchers facing this conundrum. That method’s allowance for multiple treatment areas, flexible matching algorithms, and placebo tests facilitates the evaluation of quasi-experiments under the assumption of heterogeneity within aggregated units. Though that chapter concerns the effect of a policy targeting alcohol-involved driving, a similar approach may be employed for cannabis. This may enable further research into the likely effects of various aspects of cannabis policy on local outcomes such as car crashes.

Cannabis presents some difficulties that are not as present in alcohol. First, while the relationship between blood alcohol concentration and impairment is thought to be well understood and treated as fairly simple, the case with cannabis is more complex. Further, quasi-experimental methods are limited in their ability to detect small effect sizes, especially with low-frequency events. Some measures suggest cannabis-impaired driving happens less frequently than alcohol-impaired driving, e.g. one-in-seven drivers in a AAA study reported they had driven with blood alcohol concentration close to or over the legal limit in the past-year, while about one-in-twenty (4.6%) reported driving within one hour of using marijuana (AAA Foundation for Traffic Safety 2016). Per distance or time driven, it is commonly found that cannabis-impaired driving carries lesser additional crash risk than driving under the influence of alcohol (Romano et al. 2015). Therefore, if the crash-inducing effects of cannabis use are relatively modest, quasi-experimental methods may struggle with detecting smaller expected effect sizes.

Regardless, one example of how that approach may be applied to issues relating to cannabis policy would be to estimate the effect of changes in state-level cannabis policies on car crash fatalities. A synthetic controls approach enables researchers to match units based on observable characteristics; the “microsynth” approach further would allow for de-composition of a treatment state into sub-groups, e.g. counties. Crash fatality data may be pulled from the Federal Accident Reporting System (FARS), then aggregated at the county-level, providing dozens or hundreds of observational units.

Terminus

Cannabis has now been legalized for non-medical purposes in Canada, Uruguay, eleven U.S. states and Washington DC, with more jurisdictions likely to follow suit in the near future. The world's first large corporate manufacturers, distributors, and retailers of non-medical cannabis have begun operating in Canada. Some of them are already operating in the United States – with the potential for continued expansions in scale and efficiency in the case of national legalization in the United States. This accelerated rate of policy change prompts novel topics of cannabis policy research, including evaluating past policy changes and identifying feasible policy responses for issues observed now or expected in the future.

This dissertation includes four papers, three of which focus on issues related to cannabis, with the last investigating alcohol policy but with close connections to similar issues in cannabis policy (intoxicated driving). The first chapter identifies U.S. national-level patterns of cannabis acquisition and use and from 2002 to 2013, roughly the decade of policy liberalization that preceded the first non-medical cannabis regimes. The second chapter investigates a somewhat surprising fifteen-year trend in self-report of cannabis use disorder symptoms among daily/near-daily cannabis users, who disproportionately bear many of the consequences of cannabis use. The third chapter analyzes Washington State's recreational cannabis traceability dataset (July 2014-October 2017), documenting emerging trends, e.g. declining prices, cannabinoid profiles, and product forms. The final chapter evaluates an intervention relating to reducing alcohol-involved crashes, some lessons of which can be carried over to analogous questions with cannabis-involved crashes. That study evaluated Uruguay's zero blood-alcohol-concentration (BAC) law, exploiting a novel synthetic controls method to estimate reductions in severe and fatal injury crashes, using Chile as a control.

It is a typical feature of drug policy issues that they are complex and multi-faceted, touching upon issues, such as those related to physical health, mental health, criminal justice, civil liberties, and the character of society. Contributing to the complexity of the issue is the patchwork of state and local cannabis policies, and the difficulty of evaluating the effects of any given policy on its key outcomes. Nonetheless, as the political-economic landscape regarding cannabis continues to evolve, public health-oriented policymakers would be fortunate to benefit from further research relating to these contemporary policy issues.

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