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Essays on the Effects of Medical Marijuana Laws

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Essays on the Effects of Medical Marijuana Laws

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by

Rosanna Smart

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Abstract of the Dissertation

Essays on the Effects of Medical Marijuana Laws

by

Rosanna Smart
Doctor of Philosophy in Economics
University of California, Los Angeles, 2016
Professor Adriana Lleras-Muney, Chair

Over half of the US states have adopted "medical marijuana" laws (MMLs), and 58% of Americans now favor marijuana legalization. Despite public support, federal law continues to prohibit the use and sale of marijuana due to public health concerns of increased dependence and abuse, youth access, and drugged driving. These essays contribute toward understanding the likely health consequences of marijuana liberalization using evidence from MMLs.

Chapter 1 – Growing Like Weed: Explaining Variation in Medical Marijuana Market Size provides a comprehensive analysis of the determinants of growth in legal medical marijuana markets. Newly collected data on medical marijuana patient registration rates shows that there is substantial heterogeneity in medical marijuana participation over time and across states. This variation is primarily driven by the combined effects of federal enforcement policy and state supply restrictions on legal production costs. **Chapter 2 – The Kids Aren't Alright: Effects of Medical Marijuana Market Growth on Marijuana Use** then studies the effect of growth in legal medical marijuana markets on recreational use. Findings show that expansion of legal medical marijuana market size significantly increases the prevalence of recreational cannabis use by both adults and adolescents. Reaching the median state's legal market size would increase the prevalence of marijuana use in the past

month by 6% for adolescents aged 12-17, by 9% for 18-25 year-olds, and by 18% for adults over age 25.

The welfare implications of these changes largely depend on the externalities and internalities associated with marijuana use. To study this, **Chapter 3 – On the Health Consequences of Increased Medical Marijuana Access** examines the effects of increased marijuana availability on traffic fatalities and mortality related to opioid and alcohol poisonings. In the aggregate, greater medical marijuana access decreases mortality from these causes. However, the aggregate effect masks an important welfare trade-off generated by age differences in the elasticity of substitution between marijuana and alcohol. For adults aged 45-64, greater marijuana availability reduces mortality related to alcohol and opioid poisonings by 7-11% and 12-16% respectively. In contrast, for youths aged 15-20, marijuana access generates negative externalities in the form of a 6% increase in traffic fatalities, with large and significant effects on alcohol- and cannabis-related accidents.

The dissertation of Rosanna Smart is approved.

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2016

To my parents,

who—among so many other things—

gave me my love of puzzles.

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CHAPTER 1

Growing Like Weed: Explaining Variation in Medical Marijuana Market Size

1.1 Introduction

As of 2015, twenty-four U.S. jurisdictions have medical marijuana laws (MMLs), which provide legal protection for individuals who use marijuana for medical purposes, physicians who recommend marijuana to patients with certain medical conditions, and growers and distributors who supply these patients. Past studies have exploited state-time variation in MML enactment to estimate the effects of liberalization on recreational marijuana use,[1] traffic fatalities (Anderson et al., 2013), obesity (Sabia et al., 2015), suicides (Anderson, Rees, and Sabia, 2014), and crime (Morris et al., 2014). However, interventions may not attain full steady-state effectiveness immediately upon implementation (King and Behrman, 2009), and estimation based on the timing of MML passage will likely not capture the full effects of these policies as medical marijuana markets evolve.

While MML enactment alone may signal a shift in governmental acceptance of the drug, effects on marijuana availability and price will depend on the specific regulations established by MML policy and the duration of exposure to the more liberal regime. Changes in social access, perceived community approval, and spillover effects

[1] See Pacula et al. (2015) for a review of this literature.

to illegal use and other public health outcomes may well vary according to the extent to which legal users and suppliers actively participate in the medical marijuana program. If recreational and medical marijuana consumption decisions are made based on similar consumer optimization problems,[2] both medical marijuana participation and use in the general population will follow similar patterns. Understanding the factors that drive changes in medical marijuana participation can thus offer insight into the mechanisms by which MMLs generate spillovers to recreational use and other health outcomes.

This is the first paper to investigate the determinants and dynamics of medical marijuana participation by legal users using newly collected data on medical marijuana patient registration rates. While some recent research has examined data on registered patients, these studies have either been descriptive (Fairman, 2015; Sevigny, 2014), cross-sectional (Williams, Olfson, et al., 2016; Friese and Grube, 2013), or limited to one state (Rylander et al., 2014). By collecting data on registered patient counts from both administrative and non-administrative sources, this paper presents the most comprehensive state-level monthly panel dataset to date on medical marijuana participation to date. Data was obtained from 1999-2014 for the sixteen states[3] that required individuals to register as medical marijuana patients in order to receive the legal protections afforded by the MML.

The data show that there have been dramatic changes in medical marijuana participation over the last two decades. Registered patient counts were relatively low until 2009, when they sharply increased. The number of registered patients continued to climb until mid-2011, when they leveled before resuming an upward trend a few years

[2]This proposition is clearly conceptually rather than empirically. However, research has shown that, at the individual-level, medical and recreational use are significantly correlated (Ware et al., 2005; Smith, 2011).

[3]For brevity, this paper will refer to Washington D.C. as a state.

later. These trend breaks in medical marijuana patient registration rates coincide with the timing of federal enforcement policy changes that have been widely ignored by past research. While federal law has strictly prohibited the use and distribution of marijuana since 1937 regardless of state policy, a federal statement of nonenforcement in MML states was released in October 2009 (Ogden Memo); in June 2011, another federal statement was issued to clarify that this did not apply to large-scale producers (Cole Memo).

To understand the factors responsible for driving these changes in medical marijuana take-up, I first outline a conceptual framework whereby individuals apply to register with the medical marijuana program if the expected utility (expected benefits net costs) from registering exceeds that of not registering. Costs to patients include transaction costs associated with registration fees and finding a doctor to provide a recommendation, as well as perceived risk from state and federal enforcement. Benefits include access to legitimate sources of marijuana (which encompasses the relative benefits of product variety, lower search costs and prices, etc.), which will vary depending on the production limits established by the state's specific MML regulation. The federal memos are predicted to affect medical marijuana participation through changing the perceived risk associated with federal enforcement for both registered patients and state-legal producers.

The empirical results confirm the descriptive evidence showing that the federal memos significantly affected medical marijuana take-up. Controlling for state-level demographic and economic variables or time-invariant state characteristics dampens the magnitude of these effects slightly, but they remain large and statistically significant. However, the federal memos did not affect all MML states equally. Interacting the federal memo changes with state-specific supply-side regulations shows that the magnitude of their effects was significantly larger in states that imposed relatively lax restrictions on legal producers. These findings imply that medical marijuana par-

ticipation is primarily driven by the expected benefits associated with access to legal supply. Additional robustness checks support that the extent of medical marijuana participation is highly responsive to supply-side changes in the legal market.

This paper builds on recent work recognizing that heterogeneity in the specifics of state MML regulations may generate heterogeneous effects (Sevigny et al., 2014; Pacula et al., 2015), and it contributes to a broader economic literature showing that the effects of regulatory changes depend largely on the specifics of their design, implementation, and enforcement.[4] Section 1.2 details the history of marijuana regulation in the U.S. and provides background on modern MMLs and changes in federal enforcement policy. Section 1.3 outlines a conceptual framework to suggest the factors determining medical marijuana participation. Section 1.4 presents the data, empirical framework, and results for the determinants of medical marijuana participation. Finally, section 1.5 places these results in the context of the existing literature on MMLs, and section 1.6 concludes.

1.2 History of Marijuana Policy in the U.S.

1.2.1 Early Medical Marijuana Liberalization

The first federal regulation of marijuana was introduced with the Marijuana Tax Act of 1937. The Marijuana Tax Act did not criminalize the possession or use of marijuana, as this was a potential violation of the Tenth Amendment's limitation on federal power, but instead made it illegal to grow or distribute marijuana unless the grower obtained a federal stamp. Since stamps were largely unavailable and there was no application process, the Act effectively served as federal prohibition (Bonnie

[4]Past work has examined regulation of the environment (Greenstone and Hanna, 2014), education (Davidson et al., 2013), health insurance (Wolfe and Scrivner, 2005), traffic safety (Abouk and Adams, 2013), and marijuana decriminalization (Pacula, MacCoun, et al., 2005).

and Whitebread, 1970).

Marijuana use remained limited until the mid-1960s, when the baby boom generation reached adolescence. Thicker drug markets associated with this larger youth cohort resulted in a significant increase in illicit drug use among college and high-school students (Jacobson, 2004). In 1970, Congress responded by passing the Controlled Substances Act (CSA), which repealed the Marijuana Tax Act[5] but classified marijuana as a Schedule I substance with high potential for abuse and no accepted medical value.[6] The CSA criminalized the manufacture, distribution, and possession of marijuana for both recreational and medicinal purposes, and it provided the system of federal penalties and enforcement that remains in place today.

Despite federal prohibition, marijuana use continued to rise in the United States. By the early 1970s, eight million people were using marijuana regularly, at least half a million people were consuming it daily, and 421,000 people were arrested for marijuana offenses annually (Slaughter, 1987). In 1972, the National Commission on Marijuana and Drug Abuse, which had been created as part of the CSA, released a comprehensive report based on surveys of health experts and law enforcement officials. The report recommended the removal of criminal penalties for marijuana possession and advocated further scientific research on the substance's potential medicinal value. President Nixon rejected the Commission's recommendations, but the 1972 report helped trigger a push toward liberalization policies (DiChiara and Galliher, 1994).

In 1972, the National Organization for the Reform of Marijuana Laws (NORML) filed the first petition to reschedule marijuana. In 1975, the federal government established the Individual Patient Investigational New Drug (IND) program, which

[5]The 1969 US Supreme Court decision in *Timothy Francis Leary v. United States* ruled the Marijuana Tax Act unconstitutional because it violated the 5th amendment right against self-incrimination.

[6]Title II of the Comprehensive Drug Abuse Prevention and Control Act of 1970, P.L. 91-513, October 27, 1970, 84 Stat. 1242, 21 U.S.C. 801, et seq.

enabled participating physicians to prescribe marijuana to enrolled patients. The federal program was designed to accept patients with serious illnesses and directly provide them with marijuana through the National Institute on Drug Abuse. While the IND ostensibly established a legal channel by which patients could obtain marijuana, the application process was complicated and burdensome, and only six patients were accepted into the program during its first decade of operation (Pertwee, 2014).

Still, this signaled a movement toward federal acceptance of marijuana's medicinal value, and many states began to adopt their own legislation allowing the use of cannabis for medical purposes under specified conditions (Pacula, Chriqui, et al., 2002). Figure 1.1 graphs the number of proposed state-level medical marijuana initiatives from 1972-1995. Statutes are classified as therapeutic research programs (TRPs), rescheduling provisions, or physician prescription laws. While these laws demonstrated increasing state recognition of marijuana's therapeutic value, they had little practical significance (Schmitz and Thomas, 1999).

The federal approval process for state TRPs was complicated and costly. In the few states that obtained the necessary federal permissions, enrollment was highly restrictive and largely dependent on receiving marijuana from the federal government. In theory, physician prescription laws and rescheduling provisions allow physicians to legally prescribe marijuana for medicinal purposes outside of a TRP.[7] However, since the federal CSA classification of marijuana as Schedule I supersedes any state CSA, physicians who prescribe marijuana outside of an officially recognized state TRP risk facing federal sanctions. Additionally, even should a patient obtain a physician's prescription, these statutes did not establish any legitimate supply channel for patients to obtain marijuana.

[7]An important distinction between rescheduling provisions and physician prescription laws is that patients using marijuana receive no protections under physician prescription laws but are protected under rescheduling provisions if they have a written prescription.

By 1984, the wave of state medical marijuana initiatives had quickly come to an end. This shift occurred in large part due to the spread of the crack-cocaine epidemic and increased federal emphasis on drug policy enforcement, seizures, and interdictions under the Reagan and Bush Administrations (1981-1992). It became increasingly unlikely that NORML's 1972 petition would result in federal rescheduling of marijuana, and the government's IND program was suspended in 1991 and discontinued one year later. State policy mirrored the federal stance, and by 1990 a number of the existing decriminalization and medical cannabis statutes expired or were repealed.

1.2.2 Modern Medical Marijuana Laws (MMLs)

The discovery of naturally occurring cannabinoid receptors in the human brain in the early 1990s led to a resurgence of medical interest in the potential therapeutic value of marijuana (Pertwee, 2014).[8] There was increasing evidence that smoked marijuana offered significant benefits for patients suffering from symptoms of cancer and HIV/AIDS, and in 1995 the *Journal of the American Medical Association* ran a commentary supporting the use of marijuana for medicinal purposes and calling for increased research.

In 1996, with the passage of Proposition 215, California became the first state to establish an effective medical marijuana law (MML) that removed criminal penalties for the use, possession, and cultivation of medical marijuana by qualifying patients and their primary caregivers. There are three important distinctions between California's initiative and the earlier medical marijuana statues discussed in section 1.2.1. First, since the law stated that patients needed a doctor's "recommendation" — not "prescription" — for medicinal marijuana, physicians did not need to violate federal

[8]Cannabinoids are chemicals unique to the marijuana plant. Delta-9-tetrahydrocannabinol (THC) is the most well-known and is responsible for marijuana's psychoactive effects.

law to qualify their patients.[9] Second, unlike the state medical marijuana initiatives of the 1970's described earlier, Proposition 215 was passed during a time when federal policy was firmly engaged in the drug war and opposed to recognizing marijuana's medicinal value. Last, California's MML specified that patients and their caregivers could legally grow marijuana, establishing a legitimate source of supply that did not require any cooperation from the federal government.

The federal response was swift. One month after Proposition 215 passed in California, then-Drug Czar Barry McCaffrey threatened to arrest any physician who recommended cannabis to their patients. A group of physicians, patients, and non-profit organizations challenged this threat in court and succeeded. The 1997 decision in *Conant v McCaffrey* ruled that doctors could not be prosecuted for recommending or discussing cannabis with their patients (Pertwee, 2014). By the end of 2008, twelve other states had successfully passed MMLs (see Panel A of Table 1.1).[10]

While these policies indicated state-level acceptance of the medicinal value of marijuana, federal opposition under the Clinton and Bush Administrations (1992-2008) created uncertainty regarding the risks facing those who participated in the state MML program. Federal officials repeatedly stated that users and producers operating in compliance with state MML policy could still be subject to federal prosecution (Tiersky, 1998), and federal agents conducted numerous raids of large-scale production sites, primarily in California (Vickovic, 2011).

[9]In comparison, Arizona voters also passed a medical marijuana initiative in 1996, but it was ineffective because it used the word "prescribe."

[10]MMLs in Oregon, Washington, Alaska, Maine, Nevada, Montana, and Michigan were passed by voter initiatives. MMLs in Hawaii, Vermont, Rhode Island, and New Mexico were passed by state legislatures. Voters in DC passed an initiative in 1998, but it was blocked by Congress.

1.2.3 Changes in Federal Policy: The Ogden and Cole Memos

The election of President Barack Obama in 2008 signaled a potential shift in federal enforcement policy toward MML states. Throughout his campaign, Obama had indicated that he would not use federal resources to try to circumvent state MMLs (Dickinson, 2012). On March 18, 2009, Attorney General Eric Holder issued a statement that federal authorities would cease interfering with medical marijuana dispensaries that were operating in compliance with state law (Johnston and Lewis, 2009).

This policy of federal nonenforcement was formalized October 19, 2009, when Deputy Attorney General David Ogden issued a memorandum stating that federal enforcement priorities should not be directed against users or producers compliant with a state's MML (Ogden, 2009). While the intent was to signal a shift in drug enforcement efforts and provide reassurance to states considering liberalization, the memo did not change marijuana's legal status at the federal level. It explicitly stated that marijuana remained illegal under federal law, and a careful reading of the Ogden Memo shows that it left substantial discretion to U.S. Attorneys in how they could choose to adopt the federal guidelines (Markano, 2015).

Even if the Ogden Memo did not end up affecting the actual risk of arrest or prosecution, the widespread perception was that it would. The federal statement was hailed by mainstream media and marijuana advocacy groups as a historic step toward the enactment of national marijuana liberalization. The day of Ogden's announcement, the largest marijuana advocacy group in the country posted to their website that the Ogden Memo marked the end of federal arrests of medical marijuana patients and raids on suppliers (MPP, 2009). In the days following the issuance of the Ogden Memo, representatives from the prominent marijuana advocacy group NORML spoke with dozens of mainstream media outlets, proclaiming that federal prosecution of state-compliant medical marijuana patients and their suppliers was now over (St. Pierre, 2009).

Similar to the experience of the early medical marijuana initiatives described in section 1.2.1, the federal signal had important effects on the way in which local governments regulated and implemented state law. For instance, New Mexico was the only state to pass an MML prior to the Ogden Memo that explicitly allowed for the establishment of state-licensed dispensaries in its initial legislation in July 2007. One month later, the state Attorney General warned the New Mexico Department of Health that its employees could face federal prosecution for overseeing the production and distribution of medical marijuana (Baker, 2007). The first dispensary was not licensed until the day of Eric Holder's statement in March 2009, and four licenses were issued shortly after the Ogden Memo in November 2009. All six states that passed MMLs after the Ogden Memo allowed for the operation of state-licensed dispensaries (see Panel B of Table 1.1).

The changing landscape of medical marijuana markets elicited federal reaction. Beginning in February 2011, U.S. Attorneys in several MML states sent letters to state officials indicating that large-scale marijuana production or distribution facilities would not be tolerated by federal policy, even if state law permitted their operation (O'Keefe, 2013). On June 29, 2011, following a series of federal raids of medical marijuana dispensaries, Deputy Attorney General James Cole issued a memorandum to clarify the Ogden Memo and emphasize that federal resources would indeed be used to prosecute individuals involved in large-scale medical marijuana sales and distribution businesses (Cole, 2011). The Cole Memo was widely publicized as a disingenuous reversal of the Ogden Memo, and marijuana advocacy groups issued warnings that dispensaries compliant with state law would once again be federal targets (Dickinson, 2012).

1.3 Conceptual Framework

The aim of this paper is to understand how the federal memos affected medical marijuana participation within states, and to explain variation in take-up across states. The approach is thus motivated by the economic theory of program participation (Moffitt, 1983; Blank and Ruggles, 1996; Currie et al., 2001). Attention is limited to states that required medical marijuana patients to register with the state in order to receive the full protections afforded by state MML, since participation data in the three states with voluntary or non-existent registration programs are likely measured with substantial error (see Table 1.1 for the list of states and registry opening dates).[11]

Conceptually, individuals will apply to be a medical marijuana patient if the expected benefits of applying exceed the expected costs. An individual who applies and is approved becomes a registered patient, and receives the legal protections afforded by state law. An individual who applies and is rejected decides whether to obtain marijuana illegally or to abstain from marijuana use.

Costs of Registering

Conditional on knowing about the MML's existence, an individual then makes the decision whether or not to apply to be a medical marijuana patient. To apply for medical marijuana, an individual must first obtain a doctor's certification that she has a medical condition that could benefit from marijuana use. The patient then must submit an application to the state authority, along with a registration fee. Registration must be renewed every one or two years. Registration fees represent the direct cost of applying to the medical marijuana program, but there are additional indirect costs of finding a physician to provide the necessary recommendation. This will be

[11]This excludes Washington, which does not have a registry, as well as California and Maine, which have voluntary registration.

a function of an individual's health status, search costs of finding a recommending physician, and state-specific regulations regarding the eligible qualifying conditions.

If the application is approved, a registered patient may incur additional costs from the perceived risk of federal prosecution. Under the pre-Ogden regime, individuals may have feared that having their name on a medical marijuana registry could lead the federal government to more easily target them for prosecution. There may also be "stigma" costs (Moffitt, 1983) from choosing to violate federal law. While in reality, the probability of facing federal prosecution for simple marijuana possession is almost non-existent, federal penalties are substantially higher than most state penalties.[12]

As evidence suggests individuals overweight low-probability events that carry heavy losses (Kahneman and Tversky, 1979), even a small risk of federal prosecution during the pre-Ogden period may have been sufficient to deter individuals from registering for medical marijuana. If that is the case, by reducing the expected risk of federal prosecution, the Ogden Memo would be expected to increase medical marijuana participation; conversely, by re-instating perceived federal enforcement, the Cole Memo would be expected to decrease medical marijuana participation. As the federal memos applied to all MML states, they should have similar effects on medical marijuana patient take-up in all states.

Benefits of Registering

In all MML states, one of the benefits of registering is protection from state prosecution for possession of marijuana. All states in the sample imposed a maximum possession limit with the initial law (see column 3 of Table 1.1). Limits ranged from 1 ounce to 10 ounces of usable marijuana, though several states have passed amendments increasing these limits (e.g., Oregon increased the limit from 3 to 24 ounces

[12]Under federal statute, simple possession of marijuana for personal use is a misdemeanor, carrying penalties of up to one year in federal prison and a fine of $100,000 (Eddy, 2010).

in 2006).[13] Whether this benefit alone outweighs the cost of applying will depend on the perceived probability of arrest as well as the expected penalties for possession if the patient does not register. For heavier users, higher possession limits may offer additional benefits through quantity discounts or through reducing transaction costs associated with frequency of purchases.

As noted in section 1.2.2, one of the most important benefits of modern MMLs in comparison to earlier policies is access to legitimate sources of marijuana. Benefits to registered patients could include decreased prices, increased quality or potency, greater product variety, and lower search costs due to increased legal availability. The magnitude of these benefits will depend on the size and structure of the medical marijuana market.

There is substantial variation across MML states in the regulations placed on legal supply sources. These different supply regulations will have heterogeneous effects on medical marijuana availability, and thus generate heterogeneous benefits to registered patients. Table 1.1 shows the supply regulations established by each state's initial MML law, separately for states that passed MMLs prior to the Ogden Memo in 2009 (Panel A) and after (Panel B). Legitimate supply sources are categorized as patient home cultivation (column 4), cultivation by a designated caregiver (columns 5 and 6), state-licensed dispensaries (column 7), and *de facto* dispensaries or collective grows (column 8). Table 1.1 lists the access sources allowed by the state's initial MML, but it should be noted that many of these states enacted later amendments changing these regulations.

All MMLs enacted before 2009 allowed qualifying patients to grow their own cannabis, though plant limits varied. However, if patients are not already experienced

[13]To put these numbers in perspective, estimates from Europe suggest that regular cannabis users consume about 1 ounce per month while daily-or-near-daily users (DND) consume 3-4 ounces per month (Burns et al., 2013).

growers, the start-up and maintenance costs of home cultivation likely exceed those of obtaining marijuana from the black-market. Inexperienced growers will incur the time and monetary costs of learning how to grow marijuana efficiently, produce an adequate and consistent yield, vary potency, etc. Home cultivation may not even be feasible for many patients due to physical limitations, housing issues (e.g., landlords may prohibit marijuana growing), or difficulty finding seeds or starter plants to begin cultivation.[14]

Perhaps recognizing these limitations, early-enacting MML states that permitted home cultivation also allowed patients to designate a caregiver[15] to assist with their cultivation of marijuana or to legally grow marijuana on their behalf. In states that permit caregiver cultivation, benefits to registered patients will be a function of the number of providers and production per producer, which will depend on the expected profits of legal production. Caregivers' expected revenues increase with the number of patients they are allowed to grow for and the number of plants they are allowed to grow. Some states restricted caregivers to growing for only one patient (e.g., Hawaii and Vermont). Other states allowed caregivers to grow for multiple patients, and a few states (e.g., Montana and Colorado) placed no limits on the number of patients a caregiver could serve and did not cap the amount they could grow. Many of these states had MMLs that were ambiguous with regard to group growing or storefront dispensaries and thus effectively permitted the *de facto* operation of largely unregulated large-scale production.

Some states did not permit caregivers to grow for patients, but instead established a legal framework for the creation of state-licensed dispensaries or equivalent entities as described in Pacula, Boustead, et al. (2013). Theoretically, the legalization of

[14]MMLs are typically silent as to how patients should obtain a seeds or starter plants.

[15]This paper will use the terms "caregiver," "provider," and "producer" interchangeably.

state-licensed dispensaries offered a significant benefit to patients. Patients did not need to find an individual willing to be listed as a caregiver on their application form, and could instead rely on a state-sanctioned large-scale production source. However, unlike caregivers or collectives, the number of dispensary licenses was set by MML policy, state-licensed dispensaries needed to overcome a number of regulatory hurdles before beginning distribution, and upon operation these facilities often faced substantial oversight from state authorities.

The expected costs faced by legal producers will be a function of the perceived risk of arrest and prosecution. In states that required caregivers to register, fees were minimal (and often paid by the patient), and if the caregiver did not exceed the MML production limits she was protected from state prosecution. However, the federal felony charge for cultivation of any amount can carry up to 5 years in prison and a $250,000 fine (Eddy, 2010). By reducing the perceived risk of federal prosecution for legal producers in compliance with state law, the Ogden Memo should have increased benefits to patients by increasing medical marijuana availability. The Cole Memo should have had the opposite effect. If supply-side factors are an important determinant of the relative value of medical marijuana participation, then the federal memos may have influenced patient take-up through their effects on medical marijuana access. The magnitude of these effects will depend on the regulatory framework for legal production established by state MML policy.

1.4 Determinants of Medical Marijuana Participation

1.4.1 Data and Descriptive Evidence

To measure medical marijuana participation, I collected data on the number of registered medical marijuana patients for all states with mandatory registration programs as of 2014. The full listing of data sources for each state — which include direct

contact with state officials, state department reports and websites (and archived sites accessed through *archive.web.org*), academic papers, and local news articles — is provided in Appendix A-. This paper uses monthly data from 1999-2014, and Table 1.2 presents count tabulations of data availability by year and state. The measure of interest is the registration rate, calculated as the percent of the resident adult population registered as medical marijuana patients.[16]

As shown in Table 1.2, data availability on registered patient counts varies across states. Some states provide monthly statistics, while others collect data quarterly or annually. For states with smaller registration programs (e.g. AK, VT), administrative records were not made available and had to be collected from older news articles and archived web pages. For states with more developed registration systems, statistics could be found starting from the program's inception, but the frequency of data collection increased substantially following the Ogden Memo in 2009. For months with missing data, registered patient counts were linearly interpolated using the two closest months of data. This new dataset presents the most comprehensive state panel of medical marijuana participation made available as yet.

The solid line in Figure 1.2 plots the total number of individuals registered as medical marijuana patients from 1997-2014 in states that required patient registration. As the data show, registered patient counts were relatively flat during the period of federal intervention from 1997-2008, but the Ogden Memo (leftmost vertical dashed line) led to a rapid increase in medical marijuana patient participation. The spike in patient take-up coincided with significant growth in the number of legal medical marijuana producers. According to estimates by Sevigny et al. (2014), from 2008-2010 the number of medical marijuana dispensaries increased from around 1,400 to 3,800, and the number of legal producers grew from less than 20,000 to almost 90,000.

[16]While minors under age 18 can technically qualify as medical marijuana patients, they face more stringent requirements and hence represent an insignificant share of registered patients.

As shown in Figure 1.2, medical marijuana participation stalled following the Cole Memo. Patient registration rates resumed growth in mid-2013 when Deputy Attorney General James Cole released a second memorandum re-clarifying that federal enforcement resources should focus on large-scale marijuana operations only if they are suspected of engaging in certain criminal activities such as trafficking across states lines, distributing to minors, and supporting cartels (Cole, 2013).

While the aggregate data suggest that these federal memos significantly affected trends in medical marijuana participation, the magnitude of these changes varied widely across states. To illustrate this variation, Figure 1.3 graphs trends in adult per capita patient registration rates for states with effective registry dates prior to 2010. Some states (e.g., Colorado and Montana) saw exponential growth in registration rates following the Ogden Memo and declines in registered patient counts at the time of the first Cole Memo. Other states (e.g., New Mexico and Rhode Island) show an up-tick in patient registration with the Ogden Memo but appear to have been relatively unaffected by the Cole Memos. Finally, a few states (e.g., Nevada and Alaska) have seen relatively flat trends in medical marijuana participation since program enactment.

Summary statistics for the variables used in this paper's regression analysis are presented in Table 1.3. Columns (1) and (2) show the mean and standard deviation in monthly medical marijuana registration rate data and for the other included control variables in the models. Column (3) presents the standard deviation across state averages, such that comparing columns (2) and (3) indicates how much of the data variation comes from differences across versus within states.

1.4.2 Empirical Framework and Results

Based on the conceptual framework outlined in section 1.3, this study considers the effects of federal policy changes, state regulations, and their interactions on medical

marijuana participation. Due to data limitations, I take a reduced-form approach and do not separately model eligibility, take-up conditional on eligibility, or entry and exit. The approach begins by restricting the sample to monthly data for those states with medical marijuana registries prior to the Ogden Memo (Oct, 2009) and estimating the pooled equation:

$$R_{jt} = \alpha + \kappa' X_{jt} + \beta_0(t - Ogden) + \delta_0(t - Cole) + \varepsilon_{jt} \tag{1.1}$$

where R_{jt} is the natural log of per capita adults registered as medical marijuana patients in state j at time t. Additional time-varying monthly state covariates that may influence medical marijuana participation are included in vector X_{jt}. These include the monthly unemployment rate, a dummy variable for whether the state governor was a Democrat, and dummies for whether the state legislature was controlled by the Democratic or Republican party (the omitted category being split control). In addition, I include a state-specific spline for years since the registry opened, with (discontinuous) knot points at the end of the first, second, and third year since opening. Months since the Ogden Memo and the Cole Memo are represented by $(t - Ogden)$ and $(t - Cole)$ respectively, and thus β_0 and δ_0 represent the differential effect of the Ogden and Cole Memos on monthly percent changes in the registration rate.

Table 1.4 presents results based on the specification of equation 1.1. Column (1) includes only trend breaks at the Ogden and Cole Memos and splines for years since registration opened. Column (2) adds monthly covariates, column (3) adds year fixed effects, column (4) adds state fixed effects, and column (5) includes annual state-level covariates. In all specifications, the Ogden Memo significantly increased growth in medical marijuana patient participation while the Cole Memo significantly decreased trends in patient take-up.

The framework of section 1.3 suggests that the effects the federal memos may

differ depending on specific state MML regulations. To incorporate this variation, I augment equation 1.1 to permit medical marijuana participation to vary with state policy. Defining Pol_{jt} as a matrix of dummy variables for whether state j has a specific MML policy at time t, the differential effect of the Ogden and Cole Memos for each policy variable are estimated by:

$$\begin{aligned} R_{jt} =& \alpha + \gamma' Pol_{jt} + \kappa' X_{jt} + \beta_0(t - Ogden) + \delta_0(t - Cole) \\ &+ \sum_{k=1}^{K} \beta_k(Pol_{jt}^k(t - Ogden)) + \sum_{k=1}^{K} \delta_k(Pol_{jt}^k(t - Cole)) + \varepsilon_{jt} \end{aligned} \tag{1.2}$$

where the main difference from equation 1.1 is the allowance for heterogeneous effects of state-specific MML regulations (Pol_{jt}) and their differential effects on medical marijuana participation due to the federal memos. The base policy effects, parameterized by vector γ, net out state variation in specific MML regulations adopted that may be correlated with unobservables that also affect medical marijuana take-up. The coefficients on the interaction terms β_k and δ_k, measure the extent to which medical marijuana participation changed by a differential amount following the Ogden and Cole Memos in states that had adopted policy k. These coefficients are the primary estimates of interest.

Several policy variables are included in Pol_{jt}. Supply-related regulations include a dummy variable for whether state-licensed dispensaries were legalized, and a variable for the laxness of caregiver restrictions equal to 1 if caregivers could grow for an unlimited number of patients, equal to 0.5 if they could grow for multiple patients but faced production limits, and equal to 0 if they could grow for zero or only one patient. A dummy variable for whether the state had decriminalized marijuana is included to reflect the relative risk of arrest for marijuana possession should a patient not register. To capture the relative cost of obtaining a doctor's recommendation, I include a variable equal to one if chronic pain was allowed as a qualifying condition, equal to

0.5 if chronic pain was allowed as a qualifying condition with certain restrictions, and equal to 0 if chronic pain was not allowed as a qualifying condition. Finally, continuous variables for medical marijuana possession limits (in ounces) and registration fees are also included.

Table 1.5 examines the effects of the Ogden and Cole Memos, controlling for specific state MML regulations. Since Table 1.3 shows many of these policies are time-invariant within states, specifications control for year but not state fixed effects. From columns (1) and (2), the significant effects of the Ogden and Cole Memos hold even when controlling for changes in state-specific regulations. Consistent with the predictions of section 1.3, laxer restrictions on suppliers, lower costs (or laxer criteria) for qualifying, and higher possession limits are associated with significantly higher medical marijuana participation. Having a decriminalization law (i.e., lower expected penalties of using marijuana if not registered) and higher registration fees are associated with significantly lower take-up.

Columns (3) and (4) of Table 1.5 allow the effects of specific state MML regulations to vary with time since the Ogden and Cole Memo announcements. The effects of the Ogden and Cole Memos alone lose significance. Allowing pain as a qualifying condition also significantly increases medical marijuana participation, but it has no differential effect following the Ogden and Cole Memos. The only significant differential effects are on the variable for laxness of caregiver restrictions. This suggests that benefits associated with increased legal availability are an important determinant of medical marijuana patient participation, and that legal production increased (decreased) in response to the Ogden (Cole) Memo most in states that did not impose strict capacity constraints on legal suppliers.

1.4.3 Supporting Evidence that Supply Drives Patient Take-up

These findings suggest that the effects of the federal memos on medical marijuana suppliers was an important driver of patient registration. For Colorado, there is sufficient data to disaggregate registered patient counts by those patients with and without a designated caregiver. For Colorado, Figure 1.4 shows that, indeed, the most substantial growth in registered patient counts was seen by patients reporting a primary caregiver as their source of marijuana; similarly, the Cole Memo led a larger reduction in registered patient counts among patients with caregivers compared to patients without caregivers.

Figure 1.5 provides further evidence that interest in medical marijuana flows from producers to patients. The graph shows quarterly data for Google search interest in the phrases "how to become a patient" and "how to become a caregiver." Data was collected from Google Trends, which measures relative search interest over time for these phrases from a sample of total searches. The spike in search interest for becoming a caregiver occurs at the time of the Ogden Memo, and it clearly precedes that of search interest in becoming a patient. This suggests that producers responded more rapidly to the announcement effects of the Ogden Memo than users, and is consistent with evidence that incentives to obtain information about a program are influenced by the expected net benefit of participating (Daponte et al., 1999).

To assess the relative role of supply and demand in driving medical marijuana patient registration, ideally one would have detailed state-level time series data on potency-adjusted marijuana prices. Unfortunately, since marijuana remains illegal at the federal level, accurate price data is highly limited. The most widely used data on marijuana prices comes from two data sources. *High Times* is an online magazine where users can submit the price they paid for their last marijuana purchase. The magazine reports individual price submissions by city and strain of cannabis. *Priceofweed.com* is a website that collects user-submitted data in real-time on the

price of marijuana purchases and classifies them into "high", "medium", or "low" quality. For completeness, I present evidence based on this crowd-sourced data, but they are intended only as suggestive evidence and should be interpreted with caution.

Table 1.6 presents estimates for the effects of registration rates on the natural log of price per ounce of high-potency marijuana. For the regressions, data on high-quality marijuana prices was aggregated at the state-quarter level and converted to price-per-ounce. Outlying price values (below the 1st and above the 99th percentile) were dropped.[17] The results from Table 1.6 show that increases in registration rates significantly predict lower prices. This suggests that, even if higher medical marijuana participation rates to some extent reflect increased demand, they reflect even larger effects on supply.

1.5 Reconciling Past Research on MMLs

A number of studies have exploited state-time variation in the enactment of MMLs to estimate their effects on marijuana use in the general population. Findings have varied substantially, with estimates ranging from significantly negative, to statistically insignificant, to significantly positive (see Hunt and Miles (2015) for an excellent review). However, the standard difference-in-differences (DID) approach employed in these studies implicitly assumes that the "treatment effect" of MML enactment is dichotomous, i.e. the policy change occurs at a specified date, and it is implemented completely and equally across states. Whether this assumption holds will depend on the mechanisms by which MMLs induce changes in behavior.

[17]Since *High Times* does not provide data on the purchase volume, prices are not adjusted for quantity discounts.

Perceptual Effects

According to deterrence theory, by reducing the perceived severity of legal or informal sanctions associated with marijuana consumption, MML enactment should *ceteris paribus* increase demand. Since the passage of MMLs provided similar legal protections and represented a shift in either governmental or social acceptance of marijuana, ex-ante these effects should occur simultaneously with law enactment and be similar across states.

This prediction relies on three conditions: that the statutory policy change is actually implemented, that no offsetting changes in enforcement occur simultaneously, and that the public is aware of the change in policy (MacCoun, 1993; MacCoun et al., 2009). Since MMLs provide protection from state-level but not federal prosecution, citizens may be even less likely to update their expectations about potential prosecution until it is observed or known that the federal government will not intervene. Since awareness about laws and enforcement policies will be diffused through social networks, personal experience, and the mass media, the federal memos and their coverage by the media and marijuana advocacy groups (see section 1.2.3) may have had far greater effects on public perception than MML enactment alone.

To provide suggestive evidence that knowledge about MMLs was limited prior to the Ogden Memo, Table 1.7 presents state-representative data on MML awareness from the National Survey of Drug Use and Health (NSDUH), which starting in 2002, asked respondents the following: "In your state, has marijuana been approved for medical use?" Table 1.7 reports cross-sectional variation in the percent of youths and adults who responded "yes" to this question, comparing the 2008-2009 (pre-Ogden period) and 2010-2011 (Ogden period) for each state with an MML prior to 2009.[18]

[18]State-level data for this sample was collected through the NSDUH Restricted Data Access System (R-DAS), which only provided data from 2002-2011 in two-year averages and has been made temporarily unavailable.

Although these are not causal effects, they provide some useful insights.

The first striking feature of Table 1.7 is the wide range of awareness across MML states. Oregon was the only state in 2008-2009 where over half of adult respondents (75.9%) correctly reported that the state had an MML. In contrast, less than 18% of adults in Nevada correctly responded that their state had an MML. On average, youths aged 12-17 are less aware of MML existence, but there is similar variation across states. The share of adolescents correctly reporting their state had an MML in 2008-2009 ranged from 25% in Vermont to 47% in Oregon. This variation in awareness is not explained by differences in how long the MML has been in effect.

Also of note is the substantial increase in awareness of MML status following the Ogden Memo for Colorado, Montana, and Michigan. In two years, the share of adults who correctly responded that their state law allowed for the use of medical marijuana nearly doubled. These states also show the largest increase in awareness among youths. From Tables 1.1 and 1.5, these were also states with MMLs allowing caregivers to serve multiple patients and experiencing the greatest growth in medical marijuana patient participation following the Ogden Memo.

The evidence from Table 1.7 suggests that the perceptual effect of state medical marijuana liberalization was relatively unrealized until after the Ogden Memo. It is thus unsurprising that studies only covering a time period prior to 2009 find insignificant effects of MML enactment on use for both adolescents and adults.[19]

[19]Chu (2014) is the only study to find significantly positive effects using data prior to 2009. Using data through 2008 on marijuana-related arrests and substance abuse for adult males, he finds significantly positive effects of MML enactment. However, these results are highly sensitive to the inclusion of state-specific trends and data from California and Colorado.

Availability and Price

Another mechanism by which MMLs may affect marijuana consumption is through increasing availability or decreasing prices. Research by Pacula et al. (2013) recognized that, if these are important channels through which MMLs generate spillovers, estimation needs to account for heterogeneity in the specifics of MML provisions. Accordingly, more recent studies have, in addition to using a binary measure of MML enactment, also included indicator variables for allowance for the legal operation of retail dispensaries and allowance for home cultivation by patients and/or caregivers. Still, findings have varied (Hunt and Miles, 2015).

While this approach is an improvement to treating MMLs as a homogeneous set of policies, it still relies on the assumptions of the DID approach and thus suffers from similar limitations. For example, including a categorical measure of "home cultivation allowance" implicitly assumes that all home cultivation laws are created equal. As Table 1.1 shows, this is clearly not the case. A binary variable for whether a state allowed patients or caregivers to cultivate would take a value of one for both Colorado and Vermont. However, a caregiver in Vermont was limited to growing for only one patient, and thus could only legally cultivate three plants; a caregiver in Colorado could grow for an unlimited number of patients, and could thus theoretically be legally protected (at the state level) for maintaining a large-scale grow operation with hundreds of plants.

Additionally, it is unclear whether the dummy variables for any specific policy measure should "turn on" when the law is passed, when it becomes statutorily effective, or when it becomes effective "on the ground" (Hunt and Miles, 2015). This is especially problematic for the measurement of dispensary legalization. As shown in Table 1.1, some states did not explicitly permit dispensaries but they did not explicitly prohibit them either. And for states that legalized state-licensed dispensaries in their initial MML, there were often substantial implementation lags between law

enactment, the licensing of dispensaries, and the opening of dispensaries (Anderson and Rees, 2014). Even if the date of first dispensary operation is correctly identified, production-related realities (e.g., scaling the operation) may lead to further lags before the full effects on access and price are realized. These lags are likely not random, but will be correlated with unobservable local attributes as well as enforcement efforts at the federal level.

1.6 Discussion

This paper shows that there is substantial heterogeneity both across states and over time in the extent to which users and suppliers have actively participated in state medical marijuana programs. Changes in perceived federal enforcement had far greater effects on medical marijuana take-up than MML enactment alone, and these effects were concentrated in those states that imposed relatively lax restrictions on legal producers. This indicates that medical marijuana participation is largely driven by the expected benefits associated with access to legal supply.

A few other findings deserve mention. First, states with MMLs allowing chronic pain as a qualifying condition on average have significantly higher registration rates. This is unsurprising since these states have a larger pool of eligible applicants. However, the fact that the federal memos did not have a differential effect on registration rate trends in these states with laxer qualifying standards suggests the federal policies did not differentially affect physician willingness to recommend a "marginal" patient. Second, higher registration fees significantly reduce medical marijuana participation. This is consistent with anecdotal evidence that registration fees represent a barrier to take-up for many patients (Alexandre, 2010), and future work should assess whether there is age or demographic heterogeneity in the elasticity of participation with re-

spect to application costs.[20]

From this paper's analysis, changes in medical marijuana registration rates seem to follow a pattern largely consistent with economic models of rationality. Overall, both across- and within-state variation in medical marijuana patient registration rates is primarily driven by differences in the costs of obtaining marijuana. Given evidence that supply spillovers from legal medical marijuana markets to illegal markets largely occur through diversion from registered patients to unregistered consumers (Nussbaum et al., 2015; Thurstone et al., 2011; Wadley and Barnes, 2013), changes in registration rates may more precisely reflect the spillover effects of MML policy compared to binary indicators for various dimensions of MML regulations.

The conclusions of this paper can be used to inform the methodologies employed by future work studying the effects of MMLs on substance use and other related outcomes. Using a binary measure of MML enactment to identify the effects of marijuana liberalization relies on a coarse (and therefore imprecise) measure of the impact of MML policy on the marginal user. By instead evaluating the effect of MMLs through changes in registration rates or the policy aspects that induced such changes, future work can more accurately assess the complex and dynamic effects of liberalization policies on marijuana consumption and its associated health consequences in the general population.

[20]It should be noted that many states offer fee reductions for low-income patients, which are not assessed in this analysis but offer potential avenues for future work.

Table 1.1: Specifics of Initial MML Regulation

	MML Effective	Registry Open	Patient Limit		Caregiver Limit:		Dispensaries Legal	
			Ounce	Plant	Patients	Plants	State-Licensed	De Facto
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: MML Enacted Before 2009								
OR	12/1998	5/1999	3	7	NS	NS		X
AK	3/1999	6/1999	1	6	1	6		
HI	12/2000	12/2000	3	7	1	7		
CO	6/2001	6/2001	2	6	NS	NS		X
NV	10/2001	10/2001	1	7	1	7		X
VT	7/2004	10/2004	2	3	1	3		
MT	11/2004	12/2004	1	6	NS	NS		X
RI	1/2006	3/2006	2.5	12	5	24		
NM	7/2007	7/2007	6	4	4	0†	X	
MI	12/2008	4/2009	2.5	12	5	60		X
Panel B: MML Enacted After 2009								
DC	7/2010	6/2013	2	0	1	0	X	
NJ	7/2010	8/2012	2	0	1	0	X	
AZ	4/2011	4/2011	2.5	12*	1	12*	X	
DE	5/2011	7/2012	6	0	5	0	X	
CT	10/2012	10/2012	2.5	0	1	0	X	
MA	1/2013	10/2014	10	0	0	0	X	

Notes and sources: †Caregivers are prohibited from growing marijuana and can only assist patients with cultivation. *Only allowed if patient lives more than 25 miles from an operating dispensary.

Table 1.2: Data Availability for Registered Medical Marijuana Patient Counts

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
AK	1	0	0	0	0	0	0	0	0	0	0	1	3	4	0	2
AZ													9	10	7	5
CO			1	2	0	1	2	1	1	1	12	12	12	12	12	12
CT														0	6	3
DE													0	2	0	4
DC													0	0	0	12
HI			1	2	2	1	4	3	1	2	1	1	1	2	2	3
MA																3
MI											2	10	9	5	6	2
MT							5	4	4	4	6	11	12	12	12	10
NV			1	1	1	0	2	0	0	0	1	2	1	3	4	12
NJ													0	2	5	4
NM									6	12	12	12	10	1	6	6
OR	0	1	0	3	1	2	3	4	4	4	4	4	4	4	4	4
RI								1	1	1	1	2	1	2	3	3
VT						0	1	0	0	0	1	0	2	4	3	3

Notes and sources: Registration data available by monthly counts. Data for the first 14 days of the month is counted as the prior month. Counts are included in the table if the registration program was open in that year.

Table 1.3: Summary Statistics

	(1)	(2)	(3)
	Mean	Standard Deviation (SD)	SD Across State Averages
Registration Rate Data			
Registered Patients	14,481	31,179	27,726
% Adults Registered	0.502	0.763	0.421
Policy Variables			
Multiple patients per caregiver	0.323	0.381	0.383
State-licensed dispensaries legal	0.172	0.377	0.345
Pain allowed	0.851	0.266	0.274
Decriminalized	0.534	0.499	0.488
Quantity limit (oz)	3.896	6.006	4.286
Registration fee ($)	73.224	60.272	54.884
Monthly Covariates			
Unemployment rate (SA)	6.659	2.405	1.767
Governor Democrat	0.472	0.499	0.328
Legislature Democrat	0.509	0.500	0.386
Legislature Republican	0.221	0.415	0.272
Annual Covariates			
% Black	4.614	3.522	4.408
% Male	50.056	0.972	0.990
% Elderly	10.323	2.277	2.005
Cancer incidence rate (000s)	0.502	0.760	0.760
Ln(Real state pc income)	10.351	0.999	0.976

Notes and sources: N=1374 (10 states, unbalanced panel). See Appendix A- and Appendix B- for data sources.

Table 1.4: Effects of Federal Memos on Medical Marijuana Participation
Dependent Variable = ln(registered patients/adult population)

	(1)	(2)	(3)	(4)	(5)
$[t - Ogden]$	0.102**	0.086**	0.057***	0.037**	0.037**
	(0.033)	(0.033)	(0.016)	(0.015)	(0.013)
$[t - Cole]$	-0.103**	-0.079*	-0.044***	-0.048***	-0.047***
	(0.033)	(0.038)	(0.012)	(0.011)	(0.011)
Unemployment Rate		0.103	0.075	-0.021	-0.040
		(0.099)	(0.152)	(0.081)	(0.058)
Governor Democrat		1.10**	1.17**	0.401	0.572*
		(0.394)	(0.441)	(0.431)	(0.300)
Legislature Democrat		0.207	0.169	-0.071	-0.155
		(0.450)	(0.488)	(0.135)	(0.187)
Legislature Republican		-0.188	0.111	0.221	-0.041
		(0.372)	(0.373)	(0.220)	(0.130)
Ln(Real state pc income)					-6.36**
					(2.34)
% Male					0.091
					(0.495)
% Black					-1.54**
					(0.520)
% Elderly					-1.92*
					(0.902)
Cancer incidence rate					8.50**
					(2.740)
Year FE	N	N	Y	Y	Y
State FE	N	N	N	Y	Y

Notes and sources: N=1374 (10 states, unbalanced panel). Robust SE clustered at state level. Controls included but not shown are splines for first year registry open, second year registry open, third year registry open, and registry open four years or more.

Table 1.5: Federal Memo Effects Depend on State Supply Regulations
Dependent Variable = ln(registered patients/adult population)

	(1)	(2)	(3)	(4)
$[t - Ogden]$	0.064***	0.039*	0.035	0.042
	(0.013)	(0.020)	(0.059)	(0.052)
$[t - Cole]$	-0.041**	-0.051***	0.052	0.012
	(0.013)	(0.012)	(0.112)	(0.091)
CG multiple patients	1.08***	1.02**	0.355	0.435
	(0.316)	(0.332)	(0.458)	(0.443)
$*[t - Ogden]$			0.157***	0.152***
			(0.041)	(0.032)
$*[t - Cole]$			-0.208**	-0.219***
			(0.052)	(0.049)
State-licensed dispensaries	-0.207	-0.247	0.248	-0.191
	(0.351)	(0.325)	(0.438)	(0.474)
$*[t - Ogden]$			-0.019	-0.003
			(0.035)	(0.041)
$*[t - Cole]$			0.014	-0.022
			(0.057)	(0.061)
Decriminalized	-1.12**	-0.234	1.32**	-0.682
	(0.489)	(0.356)	(0.581)	(0.511)
$*[t - Ogden]$			-0.031	-0.024
			(0.029)	(0.052)
$*[t - Cole]$			0.060	0.060*
			(0.038)	(0.032)
Pain Allowed	1.81**	0.574	2.44***	1.50*
	(0.757)	(0.629)	(0.502)	(0.707)
$*[t - Ogden]$			-0.009	-0.058
			(0.059)	(0.047)
$*[t - Cole]$			-0.069	-0.012
			(0.119)	(0.092)
Possession limit (oz)	0.084***	0.030	0.078***	0.016
	(0.008)	(0.033)	(0.010)	(0.026)
Registration fee	-0.001	-0.010***	0.000	-0.008***
	(0.003)	(0.002)	(0.002)	(0.002)
Year FE	Y	Y	Y	Y
Covariates	N	Y	N	Y

Notes and sources: N=1374 (10 states, unbalanced panel). Robust SE clustered at state level. Controls included but not shown are monthly unemployment rate, share black, share elderly, share male, cancer incidence rate, governor party, legislative party control, and splines for first year registry open, second year registry open, and registry open three years or more.

Table 1.6: The Effect of Legal Market Growth on User-Submitted Prices of High-Quality Marijuana

	Ln(Price per ounce)	
	High Times (1997-2011)	Priceofweed.com (2010-2013)
Registration Rate	-0.064**	-0.020**
	(0.027)	(0.009)
Average price per oz	377.83	339.49
N	1244	597

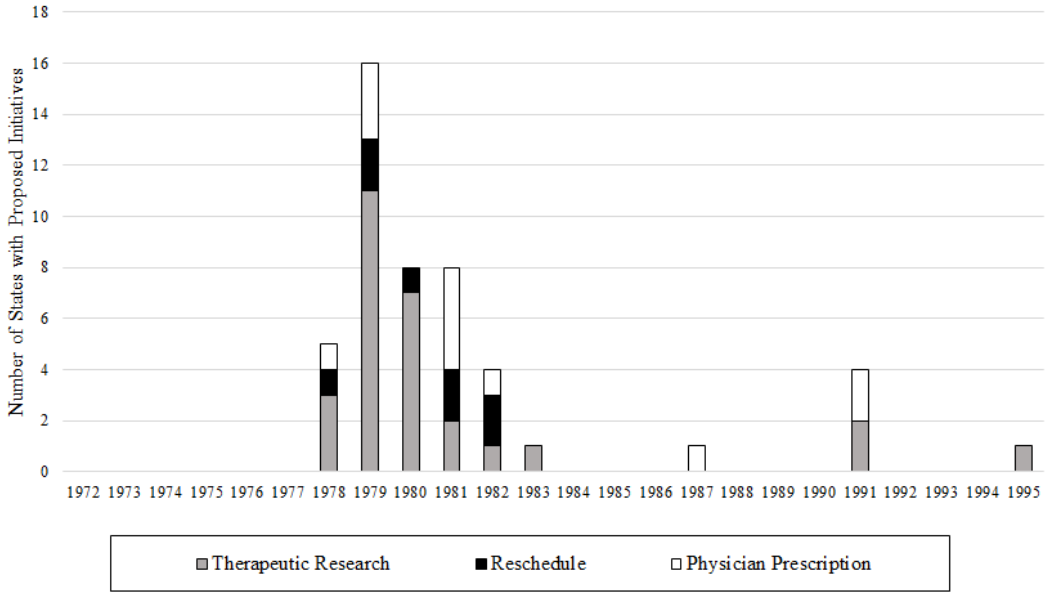
Notes and sources: Quarterly data. Regressions include state, year, and quarter fixed effects, and are weighted by the number of user submissions in the state-quarter. Priceofweed.com data only includes states from the continental US. Outlying price values (below the 1st and above the 99th percentile) were dropped. See Appendix B- four sources.

Table 1.7: Knowledge About Whether State Has a Medical Marijuana Law

	When Asked Whether State Has MML, Percent Responding "Yes"					
	Age 12-17			Age 18+		
	2008-2009	2010-2011	Change	2008-2009	2010-2011	Change
States with MMLs Prior to 2009 (Year MML Effective)						
Alaska (1998)	27.9	27.1	-0.8	37.7	40.0	2.3
Oregon (1999)	46.9	51.2	4.3	75.9	78.1	2.1
Hawaii (2000)	36.6	44.7	8.1	44.5	44.0	-0.4
Colorado (2001)	35.1	67.2	32.2	49.9	87.0	37.1
Nevada (2001)	25.7	29.8	4.1	17.5	29.3	11.7
Vermont (2004)	25.0	31.1	6.1	25.9	33.7	7.9
Montana (2004)	35.5	72.6	37.1	45.6	85.3	39.7
Rhode Island (2006)	28.4	32.9	4.5	40.4	55.9	15.4
New Mexico (2007)	30.5	36.7	6.3	33.4	47.4	14.0
Michigan (2008)	34.2	51.3	17.4	38.1	73.8	35.7
Average	*32.6*	*44.5*	*12.1*	*41.0*	*59.1*	*18.1*
State with No MML as of 2012						
Average	14.8	13.0	-1.8	5.7	4.4	-1.4

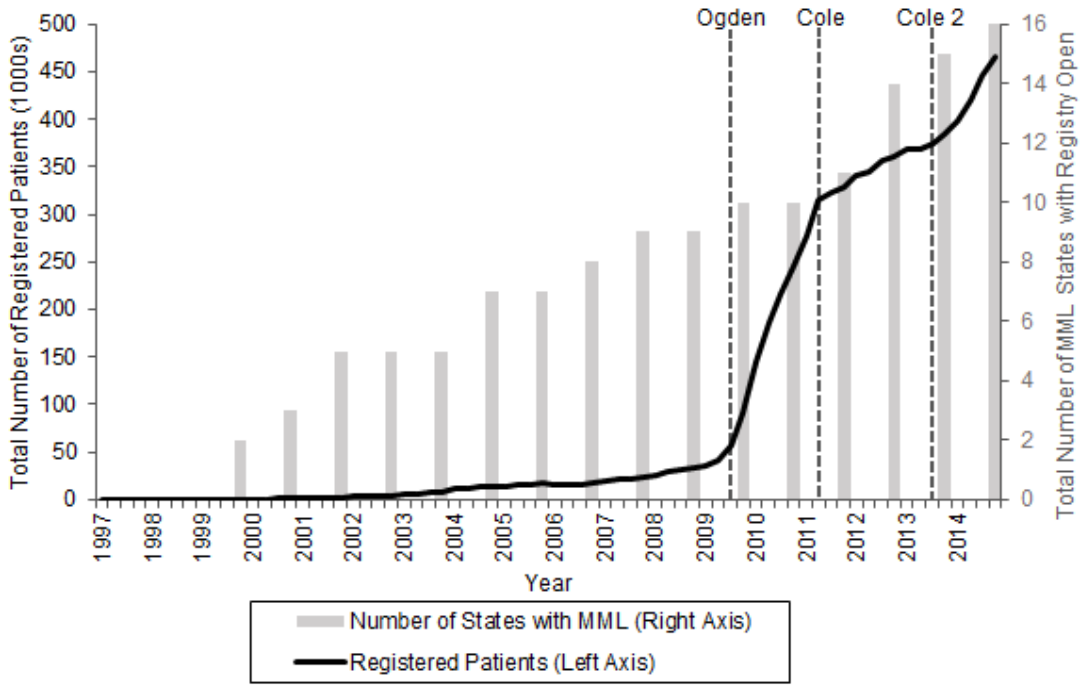
Notes and sources: From the National Survey of Drug Use and Health Restricted Data Access System (R-DAS).

Figure 1.1: Timeline of State Marijuana Liberalization Initiatives



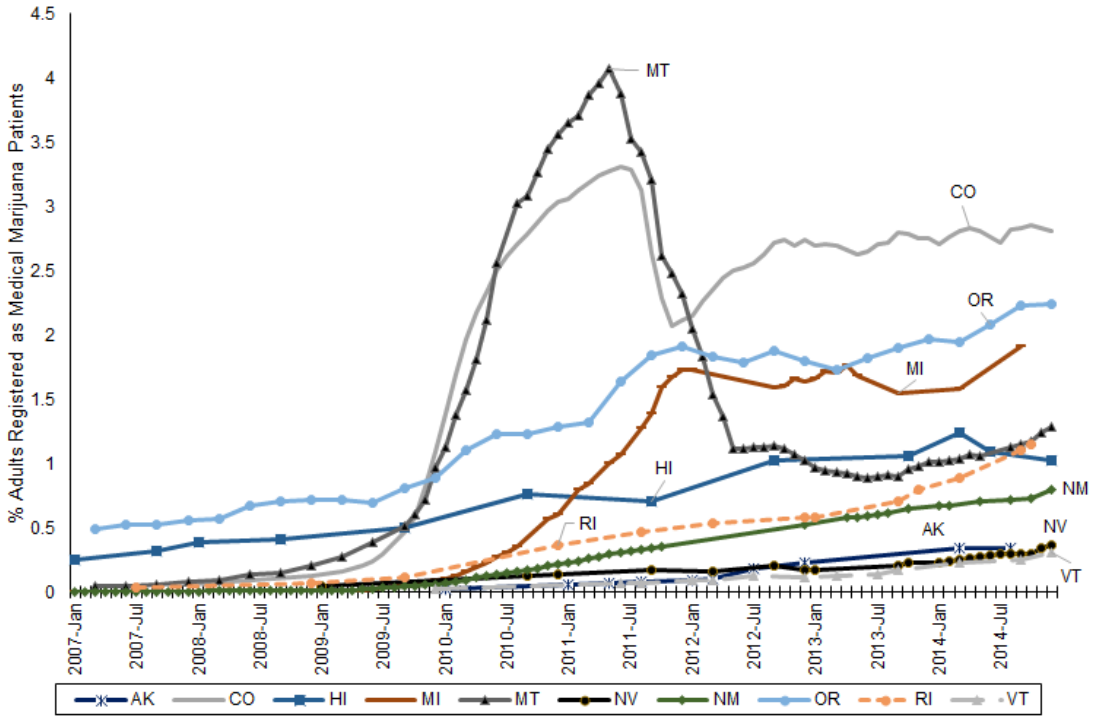
Notes and sources: Data from Caulkins et al. (2012) and own collection.

Figure 1.2: Total Number of Medical Marijuana Patients
in States with Registries, Response to Federal Memos



Notes and sources: Data from own collection. Leftmost dashed line is the time of the Ogden Memo (Oct, 2009), which decreased federal enforcement. Rightmost dashed line is the time of the Cole Memo (June, 2011), which increased federal enforcement. Bars (right axis) represent the number of states with mandatory registration and operational registries.

Figure 1.3: Trends in Percent of Adults Registered as Medical Marijuana Patients Vary Across States



Notes and sources: Data from own collection. States included are Alaska (AK), Colorado (CO), Hawaii (HI), Montana (MT), Nevada (NV), New Mexico (NM), Oregon (OR), Rhode Island (RI), and Vermont (VT).

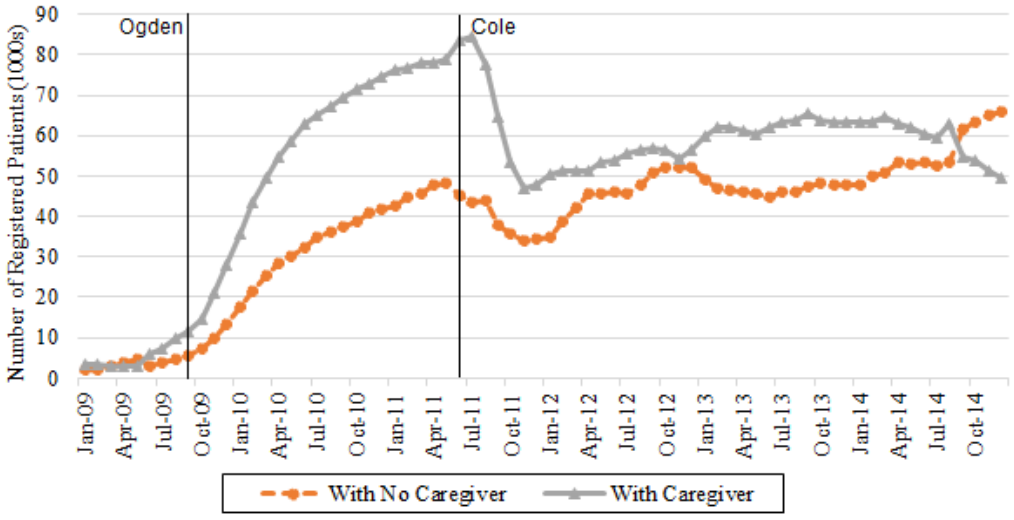


Figure 1.4: Trends in Registered Patient Counts in Colorado,
By Whether Patient Had Designated a Caregiver to Grow for Them

Notes and sources: Data from own collection.

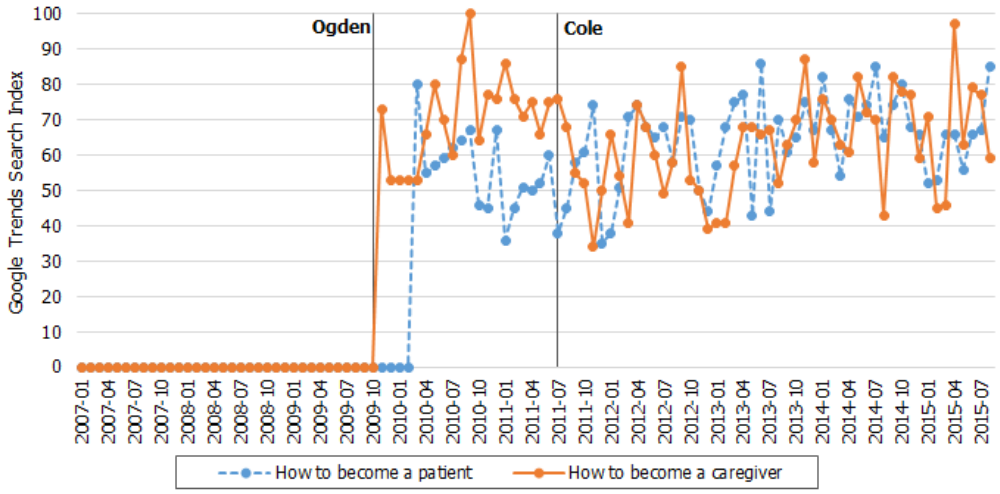


Figure 1.5: Trends in Google Search Interest for Becoming a Caregiver or Patient

Notes and sources: Data from own collection using Google Trends.

1.7 Appendices

A- Sources for Registered Patient Data

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State per capita personal income data comes from the US Department of Commerce, Bureau of Economic Analysis. Nominal data was adjusted for inflation using the Consumer Price Index-Urban conversion factors provided by the Bureau of Labor Statistics.

Demographic

Annual state-level data on share of the population over age 64, share black, and share male come from the National Center for Health Statistics Bridged-Race Population Estimates. Data were downloaded through the Centers for Disease Control and Prevention Wide-ranging Online Data for Epidemiologic Research (WONDER) system.

Cancer statistics are based on official federal statistics produced by the Centers for Disease Control and Prevention and the National Cancer Institute. Data was again downloaded through the Wide-ranging Online Data for Epidemiologic Research (WONDER) system. Additional data from the American Cancer Society's "Cancer Fact & Figures" series was used to fill in missing data points.

Price

Data from *High Times* before August, 2008 was graciously provided by Mireille Jacobson and Catherine Alford. Data from September 2008 through December, 2011 from the *High Times* website is from author's own collection. The name of the strain

was used to classify marijuana as high or low quality.

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CHAPTER 2

The Kids Aren't Alright: Effects of Medical Marijuana Market Growth on Marijuana Use

2.1 Introduction

Since 1996, growing evidence of the potential medical benefits of cannabis and increasing social acceptance of the drug have led twenty-three states and Washington D.C. to enact medical marijuana laws (MMLs), which legalize the use and cultivation of marijuana for medical purposes at the state level. Several of these states have also recently expanded legalization to allow the commercial sale of marijuana to adults for recreational purposes. Prior research has sought to estimate the effects of these policies on marijuana consumption by comparing MML states before and after law passage to states without such laws, but findings have varied.[1] However, this approach assumes that the law's passage had an equal and immediate effect on demand-side or supply-side channels that would increase consumption. The absence of reliable data on prices and transactions makes this assumption difficult to verify.

This paper instead uses improved data and a novel instrumental variables approach to directly study the effects of growth in the *size* of legal markets for medical marijuana on recreational use. Newly collected data on per capita medical marijuana patient registration rates show that changes in market size are driven by policies

[1]See Pacula et al. (2015) for a review of the literature on the effects of MML enactment.

changing supply costs and not MML enactment alone, and that growth in the legal market has the unintended consequence of significantly increasing recreational marijuana use among both adults and adolescents. Evidence suggests that changes in the supply of medical marijuana, driven by policies changing the costs faced by legal producers, generate these spillovers to adolescent markets.

A simple model of supplier behavior argues that if growth in the legal market is driven by lower production costs, then the price and availability of marijuana in the illegal market will track changes in the legal market. Specifically, the model implies that changes in federal enforcement will have larger effects on marijuana availability in states where legal producers are subject to relatively lax production limits. To confirm the model's predictions, I exploit two policies that changed federal enforcement against medical marijuana suppliers (the Ogden Memo in late 2009 de-prioritized federal enforcement in MML states, while the Cole Memo in mid-2011 escalated enforcement) as cost shifters. Empirical evidence from medical marijuana patient registration rates confirms that supply costs drive changes in the legal market. The Ogden Memo caused an additional 2% of the adult population to register as medical marijuana patients in states with loose supply regulations, compared to an additional 0.2% in states with strict regulations. Similarly, the Cole Memo significantly reduced legal market growth in loosely regulated MML states but had no effect in states that strictly regulated supply.

To estimate the causal effect of changes in medical marijuana supply on marijuana consumption, I instrument for market size with the interaction of initial state regulatory laxness and changes in federal enforcement. Results show that reaching the median state's legal market size (approximately one percent of adults registered for medical marijuana) would significantly increase the prevalence of marijuana use in the past month from 7.2% to 7.7% for adolescents aged 12-17 (a 6% increase), from 17.3% to 18.9% (a 9% increase) for 18-25 year-olds, and from 4.4% to 5.2% (an

18% increase) for adults over age 25. The significant effects found for youths are in contrast to the null findings of prior research.[2]

This paper contributes a novel approach for estimating heterogeneous effects in markets with limited legal access. However, this approach has some potential limitations. First, the identification strategy relies on the assumption that federal enforcement changes did not impact demand differently in states with different supply regulations; a number of robustness checks address this potential threat to identification. Second, since the measures of marijuana use are self-reported, the estimates may be subject to reporting bias. Evidence from arrest rates is used to support that the results are not driven by changes in reporting behavior. Third, the approach does not account for potential cross-border spillovers of marijuana supply. This would tend to bias the estimates downward, but evidence using Montana as a case-study indicates that this bias is small.

The paper proceeds as follows. Section 2.2 explains state variation in medical marijuana policies, outlines a simple model of supplier behavior, and shows that medical marijuana registration rates are a valid measure of legal marijuana market size. Section 2.3 outlines the methodological approach, section 2.4 describes the data, and section 2.5 presents the empirical results. Robustness checks are included in section 2.6, and section 2.7 concludes.

[2]Anderson et al. (2015), Hasin et al. (2015), Choo et al. (2014), Lynne-Landsman et al. (2013), and Wall et al. (2011) find no effect of MML passage on adolescent marijuana use. Salomonsen-Sautel, Sakai, et al. (2012) uses a random-effects model and is the only paper to find positive effects.

2.2 Effects of Medical Marijuana Laws (MMLs)

2.2.1 Background on Medical Marijuana Policy

With the Compassionate Use Act (Proposition 215) in 1996, California became the first state to pass a medical marijuana law (MML), removing criminal penalties for the use, possession, and cultivation of medical marijuana. The state law directly contradicts the federal ban on marijuana use and distribution established in 1937,[3] which remains in place today due to concerns cited by the Office of National Drug Control Policy (ONDCP) about legalization's effects on marijuana use and abuse (ONDCP, 2014). The potential increase in youth consumption is of particular concern as some research suggests use of marijuana during early adolescence predicts increased risk of dependence, lower educational attainment, and cognitive impairment.[4]

Despite federal prohibition of marijuana, as of 2015, twenty-two additional states and Washington D.C. have enacted laws providing some protections for the use of medical marijuana; five of these states have also legalized the sale of marijuana to adults aged 21 and older for non-medical purposes. Table 2.1 shows a summary of state laws and various dimensions on which they differ.[5] These state regulations vary greatly in how medical marijuana can be supplied. Certain states (e.g., Colorado and Montana) allowed "caregivers" to supply marijuana to an unlimited number of patients. This permitted producers to operate with virtually no quantity limits and little state oversight. Other states (e.g., Hawaii) had more restrictive supply limits, allowing only home-cultivation by the patient himself or by the patient's designated

[3]The Marijuana Tax Act of 1937 established a prohibitive tax that effectively criminalized possession and sale of the drug. See Bonnie and Whitebread (1970) for a history of marijuana prohibition in the U.S.

[4]See Hall (2015) for a comprehensive review of this literature.

[5]Since the primary analysis uses data through 2012, Table 2.1 summarizes the laws for states with MMLs that became effective before 2012. Seven states have passed MMLs since.

caregiver, who was limited to supplying only one patient. Finally, some states (e.g., New Mexico) legalized state-licensed dispensaries, which could serve many patients but were subject to substantial monitoring and limited production quotas.

Different production allowances can be expected to have heterogeneous effects on price, availability, quality, and product variety in the legal market. While laxer production limits should lead to lower access costs for registered medical marijuana patients, they may also have the unintended effect of increasing spillovers to youths. Adolescents largely do not have legal access to medical marijuana,[6] but evidence from cigarette markets shows that youth access laws are limited in effectively reducing teenage consumption due to the presence of social markets (Katzman et al., 2007). As costs facing legal users in the formal market significantly affect availability to underage users through these secondary markets (Hansen et al., 2013), changes in the size of the state medical marijuana industry may better predict changes in adolescent cannabis use than the passage of the law alone.

Previous work has mostly ignored the wide variation in MMLs and their implementation. Given the heterogeneity in state supply restrictions, differences in the findings of prior work may be partly due to which MML states are used for identification. Pacula et al. (2015) recognized the importance of accounting for differences in the specific dimensions of MML policy, but there remains debate over how to categorize these regulatory differences and interpret their effects. For instance, Pacula et al. (2015) find evidence that only MMLs that legalized dispensaries saw significant increases in recreational marijuana use. However, their finding that dispensary laws have significant effects even without the existence of operational dispensaries raises questions as to how to interpret these results (Anderson and Rees, 2014). And, as shown in Table 2.1, there is heterogeneity even within states that allowed dispen-

[6]While individuals under age 18 can qualify for medical marijuana, they have stricter qualifying standards and require parental consent. Consequently, few minors are registered for medical marijuana use.

saries (or allowed caregivers to effectively operate as dispensaries) in the strictness of production restrictions.

Another potential explanation for the varied findings of past work is the incomplete consideration of the role of federal policy in determining the size and structure of medical marijuana markets. While federal law has remained unchanged throughout years of state experimentation with marijuana liberalization, federal enforcement in these states has varied widely. Before 2009, the federal government made direct threats toward MML states, stating that even users and suppliers in compliance with state policy would remain subject to federal prosecution (French, 2005). However, between 2009 and 2012, two federal memos dramatically altered perceived federal enforcement in medical marijuana states.

The Ogden Memo, announced on October 19, 2009, formalized guidelines for federal prosecutors in MML states. The memorandum maintained the government's commitment to prosecuting significant traffickers of marijuana, but emphasized that "prosecution of individuals with cancer or other serious illnesses who use marijuana as part of a recommended treatment regimen consistent with applicable state law, or those caregivers in clear and unambiguous compliance with existing state law who provide such individuals with marijuana, is unlikely to be an efficient use of limited federal resources" (Ogden, 2009). In sum, the Ogden Memo de-prioritized the federal government's involvement in prosecuting medical marijuana users and suppliers in states with MMLs.

On June 29, 2011, the US government reversed this stance by issuing the Cole Memo as a response to the government's perceived "increase in the scope of commercial cultivation, sale, and distribution and use of marijuana for purported medical purposes" (Cole, 2011). The Cole Memo stated that individuals involved in the business of medical marijuana sales and distribution would be subject to federal enforcement action. In the months leading up to and following the memo, the Drug Enforce-

ment Administration stepped up raids on medical marijuana producers (Houser and Rosacker, 2014).

If changes in the risk of federal prosecution shift production costs, then both state-variation in supply restrictions and time-variation in federal policy will determine the size of the legal market. Moreover, in states where legal and illegal markets for marijuana co-exist, policy changes that shift production costs in the legal market may affect price and availability in the illicit market. To better understand the effects of costs associated with state restrictions and federal enforcement, I outline a simple model of supplier behavior.

2.2.2 Model Setup

The purpose of the model is to provide theoretical predictions of how supplier responses to the changes in federal enforcement (detailed in section 2.2.1) should differ depending on state MML regulations. I can then link these predictions to newly collected empirical evidence on the size of the legal market. The model also provides intuition for the regulatory variables used in the empirical analysis and clarifies the key assumptions upon which my approach relies. As the illegal market for marijuana is not directly observed, modeling the interaction between the legal and illegal markets is helpful in motivating the appropriate empirical framework to estimate how legalizing medical marijuana affects recreational consumption.

The model describes the market for marijuana in an MML state as composed of consumers and suppliers who respond to changes in the probability of being prosecuted by state or federal enforcement. Suppliers operating in the legal medical marijuana market also face capacity constraints that vary by how strictly the state regulates producers. Each state's market is assumed to operate in isolation.[7]

[7]While there is significant evidence of cross-border trafficking of marijuana, this simplifying assumption is used to make the model tractable. For the empirical analysis, violation of this assumption

Consumers

Aggregate demand $D = \beta(e_s, e_f)d(p)$ is assumed to be a downward sloping function of potency-adjusted price p. Enforcement by the state ($e_s \geq 0$) and federal ($e_f \geq 0$) government against marijuana users serves as an aggregate demand shifter, with $\partial\beta/\partial e_s \leq 0$, $\partial\beta/\partial e_f \leq 0$. Users' expected probability of arrest, penalties, and distaste for illegal activity will all be captured through $\beta(e_s, e_f)$. It is worth noting that this setup does not rule out various forms of addiction or habit formation. Both rational and irrational models of consumer behavior imply price and risk responsiveness, but the models differ in the degree of responsiveness to these costs.

With enactment of an MML, users who register as medical marijuana patients face new perceived risks from state ($e'_s < e_s$) and federal ($e'_f \geq e_f$) enforcement. The perceived federal risk of enforcement facing a registered user could exceed that facing an illegal user if, for example, individuals believed the federal government would use state medical marijuana registries to target individuals for prosecution. As users can always face the same risks as during the pre-MML period by choosing not to register, I assume aggregate demand in the MML period is no less than demand under prohibition. The magnitude by which demand shifts will depend on the enforcement risk facing a registered compared to an unregistered user, and on how users weight the relative risks of state and federal enforcement.

Producers

Each marijuana supplier i faces heterogeneous costs of production $C_i(q)$ with marginal costs $C'_i(q) = MC_i(q) \geq 0$, which include the costs of producing, processing, and

will tend to bias the estimated effects downward.

distributing quantity q of marijuana. Assuming a perfectly competitive market,[8] each supplier produces such that $MC_i(q) = p$, where p is determined by the market equilibrium.

I assume an individual firm's marginal costs can be approximated by an increasing linear function of q such that the marginal cost for firm i before MML enactment is denoted: $MC_i = a_i\gamma(e_s, e_f) + bq_i$ where $b > 0$ is common to all firms, and a_i is a firm-specific cost parameter distributed on the interval $(0, \overline{a}]$ with time-invariant cumulative distribution function $G(a)$ and probability density function $g(a)$. State and federal enforcement against marijuana suppliers raises the marginal cost of production through function $\gamma(e_s, e_f)$ where $\partial\gamma/\partial e_s \geq 0$, $\partial\gamma/\partial e_f \geq 0$, and $\gamma(0, 0) = 1$. Enforcement's effect on marginal costs captures producers' monetization of expected costs from product seizure, arrest, prosecution, and incarceration (Reuter and Kleiman, 1986).

MML enactment legalizes production by designated providers subject to the legal supply limit ($\overline{q}$) set by state law. Thus, for production quantities (q_i) below the state-imposed legal capacity constraint $\overline{q}$, an individual firm's marginal cost curve will be shifted due to the change in state enforcement ($e'_s < e_s$) and federal enforcement ($e'_f \geq e_f$). The magnitude by which the marginal cost curve shifts will depend on how producers weight the relative risks posed by state and federal enforcement. At supply quantities above the state-imposed capacity constraint $\overline{q}$, marginal costs increase at rate $b' > b$.[9]

The kinked marginal cost curve of supplier i who operates as a legal medical

[8]The important comparative statics hold if this assumption is relaxed and suppliers are instead assumed to operate under imperfect competition.

[9]Marginal costs for the legal supplier producing over the state's capacity constraint are thus allowed to eventually exceed the original blackmarket marginal cost curve. This could occur, for example, if state and federal governments are more easily able to monitor the production of legal producers. This assumption is not necessary for the primary results.

marijuana supplier can thus be written as:

$$MC_i(q) = \begin{cases} a_i\gamma(e'_s, e'_f) + bq, & if\ 0 \leq q \leq \overline{q} \\ a_i\gamma(e'_s, e'_f) + b'q + (b - b')\overline{q}, & if\ \overline{q} < q \end{cases} \tag{2.1}$$

Legal producer i chooses to supply quantity q_i^* by equating marginal cost to price. Price is assumed high enough such that at least one producer operates in the market.[10] Aggregating over all legal suppliers yields the aggregate supply curve, which is a combination of the number of firms and production per firm:[11]

$$\begin{aligned} S(p, \overline{q}, e'_s, e'_f) = &\int_0^{\frac{p-b\overline{q}}{\gamma(e'_s, e'_f)}} \left[\frac{p - a\gamma(e'_s, e'_f) - (b - b')\overline{q}}{b'} g(a)da\right] \\ &+ \int_{\frac{p-b\overline{q}}{\gamma(e'_s, e'_f)}}^{\frac{p}{\gamma(e'_s, e'_f)}} \left[\frac{p - a\gamma(e'_s, e'_f)}{b} g(a)da\right] \end{aligned} \tag{2.2}$$

The magnitude of the aggregate supply shift following MML enactment will depend on the costs associated with state and federal enforcement, and on the capacity constraints that the state MML enforces on legal producers. With sufficiently high federal risk remaining, the effect of MML passage on the legal market supply is likely to be small.

Effects of Changes in Federal Enforcement

By stating the government's intention to reduce federal involvement with state medical marijuana policies, the Ogden Memo lowered the risk associated with federal pros-

[10] This implicitly assumes $\frac{p-b\overline{q}}{\gamma(e'_s, e'_f)} > 0$.

[11] Entry and production decisions are not modeled separately as they are indistinguishable in the data.

ecution for both suppliers and consumers in MML states. For producers, decreased e'_f leads to a downward shift in the marginal cost curve for production quantities below $\overline{q}$.

Proposition 1: *Given the aggregate supply schedule presented in equation 2.2, the effect of a decrease in federal enforcement (from the Ogden Memo) on the supply of marijuana in states with higher $\overline{q}$ can be expressed as:*

$$-\frac{\partial S^2}{\partial \overline{q} \partial e'_f} = \frac{\partial \gamma}{\partial e'_f}\left[\left(\frac{b'-b}{bb'}\right)\left(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)}\right)g\left(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)}\right)\left(\frac{b}{\gamma(e'_s,e'_f)}\right)\right] > 0 \qquad (2.3)$$

Thus, decreases in federal enforcement will have larger effects on increasing the supply of marijuana in states with looser capacity constraints on medical marijuana suppliers. Correspondingly, increases in federal enforcement will lead to greater declines in marijuana supply in states with loose compared to strict capacity constraints.

As noted previously, federal enforcement additionally acts as an aggregate demand shifter, so the Ogden Memo may also have affected demand directly.

Assumption 1: *The effect of decreases in federal enforcement on demand in states with higher $\overline{q}$ is given by:*

$$-\frac{\partial D^2}{\partial \overline{q} \partial e'_f} = 0 \qquad (2.4)$$

This assumption will be key to my identification strategy. It is important to note that demand is not assumed to be independent of federal enforcement; rather, the key assumption for my approach is that demand does not respond *differentially* to federal risk in states with loose compared to strict production limits.

Under this assumption, the empirical methodology is based on the following proposition.

Proposition 2: *The effect of decreased federal enforcement on total market size can*

be expressed as:

$$-\frac{\partial Q^*}{\partial e'_f} = \frac{D_p S_{e'_f} - S_p D_{e'_f}}{S_p - D_p} > 0 \tag{2.5}$$

By Proposition 1 and Assumption 1, the magnitude of this effect is larger for states with lax capacity constraints.

To show that this model's propositions are consistent with empirical evidence on the legal medical marijuana market size, I next study the effects of state supply regulations and federal enforcement changes on medical marijuana patient registration rates.

2.2.3 Registration Rates as a New Measure of Market Size

Most MML states have mandatory medical marijuana registration programs: laws requiring medical marijuana users to register in order to receive protection from state arrest.[12] An individual who wants medical marijuana must first obtain a physician's certification that the individual has a medical condition which could benefit from the use of marijuana. The patient then must submit an application to the state authority, along with a registration fee. If the application is approved, the patient receives documentation providing access to dispensaries (in states where they are approved) and protection from state prosecution. By definition, all other consumption is illegal.

The number of registered medical marijuana patients provides an observable measure of the size of the legal market. A limitation faced by previous research has been that state records of registered patient counts are not readily available and are not maintained similarly across states. To overcome this limitation, I collected monthly

[12]Washington is the only state with no registration system in place, while California and Maine have voluntary patient registries. Many mandatory registration states also have "affirmative defense" laws, providing arrested unregistered patients protection from conviction upon demonstration of a medical condition that would qualify them under the state's MML. This paper does not separately distinguish these laws.

data from a number of sources, including contact with state officials, state department websites, news articles, and academic papers. Since my outcome variables are annual state-level prevalence measures, I linearly interpolate missing end-of-year registration rates using the nearest available months of registered patient counts. The final measure of market size is the annual registration rate, calculated as the percent of adults registered as medical marijuana patients at the end of December in a given year. I include the voluntary registration data available from California after 2005, but due to lack of data, Maine and Washington are excluded.[13]

From this data, the medical marijuana market in 2013 is estimated to consist of about 1,139,098 legal medical marijuana patients,[14] and industry reports estimate annual retail sales of legal marijuana in 2013 at $1.43 billion (Arcview, 2014).[15] While the legal market size is dwarfed by the estimated $25-$40 billion size of the illicit market (Kilmer et al., 2014), growth in the legal marijuana market over the past decade is twice that of the illicit market. Th estimate of the number of registered patients in 2013 represents a more than 300% increase in the number of medical marijuana users from 2007 compared to only a 150% increase in the number of total adult past-month users (SAMHSA, 1992-2013). The legal market for marijuana is thus rapidly expanding. To study how changes in the legal market affect the illegal market, it is important to first understand the factors driving legal market growth.

[13]Registered patient counts in California are measured with substantial error due to the voluntary nature of the registration program. Unofficial estimates suggest the number of registered patients represents only about 1-2% of the true number of legal users who possess a physician's recommendation (CANORML.org, 2011).

[14]From my own data collection, the number of patients in mandatory registration states in 2013 is estimated at 383,340. Estimates of the number of legal users in California, Washington, and Maine (MPP, 2014) were added to this to obtain the total number of legal users.

[15]For comparison, in 2012, the US beer market had retail sales of $246 billion.

2.2.4 Preliminary Evidence on the Legal Market

To isolate the supply-side drivers of growth in legal medical marijuana markets, the ideal policy variation would be such that production costs were exogenously shifted in some MML states but unchanged in others. Based on the model outlined in Section 2.2.2, the Ogden and Cole Memos approximated this ideal by shifting production costs differentially more in MML states with lax supply restrictions compared to those states with strict supply restrictions. Figure 2.1 connects the model's propositions to the data by documenting registration rate trend breaks at the Ogden and Cole Memos for a sub-sample of states that exemplify the different state production restrictions. Hawaii (Figure 2.1a) and New Mexico (Figure 2.1b) serve as examples of more restrictive production states; Colorado (Figures 2.1c) and Montana (Figure 2.1d) are representative of MML states with looser supply restrictions.

For all four states, few patients register during the first few years following MML passage. The initial slow growth in medical marijuana take-up suggests that, conditional on federal enforcement remaining high, reduced state risk following MML enactment had little effect on the size of the legal market. The empirical evidence from Figure 2.1 is also consistent with the model's prediction that the Ogden and Cole Memos had far greater effect in states with loose production limits. In Hawaii, where suppliers had strict limits and could only serve a single patient, the Ogden Memo had very little effect on registration rate trends. Correspondingly, there is also little break in trend following the Cole Memo. In New Mexico, which allowed state licensed dispensaries that had higher production limits but faced heavy regulation, the Ogden and Cole Memos also seem to have had small effects.

In contrast, the states with lax production limits saw dramatic changes in registration rates with the Ogden and Cole Memos.[16] After the Ogden Memo, Colorado

[16]Evidence of anticipatory behavior prior to the Ogden Memo may be in part due to a March,

experienced the "Green Rush," a proliferation of dispensaries that arose following decreased fears of federal intervention.[17] Alongside the expansion of unregulated dispensaries in Colorado, patient registration rates spiked (Figure 2.1c). Similarly, in Montana, where caregivers were permitted to produce for an unlimited number of patients and receive compensation for their services, the number of caregivers providing for 20 or more patients increased seven-fold within one year following the Ogden Memo. This was accompanied by a nearly six-fold increase in registered patients (Figure 2.1d). In line with the propositions from the model, the Cole Memo reversed this trend.[18] The decline in registration rates in Montana is particularly dramatic because, concurrent with the Cole Memo, Montana's legislature passed Senate Bill 423 which effectively dismantled the medical marijuana supply industry by establishing caregiver patient limits and preventing caregivers from receiving compensation.[19]

To examine this relationship for all states, I exploit the model's predicted trend reversal between the Ogden period and the Cole period in the relationship between a state's laxness of medical marijuana supply regulation and registration rates. Intuitively, in states with loose medical marijuana production limits, the Ogden Memo decreased marginal costs over a broader range of production (compared to strict regulation MML states and non-MML states), inducing producer entry and supply increases by existing producers. The Cole Memo reversed this trend by increasing supplier costs back to pre-Ogden levels (or higher). I thus estimate the following

2009 statement by Attorney General Eric Holder that federal agents would only target marijuana distributors who violated both federal and state law.

[17]Colorado police enforcement estimated that 900 medical marijuana retail dispensaries had become operational by mid-2010 (HIDTA, 2013).

[18]Registration rates may not have returned to pre-Ogden levels if federal resource constraints limited the number of producers federal enforcement could pursue, or if producers assumed the cost shock would be temporary.

[19]Following SB-423, the number of registered caregivers fell from 4,438 in June 2011 to 61 in July 2011.

linear trend break model:

$$RR_{jt} = \gamma_0 + \gamma_1[m - Ogden] * Loose_{jt} + \gamma_2[m - Cole] * Loose_{jt} + \gamma_3 Loose_{jt} + u_j + v_t + \mu_{jt} \quad (2.6)$$

where RR_{jt} is the share of adults registered as medical marijuana patients (registered patients per 100 adults) in state j at time t, $[m - Ogden]$ is the number of months following the Ogden Memo, $[m - Cole]$ is the number of months following the Cole Memo, and the model controls for state and year fixed effects.[20] $Loose_{jt}$ is a dummy variable that takes a value of 1 if the initial state MML had loose supply restrictions, 0 otherwise. Loose supply restriction states are defined as those with MMLs prior to the Ogden Memo that allowed caregivers to serve an unlimited number of patients, or that allowed caregivers to serve multiple patients and did not permit state-licensed dispensaries (see Table 2.1 for the list of states).

Table 2.2 shows the effects of the Ogden and Cole Memos on registration rates, restricting the analysis to end-of-year counts from 2002-2012 for consistency with later estimation in section 2.5. Column (1) compares the effects of federal enforcement changes in states with lax production to all other states. The estimates suggest that between the Ogden and Cole Memos, MML states with loose production limits on average saw an additional 2% of the adult population register as medical marijuana patients relative to other states. On the other hand, following the Cole Memo, states with loose production limits saw relative reductions in registration rates, declining on average by 0.04% monthly.[21]

[20] Controls for $[m - Ogden]$ and $[m - Cole]$ are subsumed by year fixed effects.

[21] The point estimate from column (1) shows a monthly effect of 0.095, and 21 months between the Ogden and Cole Memos predicts a total increase in registration rates of 0.095*21=2.0. The change in trend relative to the Ogden Memo period is -0.117, leading to an overall monthly trend following the Cole Memo of 0.095-0.137=-0.042.

Column (2) reports regression results that allow federal enforcement changes to also affect MML states with strict restrictions on supply. Consistent with the model predictions, both federal policies had far larger effects on registration rate trends in states where marijuana suppliers were relatively unrestricted. Between the Ogden and Cole Memos, states with strict production limits on average saw an additional 0.2% of the adult population register as medical marijuana patients (0.012*21=.252%), which is statistically significant but an order of magnitude smaller than the increases seen in MML states with loose supply regulations (0.097*21=2.04%). There is no effect of the Cole Memo in strictly regulated MML states, consistent with evidence that federal enforcement related to the Cole Memo targeted large-scale production. Limiting the sample to only those states with MMLs by 2012 in columns (3) and (4) yields coefficients of similar magnitude but with slightly larger standard errors.

Unlike initial MML enactment, the federal memos substantially altered the size of the legal market, with larger effects in states with looser supply regulations. The differential response of registration rates to the federal government's policies in states with lax compared to strict producer restrictions suggests that patient registration rates are driven primarily by supply-side shifters. Therefore, to estimate the causal effect of changes in medical marijuana supply on recreational consumption, my empirical strategy uses the timing of the federal memos and differences in initial MML supply restrictions as instruments.

2.3 Empirical Strategy

The empirical framework uses a differences-in-differences methodology with a continuous policy variable. Specifically, the following model is estimated separately by age group:

$$Y_{jt} = \alpha + \beta RR_{jt} + \gamma X_{jt} + u_j + v_t + \varepsilon_{jt} \tag{2.7}$$

where Y_{jt} represents the prevalence of marijuana consumption in state j in year t, and RR_{jt} is the per capita registration rate (i.e., the number of registered medical marijuana patients as a percent of the adult population) at the end of year t in state j. Using adult registration rates as the independent variable, β identifies the percentage point change in the outcome of interest due to a one percentage point increase in registration rates, controlling for state-level time-varying covariates X_{jt} as well as state and year fixed effects (u_j and v_t).

The main threat to identification is that registration rates and illegal use may be jointly determined by unobservables affecting demand. State and year fixed effects control for time-invariant state characteristics and national trends. Time-varying state covariates included that potentially affect recreational marijuana use can be categorized as: (1) demographics influencing recreational marijuana use, (2) economic characteristics, and (3) substance-related policies influencing marijuana consumption. A full listing of covariates is provided in Table 2.3. For all specifications, to account for heteroskedasticity and serial correlation, robust standard errors are clustered at the state level (Bertrand et al., 2004). To account for potential violation of the parallel trends assumption, specifications including state-specific linear trends are also presented as robustness checks in section 2.6.

Even after controlling for state and year fixed effects and state-year covariates, identification of β is challenging due to concerns of endogeneity between recreational marijuana use and registration rates. While fixed effects will account for issues of cross sectional endogeneity, β could still be biased due to some omitted state-level time-varying variable that affects both registered users and illicit users. For instance, β will be biased upward if changes in local perceptions regarding the health risks of marijuana use led to changes in both medical and recreational use. To account for potential endogeneity, I instrument for registration rates by way of two-stage-least-squares using equation 2.6 as the first-stage specification.

The instrumental variable estimates are valid as long as the exclusion restriction is satisfied. In the context of equations 2.6 and 2.7, this occurs if $E[\varepsilon_{jt} Z_{jt} | u_j, v_t, X_{jt}] = 0$, where Z_{jt} is the vector of instruments including the interaction of MML supply restrictions with trend breaks based on the exogenous timing of the Ogden and Cole Memos. As state and year fixed effects are included, the identification is not threatened by level differences between states or by national trends in marijuana consumption (e.g., state geographic proximity to marijuana exporting countries, or national trends in support for marijuana legalization). However, the exclusion restriction will be violated if changes in federal enforcement following the Ogden and Cole Memos had differential effects on demand in states with loose compared to strict production restrictions through any channel other than supply. Evidence validating the exclusion restriction is presented in section 2.6.

2.4 Data

The measures of marijuana consumption come from the National Survey of Drug Use and Health (NSDUH). The NSDUH is an annual survey funded by the Substance Abuse and Mental Health Services Administration (SAMHSA) of the US population over twelve years of age. The public-use NSDUH provides estimates of the prevalence of past-month use and past-year initiation of marijuana, available separately for age groups of 12-17, 18-25, and 26 years of age and older. Representative state-level data broken down by two-year averages is available from (2002-2003)-(2012-2013).

Table 2.3 provides summary statistics for the marijuana use measures and state-level covariates used in the NSDUH analysis. Comparing mean differences, MML states with a positive number of registered medical marijuana patients have higher levels of past-month cannabis users for all age groups than states without MMLs. However, MML states on average are more likely to have decriminalized marijuana,

have higher cigarette taxes, and consist of populations that are on average younger and more male. As such characteristics are potentially correlated with prevalence of recreational cannabis use, all regressions control for the state covariates listed in Table 2.3.

There are some limitations to this dataset. Firstly, the public-use NSDUH data is only available in two-year averages; thus the registration rate data may not correspond exactly with the marijuana outcome data, leading to a loss of precision for these estimates.[22] Secondly, the NSDUH measures of substance use are self-reported. If individuals are more likely to report marijuana consumption truthfully based on legality, analysis of the effects of legal market size compared to MML enactment should be less subject to reporting bias. However, if reporting is driven by perceived changes in social approval, growth in the legal market size may induce changes in reporting behavior. Section 2.6 and Appendix D- provide supporting evidence that the self-reported marijuana use measure captures true changes in consumption.

Despite these problems, the NSDUH is the only publicly available dataset that provides representative state-level estimates of marijuana consumption for all individuals aged 12 and older. Additionally, the NSDUH Restricted-use Data Analysis System (R-DAS) provides state-level estimates for perceptions about marijuana, which are used in section 2.6 to examine the mechanisms by which changes in the legal market affect adolescent marijuana use.[23]

[22]For this paper, primary analysis is done using the first year of the two-year average as the base year. Appendix D- provides robustness checks of this approach.

[23]The Monitoring the Future (MTF) survey has estimates of marijuana use and perceptions for a larger sample of 8th, 10th, and 12th graders, but state identifiers are not provided in the public-use MTF dataset.

2.5 Results

Figure 2.2 presents descriptive evidence of changes in marijuana consumption over time. Trends in past-month use and past-year initiation are plotted by age groups and by strictness of state MML supply regulation. All trends are normalized such that the prevalence measure is zero for 2007-2008, the years just prior to the Ogden Memo. For all age groups, marijuana consumption increases in MML states after the Ogden Memo. For youths and young adults, these increases are largest in MML states with loose supply regulations, while loose and strict MML states saw similar growth rates for older adults. For adolescents aged 12-17, there is a sharp drop in consumption in MML states with loose regulations following the Cole Memo; for adults, consumption does not decrease after the Cole Memo but trends in use flatten.

To examine whether these patterns in marijuana consumption are driven by growth in medical marijuana availability, Table 2.4 reports the first-stage and reduced-form estimates of the differential effects of the Ogden and Cole Memos in MML states with lax supply restrictions on registration rates and the prevalence of marijuana consumption. The first-stage results of Table 2.4 are replicated from Column (1) of Table 2.2 (including the time-varying state covariates from Table 2.3) and are discussed in section 2.2.4. The F-test for excluded instruments takes a value of 52.3, mitigating any concerns of finite sample bias due to weak instruments (Staiger and Stock, 1997). The reduced form results for past-month use and past-year initiation by age group have the expected signs, though the instruments have less predictive power for past-year marijuana initiation. Since this approach identifies effects off of changes in a monthly time series, ex-ante the results for past-month use are expected to perform better than the results for past-year initiation.

Table 2.5 reports the estimated effects of growth in the legal medical marijuana market on marijuana consumption, showing results separately by age group for preva-

lence of past-month marijuana use and past-year initiation. To test whether these effects are driven by omitted variables influencing both legal and illegal use, the second-stage results of the instrumental variables analysis are compared to the OLS estimates. The results indicate that growth in medical marijuana registration rates significantly increases marijuana consumption for all age groups, with the largest effects for older adults. An additional one percentage point of the adult population registering as medical marijuana patients predicts a significant 6% increase in the share of 12-17 year olds reporting past-month marijuana use, a 7-8% increase for 18-25 year olds, and a 20% increase for older adults. The effects on past-year initiation are similar but smaller in magnitude, indicating a 1-5% increase in the share of 12-17 year-olds reporting past-year initiation, a 6% increase for 18-25 year olds, and a 12-18% increase for adults over age 25.

Additionally, these estimates support that using registration rates as an exogenous measure of the size of the legal marijuana market does not produce biased estimates. The IV estimates are neither qualitatively nor statistically different than those from OLS, suggesting that changes in registration rates and recreational use are not being driven by some unobserved factor correlated with both recreational and medical demand. This conclusion will hold if the instruments are indeed excludable, supporting evidence of which is presented next.

2.6 Robustness Checks

2.6.1 Does the Exclusion Restriction Hold?

The main threat to the validity of the instrumental variables approach is a violation of the exclusion restriction. The exclusion restriction will be violated if changes in federal enforcement due to the Ogden and Cole Memos had differential effects on demand in states with lax compared to strict production restrictions through any

channel other than supply.

For example, the exclusion restriction would be violated if, when federal enforcement was removed and registration rates increased, local governments in strictly regulated states devoted more resources toward prosecuting users than state governments in states with loose regulations. I provide evidence that this did not occur in Figure 2.3, which plots changes in *per user* state marijuana possession arrest rates against changes in registration rates. Results are shown separately for juveniles and adults. There is no apparent correlation between legal market growth and state enforcement for either strict or loose regulatory regimes.

Another potential violation of the exclusion restriction would occur if, prior to the Ogden Memo, the expected user risks of federal prosecution were higher in states with loose compared to strict supply regulations. To address this, I first show that the actual risk of a marijuana user facing federal enforcement is very low. The federal government has never devoted substantial resources toward prosecuting individuals for simple marijuana possession. Figure 2.4 shows from fiscal year 1996 through 2012, less than 4% of federal prosecutions for marijuana-related offenses have been for simple possession.[24] Between 1996 and 2012, the annual average of federal prosecutions for marijuana possession was 224 compared to 6,259 for sales. Focusing on enforcement against medical marijuana specifically, reports suggest there were fewer than 20 federal prosecutions of medical marijuana users or growers from 1996-2005 (Murphy, 2005) and about the same number from 2005-2009; this enforcement was almost exclusively directed toward large-scale producers in California.

While the actual probability of federal prosecution was low, uncertainty among potential medical marijuana users about whether the federal government could access registry data may still have stifled demand. This deterrent was likely far greater in

[24]This represents less than 0.1% of all federal prosecutions for drug-related offenses.

California than in other states, as federal prosecution against suppliers was concentrated in California. Vickovic (2011)'s analysis of news article mentions of medical marijuana showed that almost all articles about federal enforcement prior to the Ogden Memo were about dispensary raids in California, and the majority of these articles were published by local sources. Thus, it may be the case that the Ogden Memo led to a relatively larger shift in demand in California (which had loose supply restrictions) compared to other MML states.[25]

To address these concerns, Table 2.6 reports the results of the instrumental variable specification excluding California. The results for past-month use are unchanged, but the effect of legal market growth on past-year initiation for adolescents becomes small and insignificant and shows evidence of endogeneity. These results are consistent with past-month use serving as a better measure to detect short-run changes in marijuana access, while past-year initiation may better reflect longer-run changes in social approval or risk perceptions.

2.6.2 How do the Effects of Legal Market Size Compare to the Effects of Law Passage?

The relationship between marijuana use and registration rates may not be proportional. There may be a spike in demand from MML enactment due to perceived governmental acceptance of the substance followed by a linear effect of registration rates reflecting changes in availability. To assess this relationship, Table 2.7 compares the effects of medical marijuana market growth on past-month marijuana use to the effects of MML enactment.[26]

[25]Additionally, the fact that California has voluntary registration and very lax regulations regarding patient qualifications may have led to a greater shift in demand when federal enforcement fell.

[26]Estimates for past-year initiation are similar and available on request.

In the regressions without state-specific trends, both registration rates and the categorical variable for MML enactment have positive effects on marijuana consumption, though the effects of the categorical MML variable are only significant for adults over age 25. However, after including state-specific linear trends to account for state differences in preexisting paths of marijuana use, the estimates for MML passage become small and insignificant and (for adolescents) switch sign. In contrast, estimates of the effects of registration rates remain positive and significant for all age groups.

The registration rate estimates are less sensitive to trend inclusion than those of the categorical variable. This could be due to the non-monotonicity of trends in registered patient counts or the categorical MML measure confounding preexisting trends with the dynamic effects of the policy (Wolfers, 2006). Additional robustness checks of sample selection and model specification in Appendix D- support that the binary MML measure misses heterogeneous effects across states and the dynamics of these policies.

2.6.3 Why Does Growth in Medical Marijuana Markets for Adults Increase Adolescent Use?

There are a number of mechanisms through which MML policy, promoted as legislation to protect cannabis use for a relatively small number of individuals with chronic health conditions, might affect marijuana consumption by adolescents. If registered adult users are more visible to adolescents, youths may increase consumption due to lower perceived risks associated with social disapproval, formal sanctions, or health consequences. If growth in the legal market increases total availability, increased adolescent use may be driven by lower search costs, increased product variety, or declines in the quality-adjusted price of marijuana following the shift in supply (Alford, 2013; Anderson et al., 2013).

Sections 2.2 and 2.5 suggest that supply channels are particularly important in

determining MMLs' effects on adolescent use. Spillover of medical marijuana supply to the illegal market serving adolescents could occur through resale or sharing of medical marijuana by legal users.[27] Recent national surveys of high-school seniors show that almost 18% of past-year users report receiving some marijuana from another's medical marijuana "prescription" (Boyd et al., 2015); focusing only on high-school seniors in states with MMLs, 34% of past-year users report one of their sources as another person's medical marijuana "prescription" (Wadley and Barnes, 2013). This indicates substantial diversion from the legal market supplying medical marijuana patients to the illegal market supplying youths.

Table 2.8 provides evidence of the mechanisms by which growth in the legal market influences cannabis consumption by youths aged 12-17 using state-level data from the NSDUH R-DAS. Columns (1)-(3) report effects on risk perceptions, and columns (4)-(6) report effects on measures of adolescent access. The outcome variable for each column is the share of youths aged 12-17 who report that: (1) using marijuana monthly poses a "great risk," (2) their friends "somewhat" or "strongly" disapprove of monthly marijuana use, (3) the maximum penalty for possession of one ounce of marijuana in their state is prison time, (4) marijuana is "somewhat" or "very" easy to obtain, (5) most students their age use marijuana, and (6) they purchased marijuana in the past year. Since these measures are likely determined endogenously, these results are intended only to provide suggestive evidence.

While growth in the legal market affects adolescent perceptions of both risk and availability, the results of Table 2.8 suggest that the legal market primarily affects adolescent use through changing access. A one percentage-point rise in registration rates significantly increases the share of 12-17 year-olds who believe marijuana is easy to obtain (3%), who believe most students their age use marijuana (5%), and who

[27]Salomonsen-Sautel, Sakai, et al. (2012) surveyed adolescents in substance abuse treatment in Denver, CO and found 74% report using diverted medical marijuana.

report buying marijuana in the past year (7%); these estimates are jointly significant with a p-value of 0.04. In contrast, estimates of the effects on risk perceptions are smaller and jointly insignificant with a p-value of 0.13. These results thus provide supporting evidence that the increases in adolescent marijuana use following medical marijuana market growth are due to supply spillovers rather than decreased risks of legal penalties or social disapproval.

2.7 Conclusion

I use newly collected data and a novel identification strategy to study whether regulated markets for medical marijuana have spillover effects to recreational users. My estimates suggest, if a non-MML state were to reach the median per capita medical marijuana registration rate of 0.972% (as measured in 2014), the average rate of past-month marijuana use among 12-17 year olds would rise from 7.2% to 7.7% percent, an increase of about 6%. The prevalence of past-month marijuana use among young adults aged 18-25 would rise from 17.3% to 18.9% (a 9% increase), and the prevalence of use among adults over age 25 would rise from 4.4% to 5.2% (an increase of 18%).

My results confirm the findings of prior research that MML enactment alone does not significantly increase marijuana consumption among youths. However, as medical marijuana markets expand, there are significant spillovers to adolescent use. Due to data limitations, this paper can only estimate the effects of legal market growth on the extensive margin of past-month marijuana use. Future work should investigate whether these effects reflect only increased experimentation among youths, or whether there are significant effects on daily or near daily (DND) marijuana use and dependence. Assessing the impact on the intensive margin of marijuana use among adolescents will provide a better understanding of the likely health consequences of spillovers to youth consumption.

Additionally, the mechanisms by which these spillovers occur will have important policy implications. This paper presents suggestive evidence that growth in medical marijuana markets significantly increases youth marijuana consumption by increasing availability. Further work is needed to examine whether this increased access is driven by imperfect monitoring of legal producers, growth in secondary markets whereby legal users sell (or share) medical marijuana to illegal users, or changes in the black-market for marijuana driven by increased competition from legal suppliers. Better understanding these mechanisms will inform optimal policy design for legal marijuana markets, but will also have applications to markets for other products with limited legal access such as tobacco, alcohol, and prescription opioids.

Table 2.1: MML Legislation Policies by State, 1996-2012

State	Effective Date Law/Amend	Home Cultivation	Max Patients Caregiver Can Grow For	Dispensaries or Collectives State-licensed	Dispensaries or Collectives Operational
Loose Regulations (MML Passed Pre-Ogden)					
CA	11/6/1996 1/1/2004	Y	NS	N Y	2003
CO	6/1/2001 6/7/2010	Y	NS	N Y	2005
MT	11/2/2004 7/1/2011	Y	NS 3	N	2009
MI	12/4/2008	Y	5	N	12/2009
OR	12/3/1998 8/14/2013	Y	4	N Y	11/2009
WA	11/3/1998	Y	1†	N	7/2010
Strict Regulations (MML Passed Pre-Ogden)					
ME	12/22/1999 4/2/2009 11/3/2009	Y	5	N Y	 3/2011
RI	1/3/2006 6/16/2009	Y	5	N Y	 4/2013
NM	7/1/2007	Y	4	Y	7/2009
AK	3/4/1999	Y	1	N	
HI	12/28/2000	Y	1	N	
NV	10/1/2001 6/12/2013	Y	1	N Y	 8/2015
VT	7/1/2004 6/2/2011	Y	1	N Y	 6/2013
Strict Regulations (MML Passed Post-Ogden)					
DC	7/27/2010	N	0	Y	5/2013
NJ	10/1/2010	N	0	Y	12/2012
AZ	4/14/2011	N*	0	Y	12/2012
DE	7/1/2011	N	0	Y	6/2015

Notes and sources: Own data collection. NS=not specified. *Allows home cultivation if resident is more than 25 miles from nearest dispensary. †WA specifies that caregivers can grow for one patient "at any given time," many caregivers interpreted as not specifying an absolute maximum number of patients.

Table 2.2: Effects of Federal Enforcement on Registration Rates, by State Supply Regulations

	All States		**MML States**	
	(1)	(2)	(3)	(4)
$[m - Ogden] * LooseReg$	0.095***	0.097***	0.088**	0.106**
	(0.034)	(0.034)	(0.036)	(0.043)
$[m - Cole] * LooseReg$	-0.137**	-0.137**	-0.137*	-0.135*
	(0.065)	(0.065)	(0.069)	(0.067)
$LooseReg$	0.097	0.094	0.046	0.036
	(0.248)	(0.249)	(0.283)	(0.288)
$[m - Ogden] * StrictReg$		0.012***		0.022*
		(0.004)		(0.011)
$[m - Cole] * StrictReg$		-0.008		-0.005
		(0.006)		(0.005)
$StrictReg$		-0.059		-0.064
		(0.022)		(0.094)
F-test	46.5***	30.0***	16.7***	13.0***
Registration Rate Mean (SD)	0.049 (0.272)		0.201 (0.524)	
Mean (SD) | Rate>0	0.235 (0.560)		0.246 (0.570)	

Notes and sources: N=539 (49 states, 11 years) for columns (1) and (2). N=154 (14 states, 11 years) for columns (3) and (4). Data on registration rates from author's own collection. Unweighted regressions include state and year fixed-effects. State and year fixed effects are included, and robust standard errors (in parentheses) are clustered at the state level. See Table 2.1 for definitions of *LooseReg* and *StrictReg* states. ***p<0.01, **p<0.05, *p<0.1.

Table 2.3: Summary Statistics for MML and non-MML States

	All	Registration Rate=0	Registration Rate> 0	Mean Difference [Standard Error]
Legal Market Size				
Registration Rate	0.049	0.000	0.235	0.235***
	(0.272)	(0.000)	(0.560)	[0.053]
Registered Patients	2,738	0	13,095	13,095***
	(13,232)	(0)	(26,580)	[2,500]
Marijuana Consumption				
Past-month marijuana use, age 12-17	7.21	6.95	8.19	1.25***
	(1.24)	(1.13)	(1.16)	[0.122]
Past-year marijuana initiation, age 12-17	5.88	5.72	6.48	0.761***
	(0.84)	(0.76)	(0.86)	[0.089]
Past-month marijuana use, age 18-25	17.32	16.69	19.63	2.94***
	(3.48)	(3.28)	(3.23)	[0.343]
Past-year marijuana initiation, age 18-25	6.89	6.71	7.56	0.852***
	(1.26)	(1.17)	(1.37)	[0.140]
Past-month marijuana use, age 26+	4.38	4.01	5.81	1.80***
	(1.20)	(0.83)	(1.34)	[0.132]
Past-year marijuana initiation, age 26+	0.16	0.15	0.19	0.039***
	(0.05)	(0.04)	(0.06)	[0.006]
State Covariates				
% Under 30	0.412	0.408	0.421	0.012***
	(0.03)	(0.03)	(0.02)	[0.002]
% Male	0.491	0.489	0.497	0.007***
	(0.01)	(0.01)	(0.01)	[0.001]
Ln(Population)	16.06	15.95	16.50	0.549***
	(0.90)	(0.76)	(1.22)	[0.121]
Unemployment rate	6.71	6.36	8.03	1.66***
	(2.24)	(1.95)	(2.73)	[0.274]
Ln(Real state per capita income)	10.35	10.34	10.40	0.062***
	(0.13)	(0.14)	(0.10)	[0.012]
Decriminalization law	0.34	0.23	0.79	0.565***
	(0.48)	(0.42)	(0.41)	[0.043]
BAC 0.08 law	0.94	0.93	0.98	0.048***
	(0.22)	(0.24)	(0.14)	[0.017]
Ln(Real beer tax)	-1.80	-1.80	-1.90	-0.135**
	(0.68)	(0.72)	(0.48)	[0.057]
Ln(Real cigarette tax)	-0.40	-0.46	-0.15	0.306***
	(0.84)	(0.91)	(0.43)	[0.060]
Observations	539	426	113	

Notes and sources: WA and ME are excluded because they do not have mandatory registration programs nor sufficient data on voluntary registration programs. Data on substance use comes from NSDUH ((2002-2003)-(2012-2013)). State-level covariates are from BLS and Census State Statistical Abstracts. Decriminalization data is from Alford (2013) and MPP.org. Beer tax data is from Brewer's Almanac and BAC laws are from the NIAAA Alcohol Policy Information System (APIS) and National Highway Traffic Safety Administration (NHTSA). Cigarette excise tax data is from Impacteen.org and TaxFoundation.org. Means are weighted by state-year population, and standard deviations are given in parentheses. Standard errors from t-test of difference in means with unequal variance in square brackets. ***p<0.01, **p<0.05, *p<0.1.

Table 2.4: Federal Memos and Regulatory Structure as Instruments,
First Stage and Reduced Form Regression Results

	First Stage	**Past-Month Use**			**Past-Year Initiation**		
	RegRate	12-17	18-25	26+	12-17	18-25	26+
$[m - Ogden] * LooseReg$	0.095***	0.044***	0.156***	0.072***	0.032	0.058***	0.001
	(0.033)	(0.016)	(0.024)	(0.021)	(0.031)	(0.021)	(0.001)
$[m - Cole] * LooseReg$	-0.139**	-0.064	-0.214***	-0.063*	-0.082	-0.117**	0.001
	(0.064)	(0.041)	(0.068)	(0.032)	(0.073)	(0.053)	(0.003)
$LooseReg$	0.123	-0.203	-0.090	-0.059	-0.371	-0.134	-0.008
	(0.228)	(0.190)	(0.940)	(0.252)	(0.228)	(0.253)	(0.013)
F-test	53.2***	2.86**	16.3***	6.66***	0.973	5.16***	4.68***

Notes and sources: N=539 (49 states, 11 years). Regressions include state and year fixed-effects and state-level covariates (listed in Table 2.3). Robust standard errors (in parentheses) are clustered at the state level. ***p<0.01, **p<0.05, *p<0.1.

Table 2.5: Effects of Growth in Legal Market on Marijuana Consumption

	(1)		(2)		(3)	
	Ages 12-17		**Ages 18-25**		**Ages 26+**	
	IV	OLS	IV	OLS	IV	OLS
Panel A: Past-Month Use						
Registration Rate	0.428*	0.442***	1.65***	1.21***	0.937***	0.865***
	(0.223)	(0.163)	(0.405)	(0.232)	(0.283)	(0.207)
	[5.9]	[6.1]	[9.5]	[7.0]	[21.2]	[19.6]
Mean Outcome	7.2		17.3		4.4	
Hansen J p-value	0.35		0.89		0.28	
Endogeneity p-value	0.90		0.21		0.86	
Panel B: Past-Year Initiation						
Registration Rate	0.103	0.319***	0.420**	0.432***	0.022**	0.029***
	(0.165)	(0.109)	(0.202)	(0.131)	(0.011)	(0.008)
	[1.7]	[5.3]	[6.1]	[6.2]	[13.8]	[12.8]
Mean Outcome	5.9		6.9		0.16	
Hansen J p-value	0.48		0.19		0.24	
Endogeneity p-value	0.26		0.63		0.42	

Notes and sources: N=539 (49 states, 11 years). ME and WA are excluded due to lack of registration data. Regressions include state and year fixed effects, and the time-varying state covariates listed in Table 2.3. For all regressions, robust standard errors (in parentheses) are clustered at the state level and percent change in the dependent variable given a unit change in the independent variable are in square brackets. ***p<0.01, **p<0.05, *p<0.1.

Table 2.6: Second-Stage IV Estimates, Excluding California

	Ages 12-17		**Ages 18-25**		**Ages 26+**	
	IV	OLS	IV	OLS	IV	OLS
Panel A: Past-Month Use						
Registration Rate	0.341*	0.454***	1.34***	1.26***	0.871***	0.872***
	(0.159)	(0.101)	(0.212)	(0.237)	(0.261)	(0.209)
Hansen J p-value	0.49		0.99		0.27	
Endogeneity p-value	0.30		0.26		0.52	
Panel B: Past-Year Initiation						
Registration Rate	0.051	0.328***	0.285**	0.450***	0.017***	0.029***
	(0.158)	(0.107)	(0.125)	(0.126)	(0.006)	(0.008)
Hansen J p-value	0.66		0.29		0.28	
Endogeneity p-value	0.06*		0.95		0.02**	

Notes and sources: N=528 (48 states, 11 years). Regressions include state and year fixed-effects and the state-level covariates listed in Table 2.3. Robust standard errors (in parentheses) are clustered at the state level. ***p<0.01, **p<0.05, *p<0.1.

Table 2.7: Effects of Legal Market Size and MML Passage on Past-Month Use

	Ages 12-17		**Ages 18-25**		**Ages 26+**	
	(1)		(2)		(3)	
Registration Rate	0.402**	0.385***	1.148***	0.607***	0.789***	0.464***
	(0.171)	(0.127)	(0.279)	(0.196)	(0.212)	(0.142)
	[5.6]	[5.3]	[6.6]	[3.5]	[17.8]	[10.5]
MML=1	0.340	-0.010	0.538	0.850	0.636***	0.077
	(0.232)	(0.389)	(0.565)	(0.556)	(0.172)	(0.136)
	[4.7]	[-0.0]	[3.1]	[4.9]	[14.4]	[1.6]
Mean outcome	7.2	7.2	17.3	17.3	4.4	4.4
State-specific trends	N	Y	N	Y	N	Y

Notes and sources: N=539 (49 states, 11 years). See Table 2.3. The categorical independent variable for MML=1 takes a value of the fraction of the year in which an MML was effective. ME and WA are excluded due to lack of registration data. ***p<0.01, **p<0.05, *p<0.1.

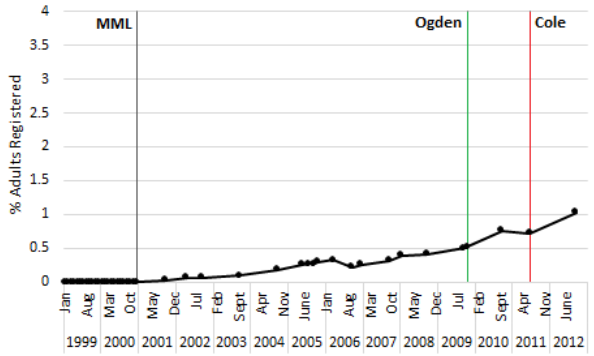
Table 2.8: Effects of Medical Marijuana Market Growth on Adolescent Perceptions of Risk and Access

	Adolescent Risk Perceptions			**Adolescent Access**		
	(1)	(2)	(3)	(4)	(5)	(6)
	Great Risk Monthly Use	Friends Disapprove	Max Penalty Is Prison	Easy to Obtain	Most Students Use	Bought in Past Year
Registration Rate	-0.795**	-0.525	-0.419	1.34***	1.25**	0.415**
	(0.333)	(0.409)	(0.386)	(0.292)	(0.595)	(0.344)
	[-2.5]	[-0.8]	[-1.2]	[2.7]	[4.9]	[5.8]
P-value for joint significance		0.13			0.04**	
Mean outcome	31.6	67.8	33.8	50.2	25.4	7.1

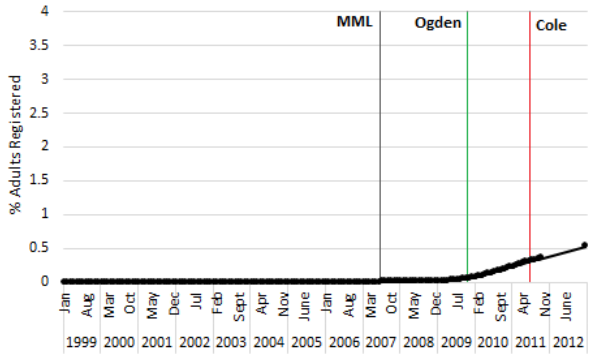
Notes and sources: N=294 (49 states, 6 years). All specifications include state and year fixed effects and time-varying state covariates. The dependent variable is the prevalence measure for 12-17 year olds from the NSDUH R-DAS. ***p<0.01, **p<0.05, *p<0.1.

Figure 2.1: Medical Marijuana Patient Registration Rate Response to Federal Enforcement, States with Strict vs. Lax Regulation of Supply

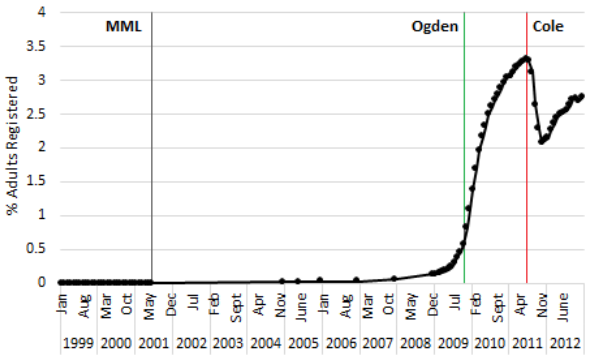
(a) Hawaii (Strict Restrictions)



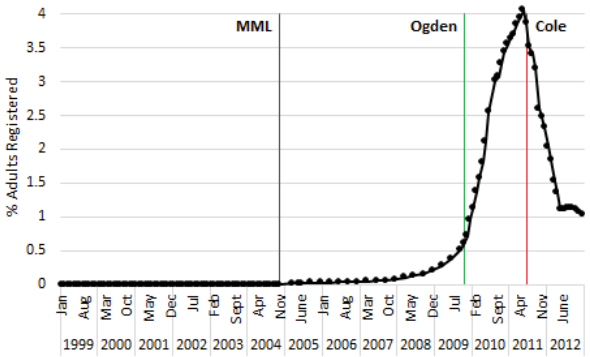
(b) New Mexico (Strict Restrictions)



(c) Colorado (Lax Restrictions)



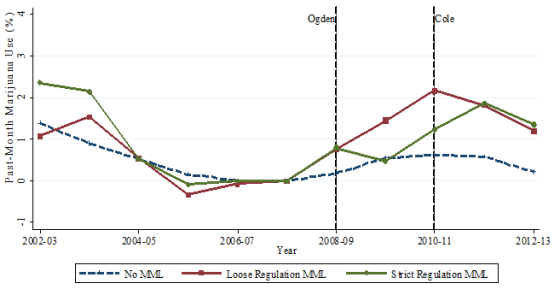
(d) Montana (Lax Restrictions)



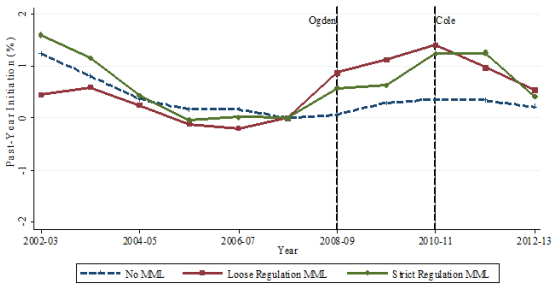
Notes and sources: Data collected by the author. MML line marks effective date of the law for each state. Ogden line marks the date of the Ogden Memo reducing federal enforcement (Oct, 2009) and Cole line marks the date of the Cole Memo reinstating enforcement (June, 2011).

Figure 2.2: Trends in Marijuana Consumption,
By State Supply Regulations

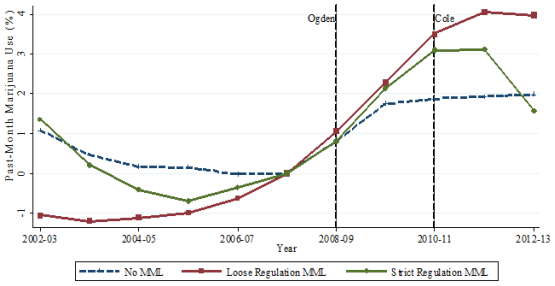
(a) Past-Month Use (Age 12-17)



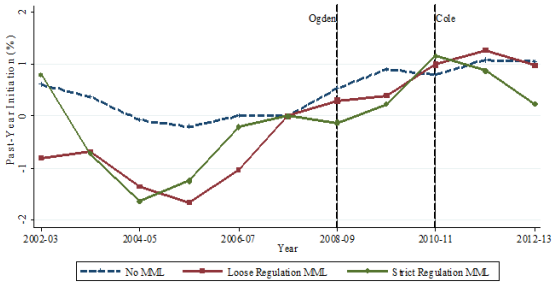
(b) Past-Year Initiation (Age 12-17)



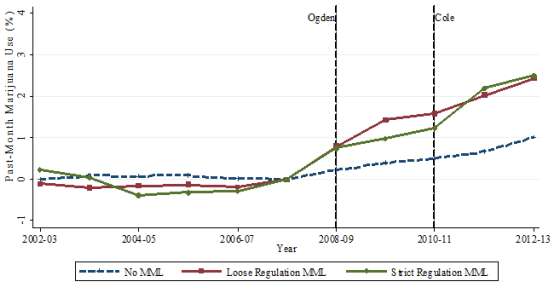
(c) Past-Month Use (Age 18-25)



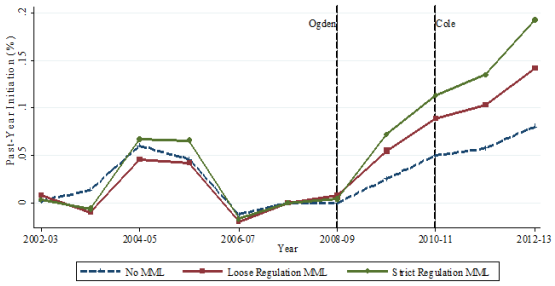
(d) Past-Year Initiation (Age 18-25)



(e) Past-Month Use (Age 26+)



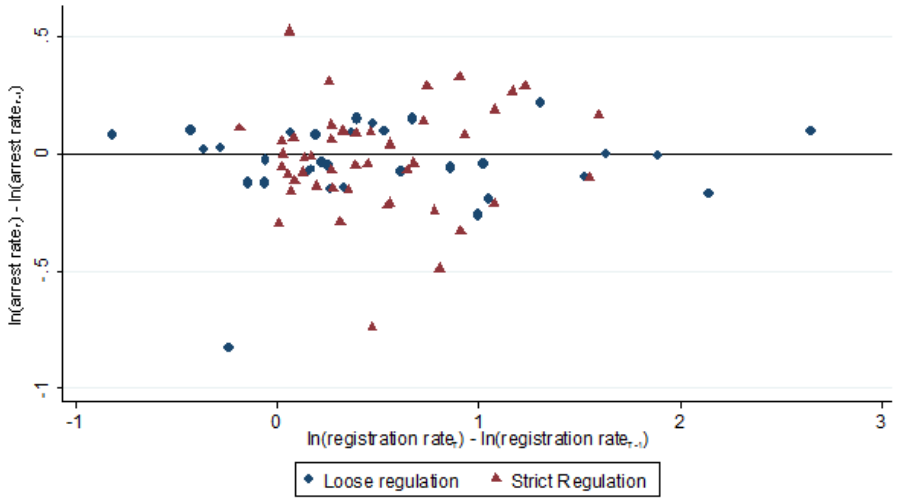
(f) Past-Year Initiation (Age 26+)



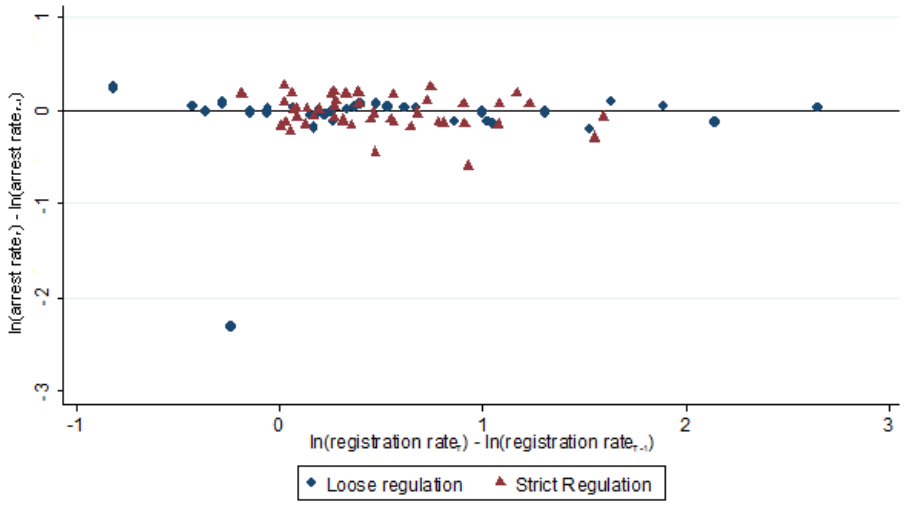
Notes and sources: Data from the National Survey of Drug and Use and Health, which provides prevalence measures in two-year averages from (2002-2003)-(2012-2013). Outcomes are normalized to zero for (2007-2008). Dashed lines mark the timing of the Ogden and Cole Memos. Definitions of the states categorized as "Loose Regulation MML" and "Strict Regulation MML" are in Table 2.1. Note that the scales are comparable for past-month use. For past-year initiation, scales for 12-17 year-olds and 18-25 year-olds are equivalent, but the y-axis scale is different for adults aged 26+ since rates of initiation are very low for this age group.

Figure 2.3: Ruling Out Differential Changes in State Enforcement

(a) Juveniles

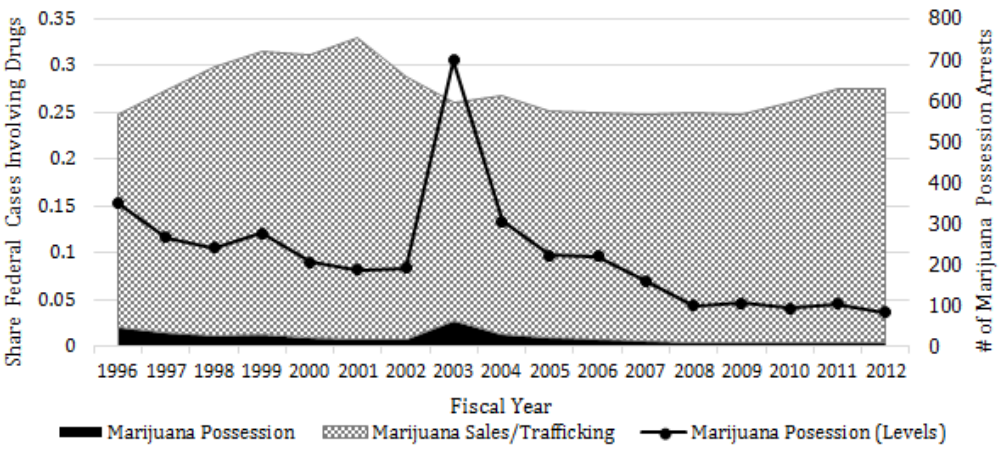


(b) Adults



Notes and sources: Arrest data from the Uniform Crime Reports (2005-2012). Graphs plot arrests per user (users calculated from the NSDUH data). The outlying observation in Figure 3.B is for California in 2011, and is explained by California's full decriminalization of marijuana possession with Senate Bill 1449 (reducing possession of up to an ounce of marijuana from a misdemeanor to an infraction), which went into effect January 1, 2011.

Figure 2.4: Low Risk of Federal Prosecution for Marijuana Possession



Notes and sources: Data from the *Sourcebook of Federal Sentencing Statistics*, Fiscal Years (1996-2012), U.S. Sentencing Commissions, FY1996-FY2012. Shaded plots (left axis) show the share of federal drug-related prosecutions that are for marijuana sales and trafficking and for simple marijuana possession. The connected line (right axis) plots the number of federal prosecutions for simple marijuana posession.

2.8 Appendices

C- Theoretical Model Proofs

Proof of Proposition 1:

Marginal costs from Equation 2.1 are expressed as:

$$MC_i(q) = \begin{cases} a_i\gamma(e'_s, e'_f) + bq, & if\ 0 \leq q \leq \overline{q} \\ a_i\gamma(e'_s, e'_f) + b'q + (b - b')\overline{q}, & if\ \overline{q} < q \end{cases}$$

Equating marginal cost to price, producer i chooses optimal production quantity:

$$q_i^* = \begin{cases} \frac{p - a_i\gamma(e'_s, e'_f)}{b}, & if\ \frac{p - b\overline{q}}{\gamma(e'_s, e'_f)} \leq a_i \leq \frac{p}{\gamma(e'_s, e'_f)} \\ \frac{p - a_i\gamma(e'_s, e'_f) - (b - b')\overline{q}}{b'}, & if\ a_i < \frac{p - b\overline{q}}{\gamma(e'_s, e'_f)} \end{cases}$$

Aggregating over the distribution function for a yields aggregate supply:

$$\begin{aligned} S(p, \overline{q}, e'_s, e'_f) &= \int_0^{\frac{p - b\overline{q}}{\gamma(e'_s, e'_f)}} \left[\frac{p - a\gamma(e'_s, e'_f) - (b - b')\overline{q}}{b'} g(a)da \right] \\ &\quad + \int_{\frac{p - b\overline{q}}{\gamma(e'_s, e'_f)}}^{\frac{p}{\gamma(e'_s, e'_f)}} \left[\frac{p - a\gamma(e'_s, e'_f)}{b} g(a)da \right] \\ &= \int_0^{\frac{p - b\overline{q}}{\gamma(e'_s, e'_f)}} \left[\frac{p - (b - b')\overline{q}}{b'} g(a)da \right] \int_0^{\frac{p - b\overline{q}}{\gamma(e'_s, e'_f)}} \left[\frac{a\gamma(e'_s, e'_f)}{b'} g(a)da \right] \\ &\quad + \int_{\frac{p - b\overline{q}}{\gamma(e'_s, e'_f)}}^{\frac{p}{\gamma(e'_s, e'_f)}} \left[\frac{p}{b} g(a)da \right] - \int_{\frac{p - b\overline{q}}{\gamma(e'_s, e'_f)}}^{\frac{p}{\gamma(e'_s, e'_f)}} \left[\frac{a\gamma(e'_s, e'_f)}{b} g(a)da \right] \end{aligned}$$

Differentiating with respect to e'_f and applying the Leibniz integral rule yields:

$$\begin{aligned}\frac{\partial S}{\partial e'_f} = &-(\frac{p-(b-b')\overline{q}}{b'})g(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)})(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)^2})\frac{\partial \gamma}{\partial e'_f}\\ &+(\frac{p-b\overline{q}}{b'})g(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)})(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)^2})\frac{\partial \gamma}{\partial e'_f}\\ &-\frac{p}{b}g(\frac{p}{\gamma(e'_s,e'_f)})(\frac{p}{\gamma(e'_s,e'_f)^2})\frac{\partial \gamma}{\partial e'_f}+\frac{p}{b}g(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)})(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)^2})\frac{\partial \gamma}{\partial e'_f}\\ &-\frac{\partial \gamma}{\partial e'_f}\int_{\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)}}^{\frac{p}{\gamma(e'_s,e'_f)}}\left[\frac{a}{b}g(a)da\right]-\frac{\partial \gamma}{\partial e'_f}\int_0^{\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)}}\left[\frac{a}{b'}g(a)da\right]\\ &+\frac{p}{b}g(\frac{p}{\gamma(e'_s,e'_f)})(\frac{p}{\gamma(e'_s,e'_f)^2})\frac{\partial \gamma}{\partial e'_f}-\frac{p-b\overline{q}}{b}g(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)})(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)^2})\frac{\partial \gamma}{\partial e'_f}\end{aligned}$$

which, after canceling out like terms yields:

$$\frac{\partial S}{\partial e'_f} = -\frac{\partial \gamma}{\partial e'_f}\left[(b')^{-1}\int_0^{\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)}}(ag(a)da)+b^{-1}\int_{\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)}}^{\frac{p}{\gamma(e'_s,e'_f)}}(ag(a)da)\right]$$

Again applying the Leibniz integral rule, the cross-partial effect on total supply of an enforcement reduction in states with laxer capacity constraints (higher $\overline{q}$) can be written as:

$$\begin{aligned}-\frac{\partial S^2}{\partial \overline{q}\partial e'_f} &= \frac{\partial \gamma}{\partial e'_f}\left[(b')^{-1}(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)})g(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)})(\frac{-b}{\gamma(e'_s,e'_f)})\right]\\ &\quad-\frac{\partial \gamma}{\partial e'_f}\left[b^{-1}(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)})(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)})(\frac{-b}{\gamma(e'_s,e'_f)})\right]\\ &= \frac{\partial \gamma}{\partial e'_f}\left[(\frac{b'-b}{bb'})(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)})g(\frac{p-b\overline{q}}{\gamma(e'_s,e'_f)})(\frac{b}{\gamma(e'_s,e'_f)})\right]\end{aligned}$$

This is greater than zero given $b' > b$.

Proof of Proposition 2:

Defining x as the equilibrium total quantity in the market, the equilibrium condition can be written as:

$$F^1(Q, p, e'_s, e'_f, \overline{q}) = x - S(p, e'_s, e'_f, \overline{q}) = 0$$
$$F^2(Q, p, e'_s, e'_f, \overline{q}) = x - D(p, e'_s, e'_f) = 0$$

where $S(p, e'_s, e'_f, \overline{q})$ is determined by Equation 2.2; e'_s, e'_f, and $\overline{q}$ are exogenous; and p and x are endogenous. From previous assumptions about the supply and demand functions, $D_p = \frac{\partial D}{\partial p} < 0$ and $S_p = \frac{\partial S}{\partial p} < 0$.

By the Implicit Function Theorem, these equations will define the unique local solution for equilibrium price and quantity as differentiable functions of e'_f because the Jacobian matrix of the equation system is invertible:

$$|J| = \begin{vmatrix} \frac{\partial F^1}{\partial x} & \frac{\partial F^1}{\partial p} \\ \frac{\partial F^2}{\partial x} & \frac{\partial F^2}{\partial p} \end{vmatrix} = \begin{vmatrix} 1 & -S_p \\ 1 & -D_p \end{vmatrix} = -D_p + S_p > 0$$

Applying Cramer's Rule to the system yields:

$$\frac{\partial x^*}{\partial e'_f} = \frac{\begin{vmatrix} S_{e'_f} & -S_p \\ D_{e'_f} & -D_p \end{vmatrix}}{|J|} = \frac{-D_p S_{e'_f} + S_p D_{e'_f}}{|J|} < 0$$

$$\frac{\partial p^*}{\partial e'_f} = \frac{\begin{vmatrix} 1 & S_{e'_f} \\ 1 & D_{e'_f} \end{vmatrix}}{|J|} = \frac{D_{e'_f} - S_{e'_f}}{|J|}$$

where the sign of $\frac{\partial p^*}{\partial e'_f}$ depends on whether federal risks have greater effect on supply or consumption decisions.

D- Robustness Checks of Model and Sample Specification

Table D.1: WLS and OLS Estimates of Effects on Past-Month Marijuana Use, Including State-Specific Linear Trends, NSDUH (2002-2012)

	(1)		(2)		(3)	
	Ages 12-17		***Ages 18-25***		***Ages 26+***	
	(i)	(ii)	(i)	(ii)	(i)	(ii)
A: MML Measures Separately						
Registration Rate	0.457*	0.387***	0.653**	0.588***	0.363*	0.463***
	(0.236)	(0.129)	(0.270)	(0.209)	(0.185)	(0.143)
	[6.2]	[5.3]	[3.8]	[3.4]	[8.2]	[10.5]
MML=1	-0.168	-0.118	0.315	0.822	0.192	0.056
	(0.329)	(0.388)	(0.401)	(0.549)	(0.336)	(0.162)
	[-1.4]	[-1.4]	[1.8]	[4.7]	[4.3]	[1.1]
B: MML Measures Together						
Registration Rate	0.481*	0.385***	0.635**	0.607***	0.352*	0.464***
	(0.256)	(0.127)	(0.258)	(0.196)	(0.184)	(0.142)
	[6.7]	[5.3]	[3.6]	[3.5]	[8.0]	[10.5]
MML=1	-0.258	-0.010	0.197	0.850	0.131	0.077
	(0.284)	(0.356)	(0.387)	(0.533)	(0.304)	(0.130)
	[-2.8]	[-0.0]	[1.1]	[4.9]	[3.0]	[1.6]
Weighted	Y	N	Y	N	Y	N

Notes and sources: N=539. See Table 2.7. Weighted Least Squares (WLS) regressions are weighted by state-year population of the relevant age group. All specifications include state and year fixed effects, time-varying state covariates, and state-specific linear trends. ***p<0.01, **p<0.05, *p<0.1.

Table D.2: OLS Estimates of Effects on Past-Month Marijuana Use, by Age, Comparing Model Specifications, NSDUH (2003-2013)

	(1)		(2)		(3)	
	Ages 12-17		***Ages 18-25***		***Ages 26+***	
	(i)	(ii)	(i)	(ii)	(i)	(ii)
A: MML Measures Separately						
Registration Rate	0.478***	0.246**	1.072***	0.057	0.893***	0.370*
	(0.174)	(0.118)	(0.345)	(0.353)	(0.249)	(0.224)
	[6.5]	[3.3]	[6.2]	[0.3]	[20.3]	[8.4]
MML=1	0.452	-0.175	0.487	0.469	0.640***	-0.012
	(0.305)	(0.359)	(0.469)	(0.554)	(0.162)	(0.223)
	[6.2]	[-1.4]	[2.8]	[2.7]	[14.6]	[-0.0]
B: MML Measures Together						
Registration Rate	0.441**	0.245**	1.048***	0.061	0.847***	0.370
	(0.180)	(0.118)	(0.376)	(0.346)	(0.254)	(0.259)
	[6.1]	[3.3]	[6.0]	[0.4]	[19.2]	[8.4]
MML=1	0.340	-0.172	0.221	0.470	0.425***	-0.007
	(0.319)	(0.354)	(0.489)	(0.554)	(0.153)	(0.210)
	[4.7]	[-1.4]	[1.3]	[2.7]	[9.6]	[-0.0]
State trends	N	Y	N	Y	N	Y

Notes and sources: N=539. See Table 2.7. The latter year of the two-year averages of the NSDUH survey data is used as the base year of analysis. ***p<0.01, **p<0.05, *p<0.1.

Table D.3: OLS Estimates of Impact of MMLs on Past-Month Marijuana Use, by Age, Comparing Model Specifications, NSDUH ((2002-2003)-(2012-2013))

	(1)		(2)		(3)	
	Ages 12-17		***Ages 18-25***		***Ages 26+***	
	(i)	(ii)	(i)	(ii)	(i)	(ii)
Two-year averaged Registration Rate						
Registration Rate	0.517***	0.402**	1.289***	0.433	1.003***	0.617**
	(0.170)	(0.169)	(0.294)	(0.366)	(0.228)	(0.244)
	[7.1]	[5.5]	[7.4]	[2.5]	[22.9]	[14.0]
State, Year FE	Y	Y	Y	Y	Y	Y
State-specific trends	N	Y	N	Y	N	Y

Notes and sources: N=539. See Table 2.7. The outcome variable of marijuana use is treated as a two-year average, and the independent variables are constructed as the corresponding two-year averages. ***p<0.01, **p<0.05, *p<0.1.

Table D.4: OLS Estimates of Impact of MMLs on Marijuana Use in Past Month, Excluding CA Voluntary Registration Data, NSDUH (2002-2012)

	(1)		(2)		(3)	
	Ages 12-17		***Ages 18-25***		***Ages 26+***	
	(i)	(ii)	(i)	(ii)	(i)	(ii)
A: MML Measures Separately						
Registration Rate	0.454***	0.391***	1.259***	0.593***	0.873***	0.466***
	(0.165)	(0.126)	(0.236)	(0.209)	(0.209)	(0.143)
	[6.3]	[5.5]	[7.3]	[3.4]	[20.5]	[10.8]
MML=1	0.480**	-0.117	0.964*	0.820	0.871***	0.063
	(0.220)	(0.388)	(0.549)	(0.552)	(0.173)	(0.164)
	[6.7]	[-1.4]	[5.6]	[4.8]	[20.5]	[1.4]
B: MML Measures Together						
Registration Rate	0.411**	0.389***	1.185***	0.611***	0.798***	0.467***
	(0.174)	(0.124)	(0.286)	(0.196)	(0.216)	(0.142)
	[5.8]	[5.3]	[6.9]	[3.6]	[18.6]	[10.8]
MML=1	0.371	-0.098	0.649	0.849	0.660***	0.085
	(0.230)	(0.389)	(0.560)	(0.559)	(0.172)	(0.138)
	[5.2]	[-0.0]	[3.7]	[4.9]	[15.6]	[1.9]
State trends	N	Y	N	Y	N	Y

Notes and sources: N=528. See Table 2.7. California (in addition to Maine and Washington) is excluded. ***p<0.01, **p<0.05, *p<0.1.

Table D.5: OLS Estimates of MML Measure Effects on Past-Month Marijuana Use, Excluding States with Highly Interpolated Registration Data, NSDUH (2002-2012)

	(1)		(2)		(3)	
	Ages 12-17		***Ages 18-25***		***Ages 26+***	
	(i)	(ii)	(i)	(ii)	(i)	(ii)
A: MML Measures Separately						
Registration Rate	0.492***	0.419***	1.288***	0.752***	0.925***	0.509***
	(0.181)	(0.139)	(0.209)	(0.200)	(0.210)	(0.148)
	[6.9]	[5.8]	[7.5]	[4.4]	[21.7]	[11.8]
MML=1	0.230*	-0.137	0.847	0.864	1.002***	0.042
	(0.126)	(0.501)	(0.519)	(0.662)	(0.194)	(0.249)
	[3.2]	[-1.4]	[4.9]	[5.0]	[23.6]	[0.9]
B: MML Measures Together						
Registration Rate	0.491***	0.418***	1.251***	0.762***	0.842***	0.510***
	(0.182)	(0.136)	(0.242)	(0.191)	(0.210)	(0.147)
	[6.9]	[5.8]	[7.3]	[4.5]	[19.8]	[12.0]
MML=1	0.004	-0.121	0.271	0.894	0.614**	0.061
	(0.125)	(0.506)	(0.492)	(0.684)	(0.230)	(0.202)
	[0.0]	[-1.4]	[1.6]	[5.2]	[14.4]	[1.4]
State-specific trends	N	Y	N	Y	N	Y

Notes and sources: N=462. See Table 2.7. Excludes CA, ME, WA, and states with more than 50% of registration data relying on interpolation (AK, DE, DC, NV, NJ, VT). ***p<0.01, **p<0.05, *p<0.1.

Table D.6: OLS Estimates of Effects of MML Measures on Prevalence of Past-Month Marijuana Use, Categorical Measure for MML, NSDUH (2002-2012)

	(1)		(2)		(3)	
	Ages 12-17		***Ages 18-25***		***Ages 26+***	
	(i)	(ii)	(i)	(ii)	(i)	(ii)
A: Exclude CA, WA, and ME						
MML=1	0.480**	-0.117	0.964*	0.820	0.871***	0.063
	(0.220)	(0.338)	(0.549)	(0.552)	(0.173)	(0.164)
	[6.7]	[-1.4]	[5.6]	[4.8]	[20.5]	[1.4]
B: Exclude WA and ME						
MML=1	0.450**	-0.118	0.853	0.822	0.852***	0.056
	(0.220)	(0.388)	(0.551)	(0.549)	(0.172)	(0.162)
	[6.2]	[-1.4]	[4.9]	[4.7]	[19.4]	[1.1]
C: Include All States						
MML=1	0.526**	-0.144	0.953	0.740	0.849***	0.028
	(0.219)	(0.392)	(0.547)	(0.530)	(0.175)	(0.166)
	[7.2]	[-1.4]	[5.5]	[4.3]	[18.9]	[0.5]
State-specific trends	N	Y	N	Y	N	Y

Notes and sources: N=528 for Panel A, N=539 for Panel B, and N=561 for Panel C. See Table 2.7 for details of model specification. ***p<0.01, **p<0.05, *p<0.1.

E- Evidence on Cross-Border Supply Spillovers

According to Department of Justice *National Drug Threat Assessment* reports, there is substantial internal movement of domestically produced marijuana, and Figure E.1 clearly illustrates that the sources of much of the marijuana trafficked domestically are the western MML states of Washington, Oregon, California, and Arizona. As marijuana markets are not isolated (as assumed in the model), supply shocks in legal medical marijuana state markets likely have spillover effects on price and availability in states without MMLs or in MML states with high production costs. For the empirical results, this should bias the estimates of the effects of legal market size toward zero.

Tables E.1 and E.2 use Montana as a case study to assess whether spillover of marijuana supply from states with large legal markets to other states is biasing the estimates from the primary results downward. Presently, Montana and Michigan are the only MML states in the continental United States that do not share a border with another MML state.[28] In addition, Figure E.1 shows that Montana and its bordering states are relatively unimportant trafficking routes for marijuana; cannabis smuggled through these states is primarily sourced from Washington and Oregon and is destined for larger, more urban centers in the midwest. Therefore, growth in the legal medical marijuana market in Montana is unlikely to have significant supply spillovers to its neighboring states.

Table E.1 compares estimates of the effects of growth in the legal market on past-month use restricting the sample to only include Montana and its bordering states (Idaho, Wyoming, North Dakota, and South Dakota) in Panel A, to the estimates using the entire sample of states in Panel B. If there are substantial supply spillovers from MML states with large markets to other states, then we would expect the effect

[28]It should be noted that both states share a border with Canada, which has medical marijuana laws.

sizes in Panel A to exceed those in Panel B. From Table E.1, for youths aged 12-25, the effects of legal market size on past-month use are larger in Panel A than in Panel B, but for adults aged 26 and older they are quite similar. This is consistent with growth in the legal medical marijuana market having supply spillovers across states in the blackmarket, where adolescents and young adults have substantially greater access than older adults.

Table E.2 replicates the analysis of Table E.1 using prevalence of past-year initiation as the outcome variable. The results are similar. Thus, there appear to be supply spillovers from medical marijuana markets to recreational marijuana markets used by youths in other states. The differences between the estimates from Montana's case study to those using the entire sample suggests that the effects of medical marijuana market growth on adolescent and young adult use may be twice as large as shown in the primary results if cross-state supply spillovers are accounted for.

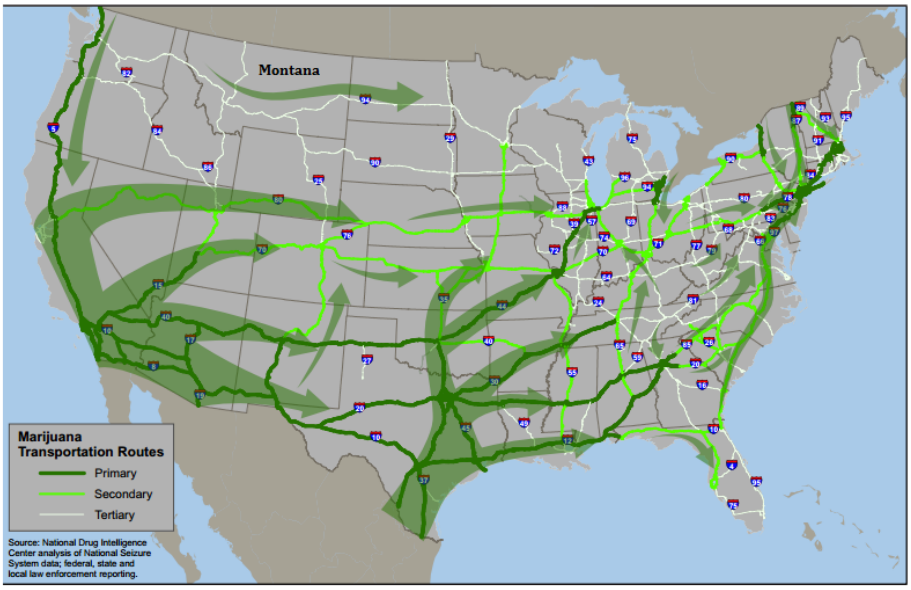


Figure E.1: Marijuana Trafficking Flows in the United States (FY2008-FY2010)

Notes and sources: From NDIC (2011). The map shows marijuana trafficking flows along primary, secondary, and tertiary routes in the United States. Montana (labeled on the map) and its bordering states almost only contain tertiary routes and are transit locations as opposed to sources or destinations.

Table E.1: Effects of Legal Market Growth on Past-Month Marijuana Use, Include Only Montana and Its Border States, NSDUH (2002-2012)

	(1)		(2)		(3)	
	Ages 12-17		***Ages 18-25***		***Ages 26+***	
	(i)	(ii)	(i)	(ii)	(i)	(ii)
A: Include Only Montana and Its Border States						
Registration Rate	0.591**	0.769**	1.796***	1.006**	0.449**	0.408**
	(0.138)	(0.226)	(0.265)	(0.356)	(0.210)	(0.148)
	[8.2]	[10.7]	[11.6]	[6.5]	[10.3]	[9.3]
Mean outcome	7.2	7.2	15.5	15.5	4.4	4.4
B: Include All States						
Registration Rate	0.442***	0.387***	1.212***	0.588***	0.865***	0.463***
	(0.163)	(0.129)	(0.232)	(0.209)	(0.207)	(0.143)
	[6.1]	[5.3]	[7.0]	[3.4]	[19.6]	[10.5]
Mean outcome	7.2	7.2	17.3	17.3	4.4	4.4
State, Year FE	Y	Y	Y	Y	Y	Y
State-specific trends	N	Y	N	Y	N	Y

Notes and sources: See Table 2.7. Panel A includes only Montana and its bordering states of Idaho, Wyoming, North Dakota, and South Dakota (N=55). Since Montana is not a large domestic source of marijuana and has no bordering states with MMLs, it is representative of legal market growth that likely had limited spillovers. To assess the possible downward bias in the coefficient on registration rates, Panel A can be compared to Panel B, which is replicated from Table 2.7 (Panel A) and includes all states except Washington and Maine. ***p<0.01, **p<0.05, *p<0.1.

Table E.2: Effects of Legal Market Growth on Past-Year Marijuana Initiation, Include Only Montana and Its Border States, NSDUH (2002-2012)

	(1)		(2)		(3)	
	Ages 12-17		***Ages 18-25***		***Ages 26+***	
	(i)	(ii)	(i)	(ii)	(i)	(ii)
A: Include Only Montana and Its Border States						
Registration Rate	0.758***	0.904***	0.809***	0.757***	0.020***	0.013***
	(0.074)	(0.114)	(0.094)	(0.106)	(0.003)	(0.001)
	[12.6]	[15.0]	[11.3]	[10.6]	[12.2]	[8.3]
Mean outcome	6.0	6.0	7.1	7.1	0.16	0.16
B: Include All States						
Registration Rate	0.319***	0.431	0.432***	0.199	0.029***	0.020***
	(0.109)	(0.296)	(0.131)	(0.317)	(0.008)	(0.005)
	[5.3]	[7.3]	[6.2]	[2.8]	[12.8]	[6.4]
Mean outcome	5.9	5.9	6.9	6.9	0.16	0.16
State, Year FE	Y	Y	Y	Y	Y	Y
State-specific trends	N	Y	N	Y	N	Y

Notes and sources: See Table 2.7. Panel A includes only Montana and its bordering states of Idaho, Wyoming, North Dakota, and South Dakota (N=55). Since Montana is not a large domestic source of marijuana and has no bordering states with MMLs, it is representative of legal market growth that likely had limited spillovers. To assess the possible downward bias in the coefficient on registration rates, Panel A can be compared to Panel B, which is replicated from Table 2.7 (Panel B) and includes all states except Washington and Maine. ***p<0.01, **p<0.05, *p<0.1.

F- Evidence on Reporting Bias

If the decision to report marijuana use is more closely related to beliefs about legal penalties or social disapproval compared to availability, then the results from Table 2.8 suggest that the effects of legal market growth on adolescent marijuana use are a true measure of consumption changes and not of reporting behavior. Tables F.1-F.2 provide additional supporting evidence that the primary results of this paper are not driven by reporting bias.

Table F.1 reports estimates for the effects of registration rates on the prevalence of past-month marijuana use by adolescents separately for the time period before the Ogden Memo and after the Cole Memo. If changes in reporting behavior are more likely to be driven by law passage than by legal market size, then registration rates should have no effect on reported past-month except due to the federal government's memos. As evidenced in Table F.1, the coefficient estimates for adolescent past-month use are not significantly different if examined before the federal policy reduced enforcement with the Ogden Memo, or after the federal government increased enforcement with the Cole Memo.

However, adolescent reporting behavior may be more sensitive to changes in risks from social or community disapproval than to changes in perceived disapproval from law enforcement. If this were the case, then changes in state marijuana policy (MML enactment) or changes in federal enforcement policy (the Ogden and Cole Memos) may have less effect on adolescent reporting behavior than changes in perceived social stigma associated with cannabis consumption, which is likely highly correlated with the number of legal users and suppliers visible in the community.

To address this potential concern, estimates of the effects of legal medical marijuana market size on juvenile arrests for marijuana possession are shown in Table F.2. Since adolescents for the most part do not qualify as medical marijuana patients, it

is unlikely that there were significant state enforcement changes regarding juvenile arrests for marijuana-related crimes, and thus effects of legal market size on adolescent marijuana arrests are likely highly correlated with effects of legal market size on adolescent cannabis use. Annual data on juvenile arrests from 1994-2012 were obtained from the Uniform Crime Reports County-Level Detailed Arrest Files compiled by the Inter-University Consortium for Political and Social Research. County data were aggregated up to the state level.

Table F.2 reports coefficient estimates for the effect of registration rates on the juvenile marijuana possession arrest rates. In Columns (1)-(4), a log-linear ordinary-least-squares specification is employed, with the dependent variable constructed as the natural log of the number of juvenile arrests for marijuana possession per 100,000 of the relevant-aged population for Columns (1)-(2), or the natural log of the number of juvenile marijuana possession arrests in Columns (3)-(4). Columns (5)-(6) employ a negative binomial specification. For all model specifications, growth in the legal market size has a positive effect on juvenile arrests for marijuana possession of similar effect size to that found for the effects on adolescent past-month use. This suggests that the observed effects on self-reported use are not driven solely by changes in reporting behavior.

Table F.1: Effects of Legal Market Size on Adolescent Use Separately Before Ogden Memo and After Cole Memo

	Past-Month Use			
	Pre-Ogden (2002-2009)		Post-Cole (2011-2012)	
	(1)	(2)	(3)	(4)
Registration Rate	0.136	0.437	0.482**	-
	(0.425)	(0.338)	(0.246)	-
	[2.0]	[6.2]	[6.6]	-
Mean outcome	7.1	7.1	7.3	-
State, Year FE	Y	Y	Y	Y
State-specific trends	N	Y	N	Y

Notes and sources: See Table 2.7. For Columns (1)-(2), N=392 (49 states, 8 years). For Column (3), N=98 (49 states, 2 years); for Column (4), state-specific linear trends cannot be included since only two years of data are available. ***p<0.01, **p<0.05, *p<0.1.

Table F.2: Effects of Legal Market Size on Juvenile (Age 10-17) Marijuana Possession Arrests

	Log Linear				**Negative Binomial**	
	Arrest Rate		Total Arrests		Arrest Rate	
	(1)	(2)	(3)	(4)	(5)	(6)
Registration Rate	0.101	0.131*	0.080	0.127*	0.113	0.060
	(0.109)	(0.069)	(0.103)	(0.066)	(0.095)	(0.100)
Observations	881	881	881	881	931	931
State, Year FE	Y	Y	Y	Y	Y	Y
State-specific trends	N	Y	N	Y	N	Y

Notes and sources: Data from the Uniform Crime Reports (1994-2012) county-level detailed arrest files aggregated up to the state level. See Table 2.3 for state-level covariates included. Mean number of marijuana possession arrests equals 19,729. Mean arrest rate per 100,000 juveniles equals 1,968. ***p<0.01, **p<0.05, *p<0.1.

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CHAPTER 3

On the Health Consequences of Increased Medical Marijuana Access

3.1 Introduction

According to estimates by Miron (2006), state and federal expenditures on enforcement of marijuana prohibition exceed $7 billion annually. Citing these costs, hundreds of economists signed a petition in 2012 encouraging state and federal officials to rethink marijuana policy in the United States. While a growing number of states are liberalizing the use and distribution of marijuana, the federal government still maintains that prohibition is necessary to limit the costs of increased marijuana use that would occur under a legalized regime (ONDCP, 2014).

Chapter 2 shows that growth in the size of legal medical marijuana markets significantly increases recreational use, but the welfare effects of this increased consumption alone are ambiguous. If individuals are rational and fully anticipate the potential negative consequences of marijuana consumption on future utility, then any increase in use induced by liberalization increases consumer welfare (Becker and Murphy, 1988). If, however, individuals underestimate the potential negative consequences (e.g., risk of dependence) or make mistakes in their consumption choices triggered by environmental cues, this increased marijuana use may decrease social welfare (Laibson, 1997; Bernheim and Rangel, 2004). Under any theory of individual decision-making, if marijuana use generates negative externalities, then the socially optimal level of

consumption is below the individually optimal level of consumption achieved under a free market regime.

This paper contributes toward understanding the potential welfare consequences of legalization by studying how growth in the legal market for medical marijuana (proxied for by the share of adults registered as medical marijuana users) affects traffic fatalities and deaths related to alcohol and opioid poisonings. These outcomes will reflect direct externalities from marijuana use due to impaired driving, as well as indirect externalities resulting from substitution or complementarity with alcohol and opioids. Since past research has found evidence of heterogeneity by age in the elasticity of substitution between marijuana and other substances (Farrelly et al., 1999), particular attention is given to differences in these outcomes by age.

In the aggregate, I find that greater medical marijuana access decreases mortality from traffic accidents and substance-related poisonings. However, the aggregate effect masks an important welfare trade-off generated by age differences in the elasticity of substitution between marijuana and alcohol. For older adults aged 45-64, increased medical marijuana availability has positive health consequences, as growth in registration rates reduces mortality related to alcohol and opioid poisonings by 7-11% and 12-16% respectively. In contrast, for youths, greater marijuana access generates negative externalities in the form of a 6% increase in traffic fatalities caused by drivers aged 15-20, with large and significant effects on alcohol-related accidents. These results are consistent with complementarity between alcohol and marijuana among youth and substitution among older adults.

The paper proceeds as follows. Section 3.2 provides a brief description of medical marijuana markets in the United States, and section 3.3 discusses the literature on marijuana's role as a substitute or complement for other additive substances. The data and empirical framework are described in sections 3.4 and 3.5 respectively. Section 3.6 presents the empirical results of the effects of growth in medical marijuana

availability on traffic fatalities and substance-related poisonings. Finally, sections 3.7 and 3.8 conclude with discussion and directions for future work.

3.2 Medical Marijuana Markets

The past few decades have seen a growing movement, both worldwide but particularly in the United States, away from a strict policy of marijuana prohibition. Over half of the U.S. population now live in states with medical marijuana laws (MMLs), which provide legal protections for the medical use of marijuana by qualifying patients and allow for the legal supply and distribution of medical marijuana. As of 2013, in all but three of the twenty MML states, an individual who wants medical marijuana must obtain a physician's certification that the individual has a medical condition which could benefit from marijuana use and register with the state.[1] The share of adults registered as patients reflects the extent of medical marijuana participation in a given state and provides a measure of market penetration.

Variation in how production is regulated has led to heterogeneity in medical marijuana take-up across states, and data on state counts of registered medical marijuana patients highlights this variation. Figure 3.1 plots the percent of the state adult population registered as legal medical marijuana users in December 2014 against months since the effective date of MML enactment. As expected, the size of the market is positively correlated with the length of time the MML has been in place. However, another important determinant of market size is the strictness of regulations facing suppliers. States that allowed large-scale production with little oversight or monitoring show growth in market size above trend, while states without operational

[1]Washington is the only state with no registration system in place, while California and Maine have voluntary patient registries.

dispensaries have seen little growth.[2]

While Figure 3.1 presents a static snapshot of the current state of MML market size, the structure and size of state medical marijuana markets have undergone substantial changes over the past decade. Although several MML policies had established legal protections for large-scale producers prior to 2009, the threat of federal prosecution and product seizure served as a sufficient barrier to entry in the state-legal market. However, in October 2009, the federal government released the Ogden Memo which formally de-prioritized prosecution of users and producers in MML states who were compliant with state law (Ogden, 2009). This decrease in perceived federal enforcement risk resulted in a significant shift in the structure of the medical marijuana industry.

Prior to 2009, California was the only state which had seen the rise of large-scale medical marijuana production collectives (Anderson and Rees, 2014). However, as detailed in Table 3.1, in states where caregivers could legally produce for multiple patients, the number of operational large-scale producers increased rapidly after the Ogden Memo. For example, in Colorado, very few medical marijuana commercial operations had opened between initial MML enactment (June, 2001) and 2009; by mid-2010, over 900 operational dispensaries were identified by law enforcement (HIDTA, 2013). In Montana, which did not have state-licensed dispensaries but allowed caregivers to produce for and sell marijuana to an unlimited number of patients, the number of caregivers serving ten or more patients grew from 84 in October 2009 to more than 480 by September 2010.

Trends in the number of registered medical marijuana patients reflect this rapid

[2]States defined as having "unregulated dispensaries" (e.g., Colorado) did not initially establish regulations for licensed dispensaries, but the law (either directly or through ambiguous language) allowed caregivers to produce for an unlimited patients. Other states (e.g., New Mexico) established provisions legalizing the operation of state-licensed dispensaries, which faced production quotas and state oversight.

expansion in the size of the market for medical marijuana following the Ogden Memo. Figure 3.2 depicts trends in the total number of registered patients, aggregated over all states with registration rate data that had MMLs effective prior to the Ogden Memo. Consistent with the increase in medical marijuana production, the number of registered patients spiked following the announcement of decreased federal enforcement. The flattening in trend in 2011 was driven by the federal government's reversal in stance and re-prioritization of involvement in MML states (Cole, 2011).

As documented in Chapter 2, growth in medical marijuana market size significantly increases marijuana consumption among all age groups. The welfare implications of this increased marijuana use will depend largely on whether marijuana consumption itself generates externalities, and on the extent to which marijuana is a substitute or complement to other addictive substances. While prior work has sought to address the effects of medical marijuana liberalization on traffic fatalities, alcohol consumption, and opioid use, there is little agreement as yet.

3.3 Literature Review

Medical Marijuana Laws and Traffic Fatalities

Alcohol and marijuana are the drugs most frequently detected in fatally injured drivers (Brady and Li, 2013), and the effect of marijuana legalization on drugged driving is a potential negative externality of primary concern in the current policy debate. While a large body of research has established the role of alcohol in increasing crash risk (Borkenstein, 1964), the effects of cannabis on driving impairment are less clear. Cognitive studies show that marijuana use impairs a number of tasks associated with driving ability (Liguori et al., 1998), but experimental research has found the effects of marijuana on driver impairment to be only modest when compared to the effects of alcohol. Still, the consumption of both alcohol and marijuana has

an additive or even multiplicative effect on driver impairment (Sewell et al., 2009), with one study finding these effects to be particularly strong during nighttime driving simulations (Downey et al., 2013).

Anderson et al. (2013) were the first to estimate the effects of medical marijuana enactment on traffic fatalities. Comparing states before and after MML enactment to states without such laws, they find that MML enactment leads to a significant reduction of about 16% in the fatality rate for individuals aged 20-40 from motor vehicle accidents. The authors also find that legalization of medical marijuana leads to a significant 13.2% decrease in fatalities from alcohol-involved accidents.

Pacula et al. (2013) recognized that heterogeneity in MML policy may result in heterogeneous effects, and they repeated the analysis of Anderson et al. (2013) distinguishing between MMLs with and without legal dispensary allowances. Their results confirm that MML enactment is negatively associated with alcohol-involved traffic fatality rates, but they show that this negative relationship is almost entirely offset in states that allow dispensaries. These results are supported by Choi (2014), who uses individual-level data from the National Survey of Drug Use and Health from 2004-2012 and finds that allowing marijuana dispensaries is associated with a 9.1 and 23.9 percent increase in reporting driving under the influence of alcohol and drugs respectively.

Why should there be differences in the effects of MMLs on traffic fatalities depending on the allowance of dispensaries? For one, Downey et al. (2013) finds that high tetrahydrocannabinol (THC) levels significantly increase driving impairment,[3] and MML states that allow dispensaries have been shown to have greater diffusion of high-potency cannabis (Sevigny et al., 2014). Comparing Colorado to non-MML states, Salomonsen-Sautel, Min, et al. (2014) find no significant increase in the propor-

[3]THC is the chemical in cannabis responsible for most of its psychoactive effects.

tion of drivers involved in a fatal motor vehicle crash who tested positive for marijuana *until* the period when medical marijuana commercialization expanded (2009-2011).[4]

The evidence from Table 3.1 can help explain the different findings of past research. There is wide variation in medical marijuana penetration depending on the supply regulations established by state MML policies and the level of federal enforcement. Using the timing of state MML enactment (or dispensary legalization) to identify the effects of medical marijuana legalization on traffic fatalities misses important changes in the availability of marijuana that occur long after initial MML passage. These omitted effects may be of particular importance when assessing the impact on youths, who are more likely to self-report willingness to drive after consuming cannabis or after consuming both marijuana and alcohol (Fischer et al., 2006).

Marijuana Liberalization and Alcohol Consumption

Irrespective of its effects on traffic accidents, marijuana's role as a substitute for alcohol has important health implications. The question of whether alcohol and marijuana are substitutes or complements has received substantial attention in the literature, but findings have varied. Given the breadth of work, I focus here on studies using marijuana liberalization policies to identify the relationship between marijuana and alcohol use.

Empirical evidence on the effect of marijuana decriminalization policies is mixed (see Pacula, Grossman, et al. (2001) for a review of the literature), and more recent work specifically examining the effects of MMLs on alcohol consumption has found similarly varied outcomes. Using data from the 2004-2012 National Survey of Drug Use and Health (NSDUH), Wen et al. (2015) report a positive effect of MML enactment on frequency of binge drinking for adults over 20 years of age but no effect

[4]They find no significant differences comparing Colorado and non-MML states in the proportion of drivers in fatal motor vehicle crashes who were alcohol-impaired.

on alcohol use by individuals under age 21. In contrast, Anderson et al. (2013) examine data from the 1993-2010 Behavioral Risk Factor Surveillance System and find that MML enactment has a significant negative impact on past-month drinking and binge-drinking among young adults.

Differences in these findings may in part be driven by the fact that the studies cover different years, and hence different state laws are used in the identification of the treatment effects. Pacula, MacCoun, et al. (2005) caution against using a binary indicator for marijuana decriminalization laws, as there is substantial variation in how these laws are implemented, enforced, and hence understood by citizens. As discussed by Pacula et al. (2015) and demonstrated in section 3.2, state MML regulations vary greatly and can thus be expected to generate heterogeneous effects.

Additionally, the categorical MML measure used in past analyses does not capture the later evolution of medical marijuana markets shown in Figure 3.2. The inclusion of state-specific trends in the empirical specification will thus confound preexisting trends with the dynamic effects of the policy (Wolfers, 2006). By using medical marijuana registration rates instead of a binary MML indicator as the policy variable of interest, this paper overcomes these limitations.

Medical Marijuana and Opioid Consumption

While there are only a few economic studies of the relationship between marijuana and opioid use, clinical studies by Cichewicz and Welch (2003) and Ramesh et al. (2011) suggest that smoked cannabis and cannabinoids have opioid sparing properties and may prevent the development of tolerance to opiates. Additionally, studies of opioid dependent patients indicate that moderate use of cannabis or synthetic cannabinoids leads to significantly improved outcomes for medication compliance, opioid withdrawal symptoms, and retention in treatment (Church et al., 2001; Bisaga et al., 2015).

The potential for medical marijuana to reduce opioid abuse is supported by Bachhuber et al. (2014), who find that MML enactment is associated with a significant 20% decrease in age-adjusted prescription opioid-related mortality, with these effects strengthening several years post-enactment. Powell et al. (2015) find no effect of MMLs (broadly specified) on opioid abuse or mortality, but they find that legalizing dispensaries reduces opioid abuse and mortality by about 15%.

While these results suggest that increased medical marijuana availability offers the benefit of significantly reducing opioid use, past work has not examined to whom these benefits are accruing. While all age groups have seen significant growth in opioid-related deaths, the rise in mortality rates has been most pronounced for adults aged 45-64 (see Figure 3.3). Indeed, recent work by Case and Deaton (2015) shows that drug poisoning deaths have significantly contributed to the reversal in mortality improvement experienced by US white non-Hispanics aged 45-54 between 1999 and 2013. By estimating the effects of increased medical marijuana availability on opioid-poisoning mortality separately by age group, this paper contributes toward further understanding whether medical marijuana can serve to improve the deteriorating mortality outcomes for older individuals.

3.4 Data

3.4.1 Traffic Fatalities

To assess whether increased cannabis use results in more automobile accidents, data was compiled from the Fatal Accident Reporting System (FARS) for 1990-2013. FARS, collected by the National Highway Traffic Safety Administration (NHTSA), contains detailed information on the circumstances of the accident, in addition to information on the characteristics of occupants and non-occupants. In order to most precisely identify which age groups experience increased risk of causing fatal accidents,

traffic fatalities are analyzed separately by age of the driver involved in single-vehicle accidents only. Summary statistics are given in Appendix H-.

It should be noted that the traffic fatality variables used in this analysis differ slightly from that used in Anderson et al. (2013). Their analysis separates traffic fatalities by age of the deceased, while my empirical model analyzes fatalities by age of the driver involved. While these two variables should be correlated, focusing on age of the driver involved provides a better indicator of which individuals are changing their alcohol and cannabis consumption in response to increased medical marijuana availability.

3.4.2 Substance-Related Poisoning Mortality

To investigate substitution between marijuana and other addictive substances, substance-related poisoning mortality data from 1990-2013 was downloaded from the Center for Disease Control's Wide-ranging Online Data for Epidemiologic Research (WONDER) interface. Alcohol poisonings are defined as deaths with ICD-10 code X45, X65, Y15, or F10.0.[5] Opioid analgesic poisonings are defined as those under ICD-10 codes X40-X44, X60-X64, or Y10-Y14, where a prescription opioid (T40.2-T40.3) was also coded. Heroin-related poisonings are defined as those under ICD-10 codes X40-X44, X60-X64, or Y10-Y14, where heroin (T40.1) was also coded. Summary statistics are given in Appendix H-.

Deaths are coded based on multiple-cause reporting instead of the underlying-cause, since this can provide a more complete representation of all conditions that contributed to the death (Redelings et al., 2006). A death is counted if the specified condition is listed on the death certificate as a contributing factor, but the condition need not be the specified as the underlying cause of death. Thus, these counts do not

[5]The code F10.0 was retired in 2007 and recoded under X45.

necessarily represent unique deaths (e.g. a fatal overdose involving a combination of alcohol and prescription opioids will be counted for both substances.

There are advantages and disadvantages in using multiple-cause as opposed to underlying-cause data. The multiple-cause data provides a fuller picture of changes in substance use contributing to mortality, but these statistics do not necessarily convey the extent to which changes in substance use due to medical marijuana laws decrease mortality. This is less problematic for opioid-related poisoning deaths as the multiple-cause and underlying-cause counts are nearly equivalent. However, for alcohol-poisoning deaths, there are nearly five times more deaths identified from multiple-cause data than from underlying-cause data. For all substances, the data are likely undercounts of true mortality, as not all autopsies undergo a full toxicology panel, and there is some subjectivity in the multiple-causes-of-death that a coroner chooses to report.

3.5 Empirical Framework

Since fatalities are count data (non-negative integer values), and a relatively rare event, a Poisson-based model is preferable to a log-linear specification. While negative binomial models (which combine the Poisson distribution of event counts with a gamma distribution of the unexplained variation in the true mean event counts) are often employed in the analysis of fatality data to account for over-dispersion, the Poisson maximum likelihood estimator is preferred since it has been shown to generate consistent estimates even with misspecification of the true underlying data generating process (Wooldridge, 1997). In this model, the expected number of deaths d_{jt} (from a given cause of interest) in state j at year t is given by the following equation:

$$E[d_{jt}|X_{jt}] = exp(\alpha + \beta RR_{jt} + \gamma W_{jt} + u_j + v_t + \Theta_j * t + ln(pop_{jt})) \tag{3.1}$$

where $ln(pop_{jt})$ is the natural log of the relevant-aged population of state j in year t and its coefficient is constrained to 1, which allows the count data of deaths to be expressed as a mortality rate. RR_{jt} is the per capita registration rate (i.e., the number of registered medical marijuana patients as a percent of the adult population) at the end of year t in state j. Time-varying state covariates W_{jt} included that potentially affect the mortality outcomes can be categorized as: (1) demographics, (2) economic characteristics, (3) substance-related policies, and (4) state-level driving-related laws that would affect motor vehicle accidents are included in the analysis of traffic fatalities. See Appendix Table G.1 for the list of covariates and their sources.

The estimate of interest, β, can be interpreted as the mean proportionate change in deaths associated with a one percentage-point change in the registration rate. State and year fixed effects (u_j and v_t respectively) control for time-invariant state characteristics and national trends, and state-specific linear trends $\Theta_j * t$ are included to account for state differences in pre-existing trends. State and year dummy variables are included rather than modifying the likelihood function as recommended by Allison and Waterman (2002). To relax the Poisson model's assumption of equidispersion,[6] sandwich standard errors are computed (Cameron and Trivedi, 2013). In all specifications, standard errors are clustered at the state level to account for auto-correlation (Bertrand et al., 2004).

[6]For all the mortality regressions, the null of no over-dispersion is rejected with p=0.000.

3.6 Results

Table 3.2 presents initial results of the effects of registration rates on traffic fatalities by age of the driver involved in the accident. Since a higher proportion of fatal crashes on weekends and at nighttime involve substance impairment, coefficient estimates from Poisson regressions are shown separately for total, weekend, weekday, daytime, and nighttime crashes. All specifications include state and year fixed effects, time-varying state covariates, and state-specific linear trends.

The results from Table 3.2 suggest that increased marijuana consumption by adolescents and young adults has the negative externality of increasing fatal traffic accidents caused by these drivers. For accidents involving a driver aged 15-20, growth in the medical marijuana market predicts an increase in total traffic fatalities, with significant effects on weekend and nighttime accidents. A one percentage-point increase in registration rates increases weekend and nighttime traffic fatalities caused by young drivers aged 15-20 by 8% and 7% respectively.[7] For drivers aged 21-24, increased registration rates have large positive effects (around 9%) on all fatal traffic accidents, but these effects are only statistically significant for daytime accidents. For older adult drivers, increased registration rates do not predict any significant change in fatal traffic accidents. However, while not statistically significant, the effects on drivers aged 45-64 are all negative, with the largest effects (-5%) for nighttime accidents.

While Table 3.2 indicates that greater marijuana availability leads to increased traffic fatalities involving young drivers, it is unclear whether these effects are driven by cannabis use alone or the joint use of cannabis with other substances. To disentangle the role of alcohol and marijuana in generating motor vehicle fatalities, Table 3.3 presents estimates of the effects of registration rate growth on traffic fatalities sepa-

[7]Percentage changes are calculated from $\exp^{\hat{\beta}} - 1$.

rately by substance involvement.[8]

Panel A reports estimates of the effects of legal market growth on fatalities in which the driver's blood alcohol content (BAC) was tested and found to be equal to zero. For all age groups, the estimates are insignificant. In contrast, for accidents in which the driver had a positive BAC value, Panel B shows that increased medical marijuana availability is associated with a significant 11.6% increase in traffic fatalities involving a driver aged 15-20 and an insignificant 5.3% decrease for drivers aged 45-64. While the results from Panel C are consistent with increased prevalence of cannabis use for drivers of all ages, Panel D suggests that it is the joint use of alcohol and marijuana that generates negative externalities in the form of increased traffic fatalities caused by drivers aged 15-24.

The results of Table 3.3 are consistent with the experimental evidence from driving simulator studies, but caution should be taken in interpreting these results. Drivers are not regularly tested for cannabinoids, and the decision to test may well be endogenous with expansion in the medical marijuana market. Also, because THC is lipid-soluble and excreted slowly over time into urine, a positive test for cannabinoids does not necessarily mean the individual has used marijuana recently — let alone that cannabis-impairment caused the accident (Logan et al., 2014). Still, the results suggest that differences between youths and older adults in the decision to use marijuana and alcohol jointly may generate different health consequences caused by greater marijuana availability.

To further examine substitution behavior, Table 3.4 presents estimates of the effects of registration rates on poisoning mortality involving alcohol (Panel A), prescription opioid analgesics (Panel B), and heroin (Panel C). Panel A shows that higher registration rates predict a large and significant decline in alcohol-related poisoning

[8]Since the FARS data does not report cannabis testing results prior to 1991, data from 1990 is dropped for this analysis.

mortality (7-11%) for adults aged 45-64. With increased medical marijuana access, older adults appear to substitute away from the heavy use of opioids. Registration rates have a significant negative effect on opioid-analgesic poisoning mortality for adults aged 45-64 of 11-15%. These results are smaller but in line with the findings of Powell et al. (2015). In contrast, there is suggestive evidence of complementarity between alcohol and marijuana for youths aged 15-24, consistent with the evidence from Tables 3.2 and 3.3.

3.6.1 Robustness Checks

As stated earlier, the Poisson specification was preferred over the more intuitive log-linear specification and the commonly-used negative binomial regression model. Since in many years, there are relatively few (or zero) single-vehicle traffic fatalities, a log-linear specification will introduce considerable noise in the analysis, and will result in biased estimates under heteroskedasticity (Silva and Tenreyro, 2006). While the negative binomial regression estimator can account for the over-dispersion apparent in the data, violation of the model's assumptions about the underlying data-generating process will produce biased coefficients (Wooldridge, 1997). Still, these alternative models can provide specification checks for the primary analyses.

Tables 3.5 and 3.6 thus present coefficients on the registration rate variable from the log-linear and negative binomial specifications for completeness. In line with the estimates from Tables 3.2 and 3.4, these alternative specifications confirm that growth in the legal medical marijuana leads to a significant increase in weekend and nighttime traffic fatalities caused by drivers aged 15-20, and significant declines in alcohol and opioid analgesic poisoning deaths for adults aged 45-64.

As the final set of sensitivity analyses, Tables 3.7 and 3.8 estimate the effects of medical marijuana market growth including only states that had enacted an MML as of 2015. The effects are thus estimated from differences in market size *within* the set

of states that presently provide legal protections for medical marijuana. Since all of these states eventually passed laws, they may be considered more similar.

For all outcomes, the results are largely unchanged. One difference of note is that the negative effects on traffic fatalities involving a driver aged 45-64 are larger and significant when the sample is restricted to MML states. The estimates from Table 3.7 are not statistically different from those of Table 3.2, but they are more precisely estimated in the restricted sample. The magnitude of the effects is largest for weekend and nighttime accidents, again suggesting that increased medical marijuana availability for older adults leads to positive externalities as they treat marijuana and alcohol as substitutes.

Overall, access to medical marijuana significantly decreases alcohol and opioid abuse for older adults. The results suggest that, for adults aged 45-64, any costs of increased marijuana use may well be outweighed by a reduction in the substantial health costs associated with heavy consumption of these other substances. This is consistent with surveys of medical marijuana patients, who often report that they use medical marijuana to quit or decrease their use of alcohol and prescription pain medications (Reiman, 2009; Smith, 2011). However, there is a policy tradeoff, as growth in the legal market significantly increases traffic fatalities (particularly for alcohol- and cannabis-involved accidents) caused by young drivers aged 15-24.

These findings do not contradict those of past research, but they highlight the importance of considering the mechanisms by which medical marijuana liberalization generates spillovers to young recreational users. Individuals whose cannabis consumption decision is affected by law passage may have a different likelihood of joint use of marijuana and alcohol or opioids compared to an individual whose consumption changes with increased marijuana availability. By estimating the effects of growth in the legal market and not initial MML enactment alone, I show that spillovers to youths generate additional negative externalities as younger users treat marijuana

and alcohol as complements.

3.7 Potential Mechanisms

These results support that marijuana and opioids are substitutes for all age groups. However, youths and adults differ significantly in their demand relationships for alcohol and cannabis. This is consistent with some past work showing cross-price elasticity estimates between alcohol and marijuana differ depending on the population studied. For instance, Farrelly et al. (1999) find higher alcohol prices significantly lower marijuana use among youths aged 12-20, but have no effect on cannabis use for adults aged 21-30.

Additionally, Williams and Mahmoudi (2004) find that the complementary relationship between alcohol and cannabis is strongest for those who use both substances simultaneously (i.e., polysubstance users), and polysubstance use is much more common about adolescents and young adults. From the 2013 National Survey of Drug Use and Health, the prevalence of past-month use of both alcohol and marijuana peaks at age 21, when about 20% of individuals report past-month use of both substances. Participation in the use of both alcohol and cannabis declines slowly until sharply dropping to about 5% for individuals aged 35-49 and 3% for individuals aged 50-64 (see Figure 3.4). Simultaneous use of alcohol and marijuana (i.e., within a couple of hours of each other) shows a similar pattern. About 11% of 18-20 year-olds report using marijuana and alcohol together in the past month, while only 2% of 35-64 year-olds report joint use (see Figure 3.5).

While this study's use of aggregate data limits identification of the mechanisms driving these differences, below I outline a few insights from behavioral economics that might explain these findings and will be explored in future study.

Decision-Making Processes

Evidence from the neuroscience literature suggests that differences between adolescents and adults in risk-taking behavior can be attributed to age differences in the stage of brain development. Development of the brain's prefrontal cortex between ages 12-25 is associated with lower impulse control, increased sensation-seeking, and limited resistance to peer pressure (Steinberg, 2008), which may make adolescents and young adults more likely to jointly consume marijuana with other addictive substances or to drive under the influence of drugs and alcohol.

Differences in brain development between adolescents and adults do not necessarily indicate that youths behave irrationally. In fact, experimental research has largely found that youths and adults are similar in their awareness of potential consequences and in their perceptions of the likelihood of facing those consequences. By age 15, individuals have logical reasoning comparable to that of adults in perceiving risk and estimating their vulnerability to it (Reyna and Farley, 2006). A number of economic studies have similarly shown that youth substance use responds to price and perceived risk (Farrelly et al., 1999; Pacula, Grossman, et al., 2001), which is consistent with some degree of rational decision-making.

This suggests that adolescents (particularly older adolescents) and adults are similarly able to assess the expected costs and benefits of addictive substance use within a rational framework. However, there is evidence that youths differ from adults in how they value the outcomes of their decisions. When presented with risky situations that have both potential rewards and costs, adolescents are more sensitive than adults to variation in rewards but less sensitive to variation in costs (Ernst and Paulus, 2005). In experimental studies, the presence of peers significantly increases risk-taking among teenagers, moderately among college-age individuals, and not at all among older adults (Gardner and Steinberg, 2005).

Differences in how youths and adults value consequences reflect differences in preferences. Traditionally, economists have dismissed preference-based explanations of human behavior since differences in preferences "explain everything and therefore nothing" (Stigler and Becker, 1977). However, this is true only if there is no empirical evidence available to place structure on a model of preference heterogeneity. In the case of risky behavior, adolescence is shown to be a period when less value is placed on self-assessed potential negative consequences compared to the potential gains from experimentation, novelty-seeking, and social acceptance. Models of identity-formation (Akerlof and Kranton, 2000), experimentation (Nakajima, 2007), and peer acceptance (DeCicca et al., 2000) offer methods for incorporating these preferences in an economic framework.

Differences in Substance Use Motives

The utility derived from the consumption of alcohol, marijuana, and opioids is likely driven by some latent demand for intoxication. Motivational models of substance use have categorized these demand drivers along two dimensions, positive vs. negative affect regulation (e.g., using to enhance well-being vs. using to cope with negative emotions) and intrinsic vs. extrinsic reasons for use (e.g., using to manage one's internal state vs. using to obtain social acceptance). Crossing these two dimensions results in four classes of motives (Cooper, 1994): (1) positive/intrinsic (use to enhance well-being), (2) positive/extrinsic (use to generate positive social rewards), (3) negative/intrinsic (use to reduce negative emotions), (4) negative/extrinsic (use to avoid social censure).

A large body of literature has shown clear age patterns in self-reported reasons for using alcohol and cannabis. Most adolescent users report use related to social motives, some for enhancement reasons, and very few for coping motives (Kuntsche et al., 2006). However, youths tend to "age out" of these positive and extrinsic motives

for substance use. Individuals who continue alcohol and marijuana use through their mid-20s are significantly less likely to report reasons for use related to having fun with friends, fitting in, and increasing the effects of other drugs; instead, adults are significantly more likely to report use of both alcohol and marijuana to relax, of alcohol to sleep, and of marijuana to decrease the effects of other drugs (Patrick et al., 2011). Continued use in adulthood thus tends to be driven by utility derived from the relief of negative affect (e.g., self-medication or stress relief).

Differences in these latent demand properties have been shown to generate heterogeneous substitution behavior. A recent study of college-aged individuals shows that most students use alcohol and cannabis for social reasons, and they tend to treat these substances as complements. However, those students who report using alcohol or cannabis to relieve negative affect are significantly more likely to treat them as substitutes (O'Hara et al., 2016). Increased marijuana availability for youths who consume to enhance positive mood or social interactions may thus have the unintended consequence of increasing alcohol use; for older individuals who consume alcohol to alleviate negative mood, access to marijuana may offer a substitute manner of coping. Potential economic models to incorporate affect in the utility-maximization process include Hermalin and Isen (2008) and Loewenstein (2000).

Access Points and Social Context

Adults and youths also differ in where they access and use alcohol and cannabis. Compared to older individuals, youths under the age of 21 are less likely to consume alcohol at bars or restaurants, and are more likely to drink in others' homes, parties, outdoors, and in vehicles. They are also significantly less likely to purchase either alcohol or cannabis. Rather, for underage youths (and college students), opportunities for alcohol and cannabis access frequently occur in shared social settings. Increased supply of marijuana may make co-use more likely due to shared availability in the

social markets where youth consumption occurs.

In contrast, adults over age twenty-one have legal access to alcohol consumption in public places such as bars or restaurants. For adults who drink socially at bars and restaurants, increased marijuana availability may keep drinkers away from these establishments and reduce their social consumption of alcohol.[9] Even if alcohol consumption is not reduced, a shift of alcohol use from public places to an individual's own home could generate significant reductions in alcohol-related traffic accidents.

The role of environment may help reconcile differences between this paper's findings and studies of the minimum legal drinking age (MLDA) that show marijuana and alcohol are substitutes.[10] Being of MLDA decreases the total cost of consuming alcohol, but increases the cost of jointly consuming alcohol and cannabis (since the use of marijuana is prohibited in public places). Figure 3.5 provides evidence in support of this hypothesis, as the prevalence of past-month use of both marijuana and alcohol peaks at age 21, but there is a sharp drop in the share of concurrent users reporting simultaneous consumption.

Bernheim and Rangel (2004) present an economic model of addiction that explicitly incorporates the role of environment in determining an individual's consumption decision. Briefly, their model describes an individual who chooses (1) an environment or "lifestyle" activity (e.g., party, work), and (2) some allocation of resources between an addictive substance and a non-addictive good. The decision-maker enters each period in a "cold" mode and rationally chooses her lifestyle activity. Along with her history of use, this decision determines the probability of encountering cues that trigger a "hot" mode. If triggered, consumption of the addictive good occurs regard-

[9]A similar explanation is offered by Picone et al. (2004) to explain negative effects of smoking bans on alcohol use among older adults.

[10]DiNardo and Lemieux (2001) find that raising the MLDA significantly increased marijuana use among young adults. Using a regression discontinuity design, Crost and Guerrero (2012) estimate a significant reduction in marijuana consumption at the MLDA.

less of whether it is optimal; if not triggered, the decision-maker rationally chooses whether or not to use.

With growth in the legal medical marijuana market, the likelihood of encountering triggers for marijuana consumption increases for both adults and adolescents. However, an important distinction between adolescents and adults is that adolescents face a more limited choice set for environment or lifestyle. Youths also likely face more uncertainty in the probability of entering the hot mode with respect to multiple addictive substances. For example, an adult wanting to engage socially may choose a restaurant environment where he knows the probability of encountering an alcohol trigger is high, but the probability of encountering a cannabis trigger is low. Alternatively, he could choose a cannabis club environment (if registered as a medical marijuana patient) where he knows the probability of encountering a cannabis trigger is high, but the probability of encountering an alcohol trigger is minimal. An adolescent, on the other hand, will often face more uncertainty about the probability of encountering one or more cues, and the "exposure" environments available to youths will often have high probability of triggering hot modes for multiple substances.

3.8 Discussion

Overall, access to medical marijuana significantly decreases alcohol and opioid abuse for older adults. This is an especially important finding given new research showing that the mortality reversal among white non-Hispanics aged 45-54 in the last decade is largely attributable to increased deaths from drug and alcohol poisoning and chronic liver diseases (Case and Deaton, 2015). Availability of medical marijuana as a substitute for these more lethal substances thus has the potential to lower mortality and morbidity from these causes. However, there is a policy trade-off, as youths treat marijuana and alcohol as complements. For adolescents and young adults, increased

cannabis consumption due to growth in legal marijuana markets has additional negative consequences by increasing alcohol-related poisonings and fatal traffic accidents.

For optimal regulation considerations, there needs to be some understanding of how we should trade off these effects. In Table 3.9, I calculate back-of-the-envelope estimates under a number of assumptions to quantify these health consequences. The numbers of lives saved and lost due to medical marijuana market expansion after the Ogden Memo are calculated by comparing actual mortality counts post-Ogden (2009-2012) to those predicted under a counter-factual regime in which no registration rate growth had occurred. The counter-factual predictions are determined using results from Chapter 2 and the coefficient estimates from the regressions used to produce Tables 3.2 and 3.4.

Overall, Table 3.9 shows that there are substantial benefits to expanding legal marijuana access for older adults, and regulations should be focused on limiting access to adolescents and young adults. These results imply that legal marijuana markets should be segmented, and costs should be increased for young adults and decreased for older adults. One such policy would be to differentially price marijuana by age, subsidizing the use of medical marijuana for older individuals while taxing younger adults. Since differential unit pricing may generate arbitrage opportunities, an optimal policy could consist of two-part pricing, in which medical marijuana purchases are subject to higher taxes but higher registration ("entry") fees are subsidized for older adults. Given Chapter 1's findings that patient registration is significantly responsive to changes in application fees and evidence that youth consumption of addictive goods is more price-elastic than adult consumption,[11] this policy could maximize cannabis access for older adults while minimizing spillovers to youths. Increasing entry costs for younger adult users may have beneficial multiplier effects if adolescent access to legal supply is driven by diversion from younger adult consumers.

[11]See Grossman and Chaloupka (1997) for a summary of theoretical explanations.

A few limitations of these calculations deserve mention. Since the legal market for marijuana is studied at early stages of its development, prior to market "saturation",[12] the calculations from Table 3.9 have limited external validity. There are also a number of other potential externalities (e.g., crime, productivity) that may be affected by increased marijuana access and are likely to be concentrated among youths and young adults. Future work will examine long-term effects such as dependence, human capital accumulation, and health outcomes. Given the effects found for youths, it will be particularly important for future research to track these younger cohorts as they age. Medical marijuana laws and commercial legalization are relatively recent policies, and efforts should be taken to collect more accurate and detailed data on prices and transactions in order to assess contemporaneous and longer term effects of supply changes in the legal market.

[12]The effects of changes in legal market size may diminish as existing demand is increasingly met by current availability.

Table 3.1: Increase in Producers Following Ogden Memo, 1996-2013

State	Effective MML Date	State-Licensed Dispensaries	1st Dispensary Operational	Number Dispensaries* mid-2009	Number Dispensaries* mid-2010
Pre-Ogden: Unregulated Dispensaries					
CA	11/6/1996	1/1/2004	2003	>400	>750
CO	6/1/2001	6/7/2010	2005	<12	900
MT	11/2/2004		2009	84	482
MI	12/4/2008		2009	0	100
OR	12/3/1998	8/14/2013	11/2009	0	30
WA	11/3/1998		7/2010	0	120
Pre-Ogden: State-Licensed Dispensaries					
RI	1/3/2006	6/16/2009	4/2013	0	0
NM	7/1/2007	7/1/2007	8/2009	1	5
Pre-Ogden: No Allowances for Dispensaries					
AK	3/4/1999			0	0
ME	12/22/1999	11/3/2009	3/2011	0	0
HI	12/28/2000	7/14/2015		0	0
NV	10/1/2001	6/12/2013	7/2015	0	0
VT	7/1/2004	6/2/2011	6/2013	0	0
DC	7/27/2010	7/27/2010	5/2013	0	0
NJ	10/1/2010	10/1/2010	12/2012	0	0
AZ	4/14/2011	4/14/2011	12/2012	0	0
DE	7/1/2011	7/1/2011	6/2015	0	0
CT	10/1/2012	10/1/2012	8/2014	0	0
MA	1/1/2013	1/1/2013	6/2015	0	0
NH	7/23/2013	7/23/2013		0	0

Notes and sources: Own data collection. *Counts of unregulated dispensaries are estimates from unofficial sources. For Montana, dispensaries are defined as caregivers serving more than 10 patients. For California, estimates vary widely across sources.

Table 3.2: Effects of Growth in Legal Market on Traffic Fatalities

	Involving Driver Aged:			
	Age 15-20	**Age 21-24**	**Age 25-44**	**Age 45-64**
A: All Accidents				
Registration Rate	0.065**	0.082	0.001	-0.027
	(0.028)	(0.059)	(0.025)	(0.042)
Mean outcome	145.1	120.8	348.5	176.5
B: Weekday Accidents				
Registration Rate	0.050	0.071	0.011	-0.041
	(0.050)	(0.062)	(0.038)	(0.036)
Mean outcome	70.3	56.4	177.3	103.8
C: Weekend Accidents				
Registration Rate	0.082***	0.093	-0.009	-0.009
	(0.024)	(0.063)	(0.028)	(0.061)
Mean outcome	74.4	63.9	169.9	72.0
D: Daytime Accidents				
Registration Rate	0.047	0.155***	0.019	0.001
	(0.042)	(0.057)	(0.034)	(0.038)
Mean outcome	46.8	31.4	119.1	85.5
E: Nighttime Accidents				
Registration Rate	0.072**	0.071	-0.003	-0.055
	(0.030)	(0.079)	(0.036)	(0.050)
Mean outcome	96.8	87.8	224.1	88.6

Notes and sources: N=1176 (49 states, 24 years). Coefficients presented are from Poisson model. All specifications include state and year fixed effects, time-varying state covariates, and state-specific linear trends. Robust standard errors (in parentheses) are clustered at the state level. State covariates included are listed in Appendix Table G.1. ***p<0.01, **p<0.05, *p<0.1

Table 3.3: Effects of Legal Market Growth on Traffic Fatalities by Substance Involvement

	Involving Driver Aged:			
	Age 15-20	**Age 21-24**	**Age 25-44**	**Age 45-64**
A: BAC= 0				
Registration Rate	-0.040	0.033	-0.048	-0.013
	(0.045)	(0.050)	(0.032)	(0.055)
Mean outcome	44.9	24.8	73.0	52.5
B: BAC> 0				
Registration Rate	0.105**	0.098	0.004	-0.055
	(0.042)	(0.073)	(0.036)	(0.085)
Mean outcome	36.7	50.5	129.1	44.1
C: Tested Positive for Cannabinoids				
Registration Rate	0.060	0.287**	0.051	0.019
	(0.073)	(0.126)	(0.106)	(0.125)
Mean outcome	8.3	7.4	13.1	3.9
D: BAC> 0 and Tested Positive for Cannabinoids				
Registration Rate	0.266***	0.254***	0.103	-0.127
	(0.069)	(0.080)	(0.121)	(0.131)
Mean outcome	4.1	4.9	8.5	2.2

Notes and sources: N=1127 (49 states, 23 years). Coefficients presented are from a Poisson specification. All specifications include state and year fixed effects, time-varying state covariates, and state-specific linear trends. Robust standard errors (in parentheses) are clustered at the state level. State covariates included are listed in Appendix Table G.1. ***p<0.01, **p<0.05, *p<0.1

Table 3.4: Effects of Growth in Legal Market on Substance-Related Mortality

	Age Group		
	15-24	**25-44**	**45-64**
A: Alcohol poisoning deaths			
Registration Rate	0.029	-0.005	-0.095***
	(0.068)	(0.036)	(0.037)
Mean outcome	25.4	131.1	143.1
B: Opioid-analgesic poisoning deaths			
Registration Rate	-0.087	-0.012	-0.118***
	(0.075)	(0.064)	(0.034)
Mean outcome	44.7	207.4	216.2
C: Heroin poisoning deaths			
Registration Rate	-0.190	-0.135	-0.246**
	(0.177)	(0.096)	(0.125)
Mean outcome	19.9	71.0	47.3

Notes and sources: N=735 (49 states, 15 years). Coefficients are presented from Poisson specification. All specifications include state and year fixed effects, time-varying state covariates listed in Appendix Table G.1, and state-specific linear trends. For all regressions, robust standard errors (in parentheses) are clustered at the state level. ***p<0.01, **p<0.05, *p<0.1

Table 3.5: Alternative Empirical Specifications for Traffic Fatality Results
Coefficient from Registration Rate Variable

	Age Group							
	15-20		**21-24**		**25-44**		**45-64**	
Accident Type:	OLS	Neg Bin	OLS	Neg Bin	OLS	Neg Bin	OLS	Neg Bin
All	0.056**	0.065**	0.034	0.079	0.000	0.001	-0.062	-0.030
	(0.026)	(0.025)	(0.061)	(0.058)	(0.031)	(0.024)	(0.053)	(0.043)
N	1171	1176	1173	1176	1176	1176	1175	1176
Weekday	0.022	0.048	0.026	0.069	0.033	0.012	-0.050	-0.041
	(0.039)	(0.048)	(0.079)	(0.063)	(0.045)	(0.037)	(0.047)	(0.036)
N	1165	1176	1165	1176	1176	1176	1174	1176
Weekend	0.068*	0.083***	0.026	0.093	-0.045	-0.010	-0.080	-0.013
	(0.039)	(0.024)	(0.057)	(0.062)	(0.034)	(0.028)	(0.074)	(0.062)
N	1161	1176	1167	1176	1175	1176	1160	1176
Daytime	0.052	0.048	0.059	0.154***	0.017	0.019	-0.008	0.000
	(0.064)	(0.042)	(0.151)	(0.058)	(0.041)	(0.034)	(0.051)	(0.039)
N	1148	1176	1135	1176	1175	1176	1173	1176
Nighttime	0.092***	0.073**	0.010	0.067	-0.008	-0.004	-0.125**	-0.055
	(0.025)	(0.028)	(0.057)	(0.077)	(0.033)	(0.034)	(0.055)	(0.050)
N	1168	1176	1171	1176	1176	1176	1170	1176

Notes and sources: All specifications include state and year fixed effects, time-varying state covariates listed in Appendix Table G.1, and state-specific linear trends. For all regressions, robust standard errors (in parentheses) are clustered at the state level. ***p<0.01, **p<0.05, *p<0.1

Table 3.6: Alternative Empirical Specifications for Poisoning Mortality Results

	Age Group					
	15-24		**25-44**		**45-64**	
	OLS	Neg Bin	OLS	Neg Bin	OLS	Neg Bin
A: Alcohol poisoning deaths						
Registration Rate	0.041	0.041	-0.039	-0.019	-0.168*	-0.118***
	(0.078)	(0.070)	(0.066)	(0.046)	(0.051)	(0.039)
N	708	735	735	735	735	735
B: Opioid-analgesic poisoning deaths						
Registration Rate	0.055	-0.022	0.023	0.041	-0.162**	-0.115**
	(0.057)	(0.050)	(0.046)	(0.037)	(0.062)	(0.048)
N	690	735	731	735	732	735
C: Heroin poisoning deaths						
Registration Rate	-0.082	-0.087	-0.177	-0.135	-0.276	-0.238
	(0.328)	(0.174)	(0.111)	(0.090)	(0.228)	(0.176)
N	512	735	639	735	585	735

Notes and sources: All specifications include state and year fixed effects, time-varying state covariates listed in Appendix Table G.1, and state-specific linear trends. For all regressions, robust standard errors (in parentheses) are clustered at the state level. ***p<0.01, **p<0.05, *p<0.1

Table 3.7: Effects of Growth in Legal Market on Traffic Fatalities, Only States with MMLs Before 2015

	Involving Driver Aged:			
	Age 15-20	**Age 21-24**	**Age 25-44**	**Age 45-64**
A: All Accidents				
Registration Rate	0.076***	0.077	-0.008	-0.082**
	(0.024)	(0.062)	(0.026)	(0.038)
Mean outcome	155.9	138.0	394.8	201.0
B: Weekday Accidents				
Registration Rate	0.011	0.072	0.013	-0.077*
	(0.036)	(0.065)	(0.036)	(0.039)
Mean outcome	76.5	65.1	203.2	119.8
C: Weekend Accidents				
Registration Rate	0.135***	0.087	-0.033	-0.087*
	(0.030)	(0.065)	(0.035)	(0.048)
Mean outcome	79.0	72.4	189.5	80.2
D: Daytime Accidents				
Registration Rate	0.043	0.152**	-0.006	-0.061*
	(0.052)	(0.073)	(0.041)	(0.037)
Mean outcome	50.0	37.1	139.5	97.9
E: Nighttime Accidents				
Registration Rate	0.084***	0.063	-0.003	-0.101**
	(0.032)	(0.080)	(0.039)	(0.044)
Mean outcome	103.9	98.7	247.6	99.4

Notes and sources: N=552 (23 states, 24 years). Coefficients presented are from Poisson specification. All specifications include state and year fixed effects, time-varying state covariates, and state-specific linear trends. Robust standard errors (in parentheses) are clustered at the state level. State covariates included are listed in Appendix Table G.1. ***p<0.01, **p<0.05, *p<0.1

Table 3.8: Effects of Growth in Legal Market on Substance-Related Mortality, Only MML States

	Age Group		
	15-24	**25-44**	**45-64**
A: Alcohol poisoning deaths			
Registration Rate	0.063	0.011	-0.088**
	(0.072)	(0.051)	(0.041)
Mean outcome	30.0	166.2	191.6
B: Opioid-analgesic poisoning deaths			
Registration Rate	-0.064	0.012	-0.101**
	(0.050)	(0.044)	(0.042)
Mean outcome	52.0	247.3	288.2
C: Heroin poisoning deaths			
Registration Rate	-0.229	-0.090	-0.122
	(0.206)	(0.096)	(0.148)
Mean outcome	20.5	85.6	63.7

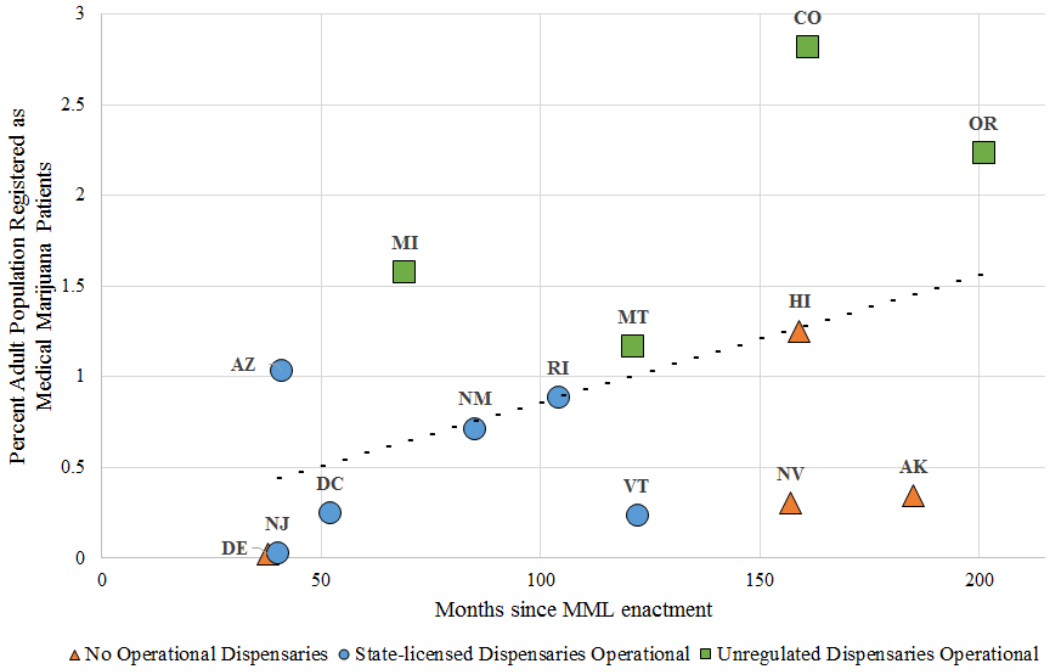
Notes and sources: N=345 (23 states, 15 years). Coefficients are presented from Poisson specification. All specifications include state and year fixed effects, time-varying state covariates listed in Appendix Table G.1, and state-specific linear trends. For all regressions, robust standard errors (in parentheses) are clustered at the state level. ***p<0.01, **p<0.05, *p<0.1

Table 3.9: Counterfactual-Actual Counts
if Registration Rates Stalled Prior to Ogden Memo (2009-2012)

	Lax Supply Restrictions		**Strict Supply Restrictions**	
	Age 15-24	Age 45-64	Age 15-24	Age 45-64
Past-month marijuana users	-73,725	-146,765	-15,779	-17,819
Traffic fatalities caused	-118	+88	-13	-10
Alcohol-poisoning deaths	-11	+244	-9	+0
Opioid-poisoning deaths	+13	+377	-6	+46
Heroin-poisoning deaths	+21	+157	-4	+35
Population (2009)	*2,748,334*	*5,381,770*	*1,190,240*	*2,263,356*

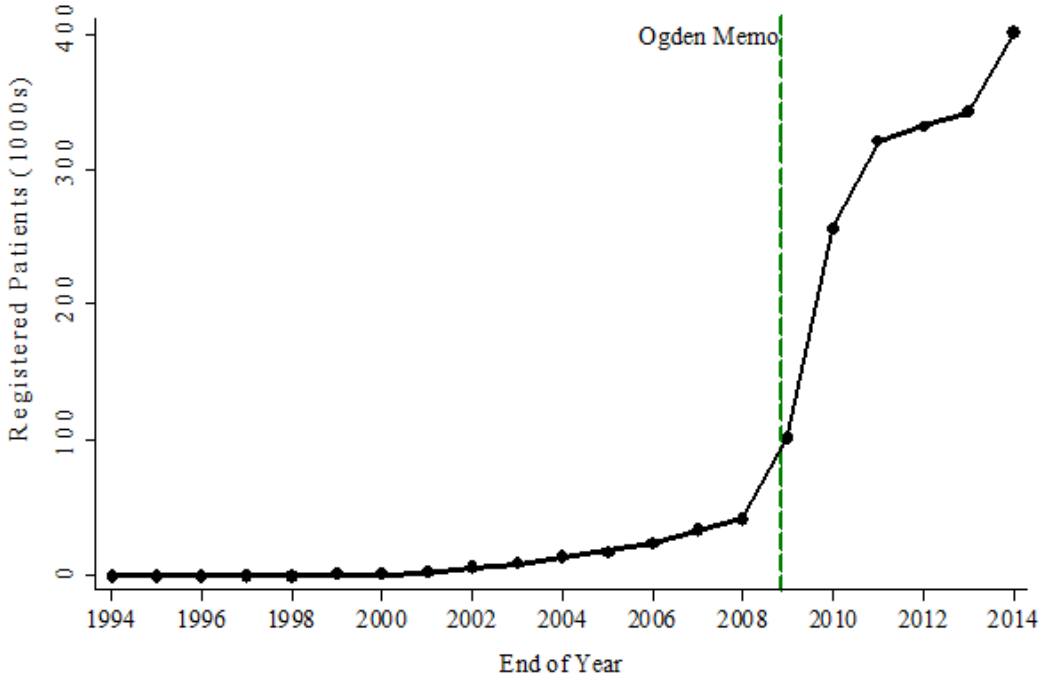
Notes and sources: Washington and Maine are excluded. California is also excluded due to measurement error in voluntary registration rates and the high share of loose-MML state population accounted for by California. Counterfactual counts were calculated by setting registered patient counts to the level at the end of 2008 and applying this number to all years forward, then predicting the outcome of interest using the specifications described in the text.

Figure 3.1: State Registration Rates (2014)



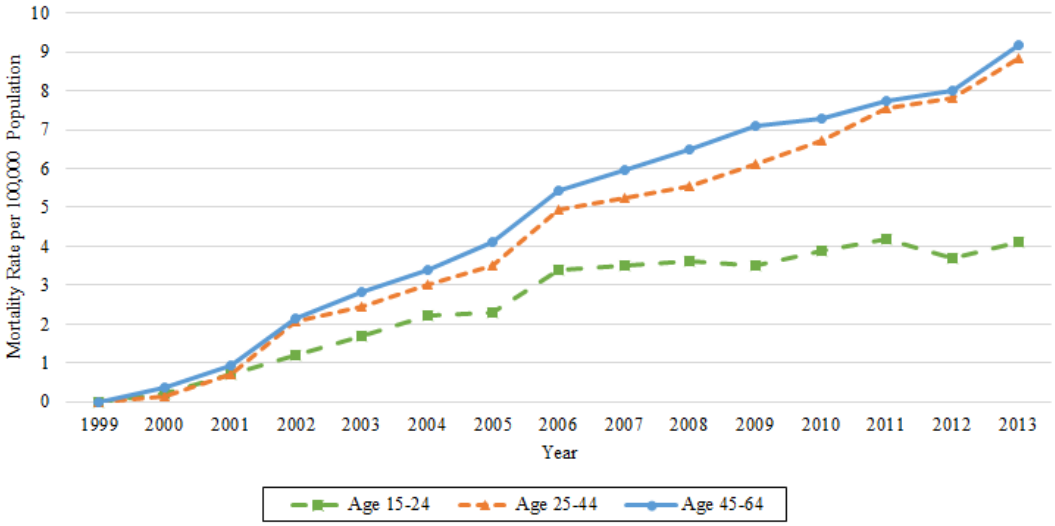
Notes and sources: Data from own collection. Dashed line is a fitted line through the scatter points.

Figure 3.2: Registration Rate Growth After Ogden Memo



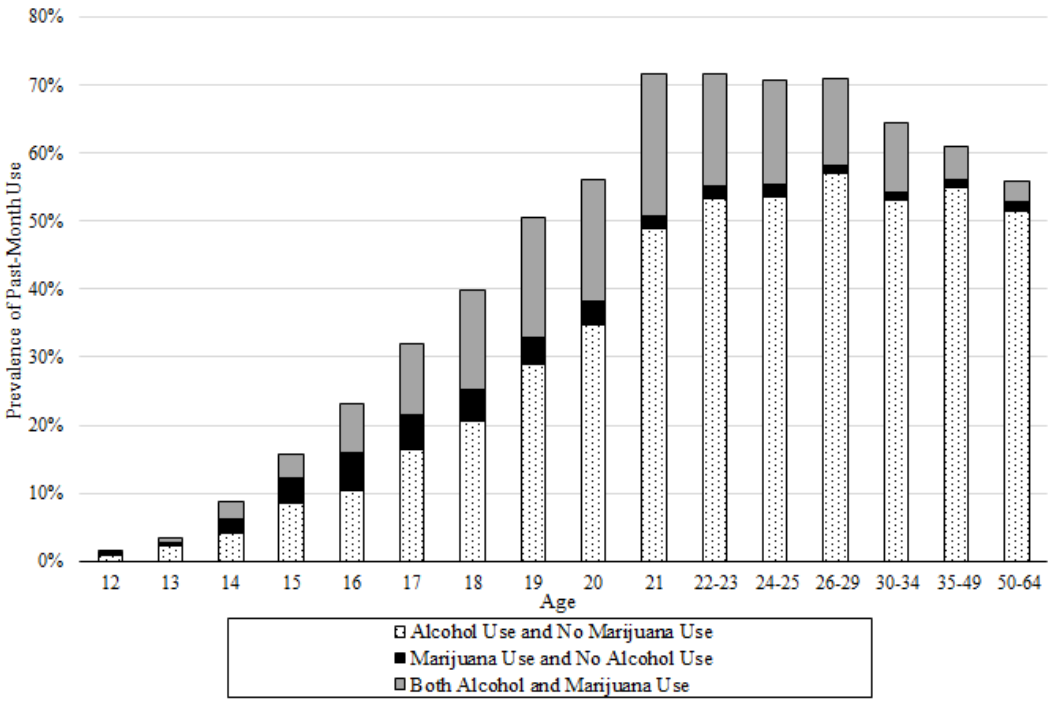
Notes and sources: Data from own collection. Registered patient counts summed over states with MMLs enacted prior to the Ogden Memo. Vertical dashed line depicts timing of the Ogden Memo.

Figure 3.3: Rising Mortality from Opioid-Related Poisonings



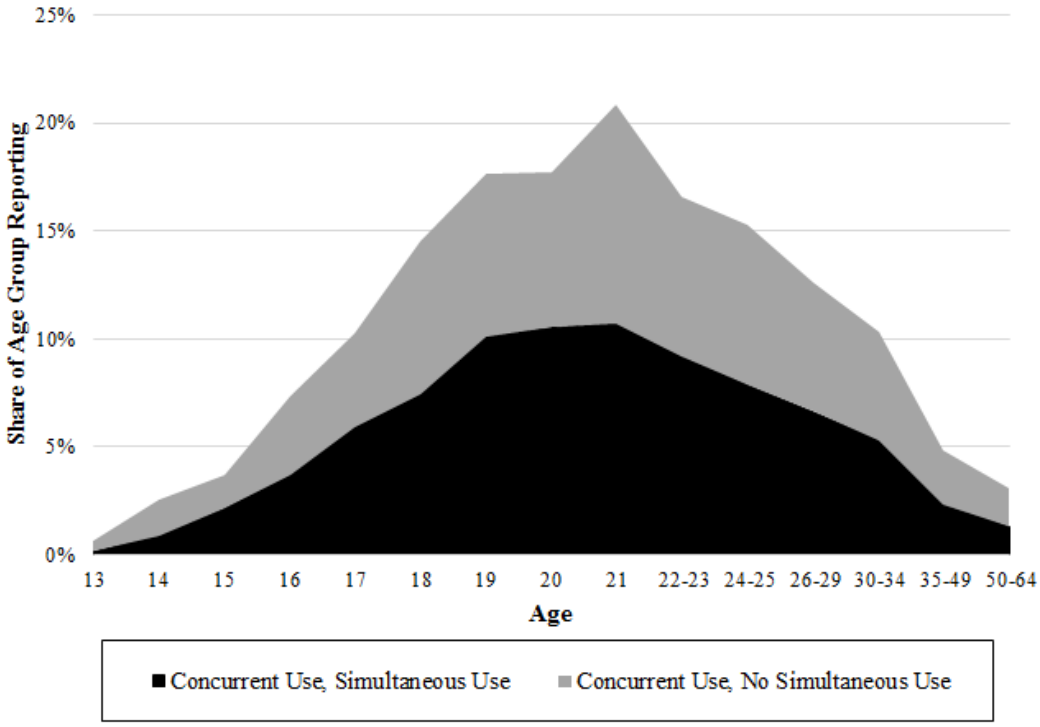
Notes and sources: Data from CDC's Multiple-Cause of Death Files. Death rates from poisoning by opioid analgesics and heroin are expressed per 100,000 of the relevant-aged population and are normalized for each age group to zero in 1999.

Figure 3.4: Age Profile of Past-Month Use of Alcohol and Marijuana



Notes and sources: Data from the National Survey of Drug Use and Health (2013).

Figure 3.5: Age Profile of Past-Month Use of Both Alcohol and Marijuana, by Whether Used Substances Concurrently



Notes and sources: Data from the National Survey of Drug Use and Health (2013). Concurrent past-month use of marijuana and alcohol is defined as those who used both alcohol (more than a few sips) and marijuana within a couple hours of each other.

3.9 Appendices

G- List of Covariates

Table G.1: List of Covariates

Variable	Available	Source
Demographics		
Share population under age 30	1990-2013	NCHS
Share population male	1990-2013	NCHS
Economic		
Unemployment rate	1990-2013	Bureau of Labor Statistics
Ln(Real state per capita income)	1990-2013	Bureau of Economic Analysis
Ln(Population)	1990-2013	Census Bureau
Substance-Related Policies		
Decriminalization law	1990-2013	Alford (2013)
Ln(Real beer tax)	1990-2013	*Brewers Almanac* (Beer Institute)
Ln(Real cigarette tax)	1990-2008	Impacteen.org
	2009-2013	TaxFoundation.org
BAC 0.08 law	1990-2013	NHTSA
Other Traffic-Related Policies		
Vehicle miles driven	1990-2013	*Highway Statistics* (USDOT)
Graduated driver licensing law	1990-2013	IIHS
Administrative license revocation law	1990-2013	NHTSA
Texting ban law	1990-2013	McCartt et al. (2014)
Hands-free cell phone law	1990-2013	McCartt et al. (2014)
Primary seat-belt law	1990-2013	Cohen and Einav (2003)
		IIHS
Secondary seat-belt law	1990-2013	Cohen and Einav (2003)
		IIHS
Drug per se law	1990-2013	NHTSA
Zero tolerance law	1990-2013	NHTSA

Traffic-related policies are only included in the regression analysis of the effects on traffic fatalities. NCHS: National Center for Health Statistics, NHTSA: National Highway Traffic Safety Administration, USDOT: U.S. Department of Transportation, IIHS: Insurance Institute for Highway Safety.

H- Summary Statistics

Table H.1: Summary Statistics for Traffic Fatality Rates, by Driver Age and MML Status

		All States	Registration>0	Registration=0
Aged 15-20:	All	2.78	1.82	2.94
		(1.29)	(0.68)	(1.29)
	Weekday	1.49	0.96	1.58
		(0.70)	(0.37)	(0.70)
	Weekend	1.29	0.85	1.36
		(0.63)	(0.34)	(0.63)
	Daytime	1.24	0.78	1.31
		(0.63)	(0.32)	(0.63)
	Nighttime	1.53	1.03	1.62
		(0.71)	(0.39)	(0.71)
Aged 21-24:	All	2.29	1.72	2.39
		(0.87)	(0.47)	(0.88)
	Weekday	1.20	0.89	1.25
		(0.47)	(0.28)	(0.48)
	Weekend	1.09	0.82	1.13
		(0.43)	(0.23)	(0.44)
	Daytime	0.91	0.66	0.95
		(0.40)	(0.21)	(0.41)
	Nighttime	1.37	1.04	1.42
		(0.51)	(0.29)	(0.52)
Aged 25-44:	All	7.13	5.12	7.47
		(2.80)	(1.40)	(2.84)
	Weekday	4.08	2.89	4.29
		(1.61)	(0.84)	(1.63)
	Weekend	3.03	2.21	3.18
		(1.24)	(0.60)	(1.27)
	Daytime	3.42	2.43	3.59
		(1.42)	(0.75)	(1.44)
	Nighttime	3.66	2.63	3.83
		(1.47)	(0.71)	(1.49)
Aged 45-64:	All	4.40	3.58	4.54
		(1.60)	(0.98)	(1.64)
	Weekday	2.78	2.20	2.88
		(1.02)	(0.61)	(1.05)
	Weekend	1.61	1.37	1.65
		(0.62)	(0.41)	(0.64)
	Daytime	2.63	2.08	2.72
		(1.01)	(0.66)	(1.03)
	Nighttime	1.75	1.46	1.80
		(0.66)	(0.38)	(0.68)
Observations		1176	143	1033

Notes and sources: WA and ME excluded. Data from the Fatal Accident Reporting System (FARS) from 1990-2013. Means are weighted by state-year population and standard deviations are given in parentheses.

Table H.2: Summary Statistics for Poisoning Mortality Rates, by Age Group, Substance, and MML Status

	All States	Registration>0	Registration=0
Aged 15-24:			
Alcohol	1.66	1.49	1.70
	(1.14)	(1.09)	(1.15)
Opioid Analgesic	2.73	2.37	2.82
	(2.06)	(1.76)	(2.12)
Heroin	1.11	1.10	1.11
	(1.17)	(1.23)	(1.52)
Aged 25-44:			
Alcohol	4.06	4.05	4.06
	(2.15)	(2.44)	(2.07)
Opioid Analgesic	6.51	5.95	6.65
	(4.77)	(3.45)	(5.04)
Heroin	2.02	2.31	1.95
	(2.21)	(2.00)	(2.26)
Aged 45-64:			
Alcohol	4.62	5.81	4.32
	(2.33)	(2.56)	(2.17)
Opioid Analgesic	6.75	8.62	6.28
	(4.51)	(4.21)	(4.46)
Heroin	1.32	2.16	1.11
	(1.30)	(1.25)	(1.23)
Observations	735	140	595

Notes and sources: WA and ME excluded. Data from NCHS Multiple-Cause-of-Death files (accessed through the CDC WONDER system) from 1999-2013. Rates are per 100,000 of the relevant aged population. Means are weighted by relevant-aged state-year population and standard deviations are given in parentheses.

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