Flying High?
Legalization and the Black Market for Cannabis *

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Job Market Paper

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Abstract

How does legalization affect the black market for cannabis? I assemble a novel dataset on US city-level prices and THC potencies, used as proxies for quality, in both prohibition and legalization environments. Difference-in-difference and event-study analyses show that legalization yields an immediate and sensible drop in equilibrium prices (up to 18%), as well as a delayed and limited (up to 2%) increase in equilibrium quality. This effect on price is driven by medium potency products being subject to important decreases in price, whereas the price of the most potent products increases *ex-post*. This heterogeneity suggests legalization selecting high potency products on the black market. While the empirical literature has overlooked consumer preferences for cannabis quality, policy design cannot ignore this dimension. To better understand how quality affects the demand and supply of cannabis, I complement the analysis by evaluating a structural model accounting for quality, combining administrative data on legal prices and consumption microdata for the state of Washington. Cross-price elasticities of consumption between legal and illegal cannabis are relatively small. However, changes in THC potency yield sensible substitution between the two products. Counterfactual analysis presents high quality provision as a creditable tool to drive illegal retailers out of the market.

Keywords: cannabis, legalization, policy, demand estimation

JEL Classifications: D12, H80, I18, K49, L19, L51

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1 Introduction

In response to the rising concern about the efficiency of the *War on Drugs*, the last decade has seen an acceleration in the global movement to liberalize cannabis. The year 2012 primed this movement with the states of Colorado and Washington then voting "yes" to legalization. As of fall 2021, such policy changes have spread to sixteen other states and the District of Columbia.[1] While these policies have mirrored various government priorities, they gather around one common goal: counteracting the black market and its inherent negative externalities.

Although the legal market is theoretically able to drive the smugglers out of business, there is little empirical evidence on the extent to which existing policies have achieved this goal. Analyzing changes in cash circulation around the Canadian legalization, Goodhart and Ashworth (2019) suggest sensible damage to the black market. On the other side of the Atlantic, an unintended experience of cannabis liberalization in Italy decreased revenues from cannabis sales on the illegal market by 90-170 million euro (Carrieri et al., 2019).

A number of key empirical issues hinder estimating the effects of legalization on the demand for black market cannabis. These indeed rely on consumers substitution patterns between the legal and the illegal sectors; the estimation of which requires information on products from both sectors within the same market. Due to its illegal – and thereby hidden – nature, seeking data on the black market is particularly challenging. Most data sources on illegal cannabis used by governments and researchers are surveyed or crowd-sourced. Most of them focus on prices and either ignore quality (e.g. the National Survey on Drug Use and Health) or rely on self-assessed discrete categories for quality (e.g. crowd-sourced data from `www.priceofweed.com`[2]). Yet, because the black market for cannabis features high vertical differentiation (Červenỳ and van Ours, 2019), studying the market for cannabis requires objective information on quality. Finally, such an analysis calls for modeling the simultaneous equilibrium interactions between the two markets. This involves obtaining information on cannabis consumption; which remains sensitive, even though social norms have been evolving, and constitutes then another data requirement challenge.

In this paper, I investigate the ability of legalization policies to eradicate the black market. I digitize a novel dataset on city-level crowd-sourced cannabis prices

[1] Around the world, the recreational use of cannabis is now legal in Uruguay, Canada, South-Africa, Georgia and Mexico.

[2] The possibility to browse price data by strain on this website was not available until 2021.

and strains in the US, known as the Trans-High Market Quotation (THMQ). I match these strains with their expected THC potency levels, which I scrappe from Leafly's online cannabis consumer guide. These objectively capture quality.[3] To analyze the interactions between the illegal and the legal market, I complement this dataset with two additional data sources: legal retail prices from the Washington State Liquor and Cannabis Board (WSLCB) and the Behavioral Risk Factor Surveillance System (BRFSS).[4] This provides me with local prices and quality for both sectors, as well as local cannabis consumption across the state of Washington. Exploiting these data, I model equilibrium responses to legalization using reduced-form and structural methods.

The first part of this work quantifies average black-market price and quality responses to legalization and the implementation of retail sales for legal cannabis. It relies on the THMQ data. Difference-in-difference and event-study estimations show legalization reforms are responsible for the equilibrium black-market prices dropping by up to 18% and THC potency rising by almost 2%. Legalization mechanically enhances competition, bringing down the price-cost margin of black-market cannabis. However, this result is driven by medium potency black market products, which are subject to important drops in prices *post-legalization*. This is not the case for higher potency products. These display zero to positive change in price. This reduced-form analysis confirms the ability of the black market to respond to the legal retail market by combining price and quality adjustments. However, it does not allow to confirm whether the illegal market thrives or shrinks. In a scenario where the price for legal cannabis is "too high" for the legal market to compete efficiently with illegal market, the black market could still respond to the legal market by reducing its price and flourish (see Auriol et al., 2020).

Based on the reduced-form evidence, I propose a strutural model of cannabis supply and demand to study the role of price and quality changes induced by legalization. Consumers value price and quality, both on which retailers compete. The core of the analysis relies on a random utility discrete choice model evaluating the choices of consumers in the state of Washington. I estimate the price-elasticity

[3]Using purity or potency as a measure of quality is relatively standard in the literature on drugs (see for example Galenianos and Gavazza, 2017)

[4]This annual health survey is conducted by the Centers for Disease Control and Prevention (CDC) and collects state data about US residents.

of participation[5] to the black market to lie between -0.2 and -0.3.[6] The elasticity of participation to the legal market is around -0.5. While I find low substitution between the legal and the illegal products with respect to price, consumers are more likely to switch between products upon changes in THC potency. Counterfactuals enable to characterize eviction price and quality strategies for legal cannabis, such that the black market does not survive.

The contribution of this paper to the literature on cannabis legalization is twofold. While the social effects of policy changes have been largely investigated, few projects have quantified the responses of consumption to combined changes in policy and product characteristics. This work further contributes to the literature by being the first to provide estimates for consumer sensitivity with regards to changes in quality (here measured by THC potency).[7] This dimension in consumer preferences has been overlooked in the literature, which has focused on sensitivity to price, availibility and risk.

Following the 2010s wave of legalization, a new strand of literature has studied the reactions to policy changes in terms of crime and consumption. Liberalization policies have resulted in local (Dills et al., 2017; Dragone et al., 2019; Brinkman and Mok-Lamme, 2019) and trans-border decreases in drug trafficking crime (see Morris et al., 2014; Gavrilova et al., 2019; Chang and Jacobson, 2017, for the example of the US-Mexico border). While cannabis legalization shows the intended effects of reducing the negative externalities associated with prohibition, it also increases overall use, as highlighted by Miller et al. (2017) using survey data on undergraduate students at Washington State University.

Three channels drive this effect: price, risk and availability. Most saliently, legalization creates a *riskless* alternative for cannabis consumption and causes the risk of getting caught for illegal consumption to practically disappear.[8] Therefore, since cannabis consumers respond to risk (Jacobson, 2004), they naturally tend to consume more. Retail sales make cannabis more available, granting easier access

[5] The price-elasticity (respectively quality-elasticity) of participation is defined by the variation in the extensive margin of consumption following a 1% change in price (respectively quality).

[6] This is in line with the results of Jacobi and Sovinsky (2016).

[7] Data have limited other work to discrete measures of quality. Davis et al. (2016) include an indicator for self-assessed high quality in their analysis, while Jacobi and Sovinsky (2016) differentiate "leaf", "head" and "hydro" product types. In my data, quality is objective and continous; which enables me to evaluate elasticities of demand with respect to this dimension.

[8] Under prohibition, simply possessing cannabis is illegal and, hence, liable to sanctions. The legal status of cannabis decreases this risk, making illegal transactions more difficult and more costly to detect.

to the substance. Using a structural model of demand, Jacobi and Sovinsky (2016) extrapolate that stigma and availability effects of legalization would cause cannabis use to increase by 48%. While responses to risk and availibility are well documented, analyses led under prohibitive frameworks miss part of the information necessary to assess retailers' strategic responses. Retail sales of legal cannabis introduce competition with the illegal market, which reacts by setting lower prices. Since both the intensive (Davis et al., 2016; van Ours and Williams, 2007) and the extensive (Jacobi and Sovinsky, 2016) margins of consumption for black-market cannabis are sensitive to price, this strategic response drives up consumption, Consumers are also sensitive to the price of legal cannabis (Hansen et al., 2017; Hollenbeck and Uetake, 2021). While price reveals to be a potential tool for regulating the market for licit cannabis, the literature has focused on either the black market under prohibition or the legal market. This paper is the first to combine information on both illegal and legal products simultaneously to directly evaluate the impact of legalization on the demand for illegal cannabis.

The sensitivity of consumers to prices provides governments with pricing tools able to reduce increases of consumption induced by legalization (like suggested by Auriol et al., 2020). Taxing legal cannabis not only provides governments with fiscal revenues, it also enables to adjust the price of legal cannabis – and thereby curb use. Hollenbeck and Uetake (2021) show that the retail market for cannabis in the state of Washington, where taxes reach 37%, is still on the upward sloping portion of the Laffer curve. In addition, targetting a given level of consumption through price regulation yields higher social welfare than when employing supply quotas (Thomas, 2019). However, heterogenous effects of legalization on the price of black-market cannabis suggest the equilibrium response of the black market potentially involves the selection of higher potency products, which are more harmful (Di Forti et al., 2019). Quantifying the preferences for potency is therefore key to design legalization policies. The structural results of this paper on both price and quality preferences allow to explore alternative counterfactual policies aimed at eliminating the black market. I show that when the legal sector only competes in price, it has to sacrifice traceability requirements and controls to be able to eradicate the illegal retailers. Enhancing the quality on the legal market overcomes this trade-off.

This document is organized as follows. Section 2 describes the data used in this project. I describe the relationship between the market equilibrium dynamics in terms of prices and THC potencies and the legal status of cannabis in Section 3, employing reduced-form techniques. The structural demand model appears in Section 4. Finally, Section 5 discusses the results, the possible extensions of this work and concludes.

2 Data

This section presents the data used throughout the project. I use a combination of three data sources. Black-market prices on which I focus in the first part of this work were retrieved from *High Times'* Trans-High Market Quotation (THMQ). In the second part of the project, I add detailed administrative data on the retail market transactions for legal recreational cannabis in the state of Washington from the Washington State Liquor and Cannabis Board (WSLCB), along with consumption and health data from the Washington State Behavioral Risk Factor Surveillance System (BRFSS) survey and the THMQ data for this state. Combining both prices on the black market and retail prices for licit cannabis with consumption data enables me to estimate substitution patterns between legal and illegal cannabis after legalization. These data sources are described below, with larger detail provided on the THMQ data, since it has been scarcely used in the literature – while data on retail transactions from the the WSLCB was recently used in several IO papers (Hollenbeck and Uetake, 2021; Hansen et al., 2017; Thomas, 2019) and the BRFSS has been well established as a data source in the Health Economics literature.

Consumption data from the WA BRFSS

The BRFSS is a state-based yearly survey, conducted throughout the United States and their territories. The survey is partnered with the Centers for Disease Control and Prevention (CDC) to ensure federal and state public health surveillance. In particular, it aims at monitoring individual health behaviors and conditions, as well as preventive health services.

I use the Washington State BRFSS data, from 2011 to 2017. This micro data includes core questions on individual demographics, socio-economic background and general health. It also includes indicators of extensive margins of cannabis consumption: these consist in two binary variables indicating whether an individual has used cannabis in the past month or year. Since the BRFSS does not provide information on cannabis prices, I combine this data with the price data for the legal and the illegal markets described in the following paragraphs.

Legal prices from the WSLCB *seed-to-sale* tracking system

The data on legal prices come from the Washington State Liquor and Cannabis Board (WSLCB), which is the administration in charge of regulating Washington's retail cannabis market.

All transactions from the implementation of the legal retail market for cannabis, up to 2017, were to be registered in the government *seed-to-sale tracking system* BiotrackTHC. [9] This requirement has aimed at easing traceability and controls of the legal market, protect consumers and fight against the *grey economy*. Each plant or clone, is given a unique 16 digit identifier at the cultivation stage. This identifier records all relevant information relative to the growing and plant maturation process. After harvest, all cannabis components and derivatives are organized in batches. These batches are then assigned another 16 digit identifier, which is linked to the plant identifier – and hence the information it contains. Once at the dispensary, each individual product is given a new code, which is itself linked to the batch.

The data I use accounts for all retail transactions for legal cannabis in the state of Washington from 2014 to 2017. Each observation corresponds to a product sold at the retail level. It contains the retailer license code, the date of transaction, the product type, its strain, prices – both at the upstream and downstream levels – and quantities sold. [10] I aggregated this data into local price indices, at the Metropolitan Statistical Area level (see Appendix B.1 for detail).

Black market prices from the THMQ data

The Trans-High Market Quotation (THMQ) data is collected by the *High Times* magazine. This monthly magazine was first published in 1974 and aims at informing and diverting cannabis *aficionados*. It advocates for the legalization of a safe cannabis industry and takes part to the legalization activist movement through sponsored events.

High Times readers are encouraged to share information on the street value of cannabis, as well as, more scarcely, other drugs. Consumers, sometimes along with retailers, would then submit data on the current market and their transactions,

[9] In 2017, the WSLCB decided to end its partnership with Biotrack and since then *seed-to-sale* in Washington has been contracted to Leaf Data Systems.

[10] To allow for comparison between quantities of dried cannabis and concentrates, the data includes information of *usable weight*, which refers to the amount of dried cannabis that can be smoked directly, in addition to the variable *weight*.

including the state, city, strain, price and quantity of the purchase. This data is then selected by the magazine team into a monthly price index.

Black-market transaction data used in the literature until now has mainly relied on relatively short-term spanned data from questionnaire surveys or online crowd-sourced data such as priceofweed.com (as in Davis et al., 2016). This data has also been used by governments, such as Canada. Another source of data for cannabis prices is the System to Retrieve Information from Drug Evidence (STRIDE), managed by the Drug Enforcement Administration (DEA). However, this data is obtained from undercover buys made by DEA agents. It reflects interactions between law enforcement and targetted suppliers, whereas self-report sources provide information on prices paid by users. Since most transactions occur between people who are already acquainted (Caulkins and Pacula, 2006), the choice of crowd-sourced data, such as the THMQ, could better represent the prices paid by consumers. While the website priceofweed.com was launched in 2010, i.e. at the verge of the first legalization wave, the *High Times* magazine has been monthly publishing the THMQ for nearly fifty years. This index for black-market prices has become well established in the pool of cannabis consumers, as well as an advantageous data source for studies covering long periods of time.

The THMQ is an unbalanced panel of prices, classified by state. To each state is associated one or several locations – usually a city – to which is associated in turn at least one cannabis strain and its corresponding price. Recent versions of the THMQ usually display prices per ounce, as in Figure 1. Older versions, as in Figure 2, provide more detail and quantity-price couples and thereby possible quantity discounts.

I collected the THMQ data covered in the *High Times* issues from January 1999 to February 2019 – partly using Optical Character Recognition (OCR), yet mostly manually, due to the fuzzy data organization in most issues. The prices listed are usually collected 3 months before the magazine is issued. Dropping the observations relating to other drugs than cannabis and outside of the United-States, this data set includes 10, 379 prices covering all the states as well as the District of Columbia. Computing the average price per ounce at which each product (strain) is sold in each location at a given point of time yields a dataset of 8,918 observations.

Information on strain is relatively specific to the THMQ data – compared to other data sources on *illegal* cannabis prices. Strains do not only represent different kinds of plants and tastes, they also reflect diverse THC potencies. In the literature

TRANS HIGH MARKET QUOTATIONS

STATE	CITY	STRAIN	PRICE
ALABAMA	Prattville	Northern Lights #5	$285
ARKANSAS	Little Rock	Tahoe OG	250
ARIZONA	Phoenix	Grape Ape	350
CALIFORNIA	Los Angeles San Francisco	Kosher Kush Guava Chem	300 320
COLORADO	Denver Pueblo	Blue Dream Ghost Train Haze	300 250
CONNECTICUT	Hartford	Trainwreck	360
FLORIDA	North Port	Lamb's Bread	250
GEORGIA	Atlanta	Juicy Fruit	380
HAWAII	Maui	Northern Lights	360
ILLINOIS	Chicago	Gorilla Glue	380
INDIANA	Indianapolis	Critical+	380
IOWA	Des Moines	Death Star	350
KENTUCKY	Albany	Lithium OG Kush	300
LOUISIANA	New Orleans	Skywalker OG	400
MAINE	Portland	Sour Diesel	260
MARYLAND	Baltimore	Blue Dream	380
MASSACHUSETTS	Provincetown	Dakini Kush Girl Scout Cookies	240 240
MICHIGAN	Ann Arbor	Deadhead OG	350
MINNESOTA	Minneapolis	Purple Haze	375
MISSISSIPPI	Oxford	Master Kush	380
MONTANA	Helena	Blue Dream	330
NEVADA	Las Vegas	Three Kings	380
NEW JERSEY	Trenton	Tahoe OG	380
NEW YORK	New York Brooklyn	Gorilla Glue #4 Strawberry Cough	375 360
NORTH DAKOTA	Fargo	Funky Monkey	300
OHIO	Columbus	G-13	360
OREGON	Portland	Goji OG	250
PENNSYLVANIA	Philadelphia	Grand Daddy Purp	400
TENNESSEE	Nashville	Mids Hydro	130 300
TEXAS	Austin	East Coast Sour Diesel	380
UTAH	Salt Lake City	Jedi Kush	360
VERMONT	Bennington	Tangerine Dream	320
VIRGINIA	Richmond	Super Silver Haze	380
WASHINGTON	Seattle	Godfather OG	260
WISCONSIN	Madison	Banana Kush	375
INTERNATIONAL			
CANADA	Montreal Toronto	Bruce Banner Girl Scout Cookies	$C180 150
BELGIUM	Brussels	Jack Herer Casey Jones	€227 227
UNITED KINGDOM	Birmingham	Cheese	£300

Figure 1: THMQ for the September 2017 issue of *High Times*

OHIO

Youngstown: Commercial Brown Brick, "Smells bad, looks bad, tastes bad, but man, did it ever fuck me up, nice quick high, shared four bowls with my four buds, and we were hitting on the mailbox": **$20** 1/4-oz; **$40** 1/2-oz; **$80** oz.

Avon: Kind Buds, "Said to be AK-47 but I am uncertain, bright-green with a great piney taste, fat, dense nuggets with bright-orange hairs and many crystals, uplifting four-hour high off two or three hits": **$50** 1/8-oz; **$100** 1/4-oz; **$400** oz.

North Canton: The Grape, "Light-green and completely covered in crystals, smells like somebody opened up a jar of Smucker's": **$100** 1/4-oz.

Afghani, "A friend in town grew this bud, the buds from this plant are absolutely gorgeous, he got the seeds from a friend in Athens and definitely did well with them, this is the best Afghani around, unfortunately, it's grown only for personal use": **FREE!**

B.C. Buds, "Seeds from this herb came straight from British Columbia, buds are dense, covered in crystals, and large, killer on the head": **$185** 1/2-oz; **$350** oz.

NEW JERSEY

Brick: Blueberry Hydro, "Green nugs with a hint of blue, hairy as hell, loaded with crystals, packs a delightful fruity taste, two hits is more than enough to do the trick": **$65** 1/8-oz.

PENNSYLVANIA

Sayre: RuPaul Bud, "Dark-purple buds with yellow hairs, good high that lasts about five hours with an intense 30-minute plateau": **$75** 1/4-oz; **$125** 1/2-oz; **$210** oz.

Pittsburgh: Kind Nugs, "The buds are dark with a strong musty odor, plenty of hairs and no seeds": **$60** 1/8-oz; **$300** oz.

TENNESSEE

Oak Ridge: Commercial Bud, "Killer shit, great high, one joint will do it, this stuff is really cheap": **$105** oz.

LSD, gel-tabs, "Dark-purple gels, good trip, lasts about 6-8 hours": **$6**/hit.

Oak Ridge Killa, "Light-green, not much smell to it, but it comes through the back door on ya', roll a phatty and get gone!": **$60** 1/2-oz; **$110** oz.

Murfreesboro: Schwag, "Compressed, short-lived buzz, get ya' high but not stoned, this one's good for everyday smoking, going to work and catching a daytime buzz": **$25** 1/4-oz; **$100** oz.

ILLINOIS

Clarendon Hills: White Widow, "Don't buy into this bullshit, nice popcorn puffy buds and a good smoke but not worth the price, better-than-average high with an easy comedown period": **$30**/gm.

Wonka, "This is some quality greenery, one of the longest-lasting highs I have ever experienced, after eight hours you feel so clean that you are in love with everything": **$60** 1/4-oz.

Oak Park: Decent Schwag, "This is OK shit, a few bong rips will get you fucked up, cheap": **$70** oz.

Ecstasy, "Stickman": **$25-$30**/tab

NEW YORK

Buffalo: Killer Green, "*Sativa*, decent-size buds, not the best shit, but it works, a joint does the trick, this one's a C-r-e-e-p-e-r, these are decent buds at a decent price": **$90** oz.

Nasty-Ass Schwag, "Brown, stems, seeds and it smells like dogshit! Sorely lacking hairs and crystals, bricked like a house, can't tell you about potency because I won't touch the shit, get the green, it's a better deal": **$35** 1/4-oz; **$110** oz.

Skunk, "A joint of this and you will stink for a week, knocks you off your chair and right on your ass, the real two-hit shit here, no deals on quantity": **$100** 1/2-oz; **$200** oz.

Schwag #2, "It looks good, it smells good, it tastes good, but it's just not kind bud, got me buzzed for a half hour and then sent me straight to bed, the price on this shit is outrageous, it's more than the Skunk!": **$250** oz.

'Shrooms, "No review, but available": **$100** oz.

KENTUCKY

Louisville: Commercial, "Green buds with plenty of seeds, decent buzz and worth the price": **$35** 1/4-oz; **$65** 1/2-oz.

NORTH CAROLINA

Charlotte: Nice Green Bud, "A few seeds, some orange hairs, excellent taste and aroma, about 3-4 hits for a nice 2-3 hour buzz": **$40** 1/4-oz; **$70** 1/2-oz; **$120** oz.

HAWAII

Maui: Puna Butter, "The real deal, avocado in color, nice smell, one bowl from the pinch-hitter and you're very blind, only one seed in the whole, I germinated it, then it died (sniff, sniff)": **$100** 1/4-oz.

Backyard Greens, "My third crop, it's coming along and it gets you pleasantly stoned, unavailable on the market, I grow it for myself, you sure can't beat the price!": **FREE!**

WASHINGTON

Tacoma: Bubblegum, "Tasty killer green bud, gets you so loaded you forget to REBAKE until hours later, it has a light green that almost belongs on *The X-Files*, a nuclear-green glow as well as a nuclear high, hard to wipe the grin": **$40** 1/8-oz; **$350** oz.

Vancouver: Purple Buds, "Fields of crystals coating dark gray nugs, top-quality buds with a top-quality stone, two tokes and you know why they call it the Evergreen State!": **$50** 1/8-oz; **$345** oz.

Chemo, "Giant colas, fuzzy, light-green with large calyxes and dark-green leaves, all covered with a thick layer of crystals, tastes like no other and burns slow and long": **$45** 1/8-oz; **$310** oz.

Beaster, "B.C. mid-grade commercial hydro, mostly popcorn buds with an occasional big bud, nice smell and a decent taste, when you can't get any Washington ganja this is what to get, always around, always gets you stoned and fairly priced": **$80** 1/4-oz; **$220-$250** oz.

'Shrooms, "Nice Northwest closed caps that send you to the other side, lots of blue stems and phat caps": **$20** 1/8-oz; **$100** oz; **$300** 1/4-lb.

GUYANA

Georgetown: Amazonian Heritage Weed, "Nice smooth high, sometimes it can be a bit harsh due to inadequate handling and drying, but this is no dirtweed, though a bit seedy, these prices are for real!" **$5-7** oz; **$20** 1/4-lb; **$55-60** lb.

Jamaican, "From Mt. Roramina, has a heritage from the Blue Mountains of Jamaica, crossed with some native Amazon, nice high": **$50** lb.

Figure 2: THMQ for the December 1999 issue of *High Times*

on markets for illicit drugs, measuring quality by using potency or purity is relatively conventional (see for instance Galenianos and Gavazza, 2017). For this reason, I paired the observed cannabis strains with THC potencies scrapped from the website `leafly.com`. [11] Appendix B.2 provides detail on how the data were cleaned and matched.

3 The black market going to pot?

This section provides reduced-form results on the black market equilibrium response to legalization. Two strategic outcomes are observed: price and quality.

As one would expect, legalization causes the price for black market cannabis to drop. The newly retail market for legal cannabis introduces competition with the illegal market. Further, legalization introduces licit products which could be diverted to the illegal market, while making illegal behavior more difficult to detect. It could thereby lower barriers to enter the black market and atomize its supply. I first assess the effect of cannabis legalization policies on the illegal price, employing an event-study method. This provides a sense on the magnitude and permanence of the impact of cannabis legalization reforms.

On quality, difference-in-difference estimation on prices and THC potency show that operating legal retail sales of cannabis seems to yield higher quality on the black market. This supports the hypothesis of the black market becoming more competitive and responding to legalization by price and quality differentiation.

However, one should keep in mind that these are equilibrium results; in particular the effects of legalization on supply could be outweighed by a boom in demand following the reform.

3.1 Black market response to legalization

I enquire how the equilibrum price and quality on the black market for cannabis evolve after legalization, using an event-study type of analysis. Quality is measured by THC potency, which was matched to strains using information from Leafly's strain browser. This exercise allows to distinguish short-term effects from long-term effects of cannabis policies on the illegal market. Shedding light on the permanence

[11] This website is one of the largest online cannabis consumer guides. Among other things, it produces a cannabis strain explorer, which, along with crowd-sourced information on effects and reviews, provides the average expected THC potency for each strain.

of such responses provides hints about the temporality of the market responses of both the illegal supply and the demand; and how fast one they would adapt to structural changes in the cannabis market.

Consider the following econometric model:

$$y_{ist} = \sum_{\tau=-q}^{m} \beta_\tau D_{st}^{\tau} + \theta_s + \psi_y + \epsilon_{ist} \tag{1}$$

where y_{ist} is the outcome of interest for observation i collected in state s during month t, θ_s is a state-level fixed effect, ψ_y is a year fixed effect, [12] and ϵ_{ist} is a state-level error term that may exhibit within group correlation but is independent from the other regressors.

In particular, y_{ist} alternatively designates the logarithm for the price per ounce of black market cannabis i, the logarithm of its THC potency or the difference between the two logs.

The D_{st}^{τ} are a series of "event-time" binary variables that equal one when the legalization policy is implemented τ quarters away in state s; formally:

$$D_{st}^{\tau} \equiv \begin{cases} \mathbb{1}\left[3(\tau-1)+1 \leq t-e_s \leq 3\tau\right] & \text{, if } \tau \geq 1 \\ \mathbb{1}\left[3\tau \leq t-e_s \leq 3(\tau+1)-1\right] & \text{, if } \tau \leq -1 \end{cases} \tag{2}$$

with e_s being the time at which legalization came into effect in state s.

The coefficients $(\beta_\tau)_{\tau\in\{-q,\dots,m\}}$ estimate the time path of the average price per once of cannabis before ($\tau = -q, \dots, -1$) and after ($\tau = 1, \dots, m$) legal recreational use of cannabis is implemented ($t = e_s$), conditional on state- and year- fixed effects. Legalization being randomly implemented, conditional on the fixed effects, implies that legalization should not be preceded on average by any geographical-specific trend in average cannabis prices. Formally:

$$\beta_\tau = 0, \forall \tau < 0 \tag{3}$$

I estimate the model described by equation (1) using ordinary least squares, including a set of event-time binary variables along with binary variables for the

[12] Given the number of observations, I chose to use fixed effects at the year level, in contrast to a finer level. This decision is also motivated by the fact that most ballots are voted in November, which would cause month or quarter effects to be correlated with the binary variables describing legalization policies.

state and year-fixed effects. Standard errors are clustered at the state level, to correct for eventual intra-state correlation. In the presence of geographical fixed effects, all the coefficients β_τ are perfectly collinear. For this reason, I restrict the estimation to a window covering 18 months before and 24 months after the date of policy implementation; formally $\tau \in \{-6, ..., -1, 1, ..., 8\}$. Further, I impose $\beta_{-1} = 0$, so that all post-treatment coefficients should be thought as treatment effects.

Figure 3 displays the regression estimates for the dynamic effects of recreational cannabis being legalized on the black market price for cannabis. The condition described by equation (3) is satisfied. After controlling for state and year, legalization is as good as random: the coefficients β_τ are not significantly different from zero when $\tau \leq -2$. Results suggest recreational cannabis legalization would cause the price for cannabis to decrease sustainably. On average, over the next 24 months, recreational cannabis legalization coming into effect would decrease the black market price of an ounce of cannabis by at least 12%.

Analogously, the regression results of Figure 4 present the dynamic effects of retail sales for recreational cannabis on the black market price for cannabis. As earlier, the condition described by equation (3) is satisfied. Retail sales of recreational cannabis would cause further decrease in the black market price. On average, over the next 24 months, retail sales of recreational cannabis would decrease the black market price of an ounce of cannabis by at least 15%.

I check whether effects on the price could be induced by external factors leading to liberalization waves. I implement a placebo analysis, of the effects of unsuccessful ballot initiatives. As expected, averted ballot initiatives do not seem to be leading to any significant effects on the black market price for cannabis (see figures in Appendix C). Both legalizing and implementing retail sales for recreational cannabis would cause a relatively permanent decrease in its black-market price.

I conduct a similar analysis focusing on the evolution of the THC potency (see Figures 5 and 6). Results suggest that THC potency on the black market progressively rises after retail sales for legal cannabis are implemented. While price can be quickly altered, adjusting quality is not immediate. Here, signs of response in quality begin to appear a year – i.e. one outdoor cannabis harvest cycle – after legal retail sales for cannabis are implemented.

These results suggest that the black market responds strategically – at the very least – and could be weakened by legalization. This response includes two dimen-

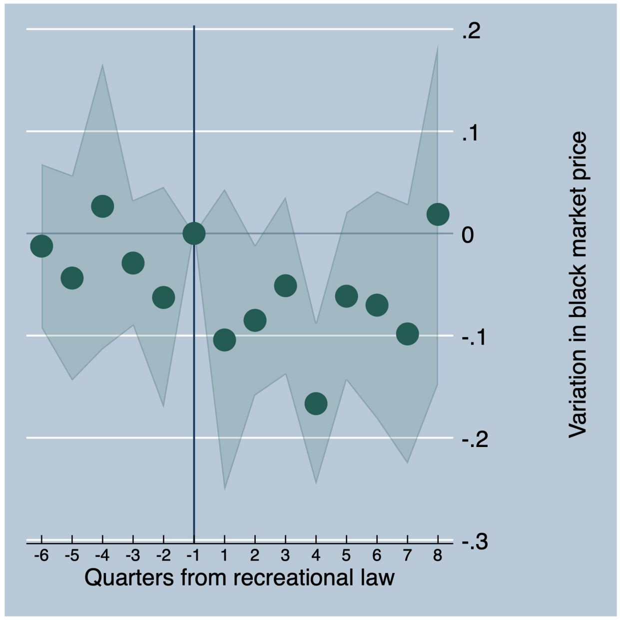


Figure 3: Dynamic effect of recreational cannabis legalization being implemented on the black market price for cannabis

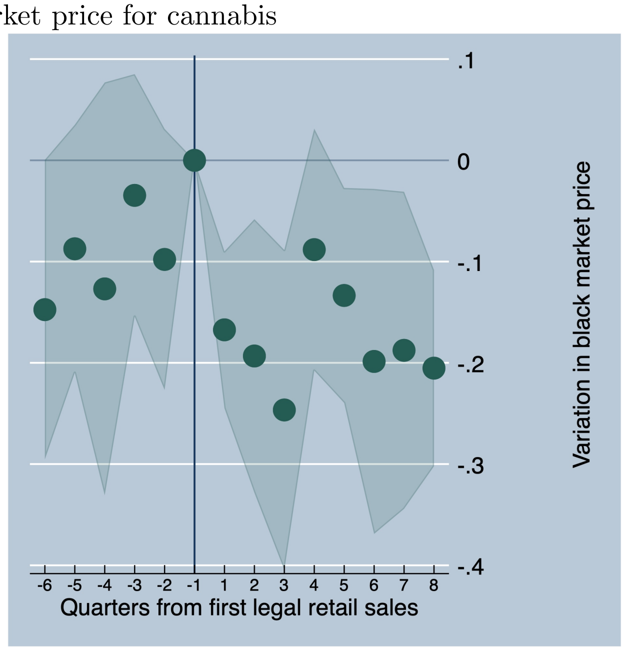


Figure 4: Dynamic effect of recreational cannabis retail sales on the black market price for cannabis

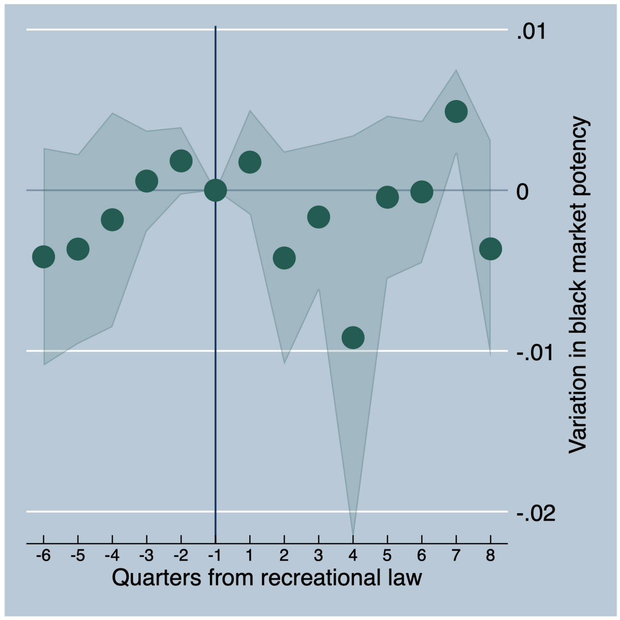


Figure 5: Dynamic effect of recreational cannabis legalization being implemented on the potency of black market cannabis

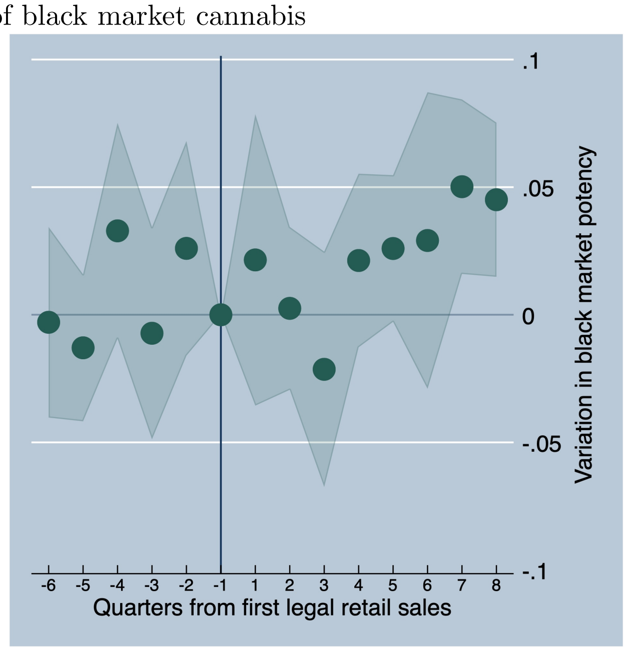


Figure 6: Dynamic effect of recreational cannabis retail sales on the potency of black market cannabis

sions: price and quality; the former being instantaneous, the latter being delayed by at least one outdoor cannabis harvest cycle. The next section attempts to quantify the average sizes of these responses. I also show that they are heterogeneous, depending on the quality of the product.

3.2 Average effect on black-market prices and quality

In this paragraph, I attempt to quantify the average changes in equilibrium on the black market for cannabis, *post-legalization*, in terms of price and quality.

Consider the following econometric model:

$$y_{ist} = \theta_s + \psi_y + \beta_L L_{st} + \epsilon_{ist} \tag{4}$$

where, as earlier, y_{ist} is the outcome of interest for observation i collected in state s during month t, θ_s is a state fixed effect, ψ_y is a year fixed effect, L_{st} is a binary variable indicating the legalization status in state s at time t, and ϵ_{ist} is a state-level error term that may exhibit within group correlation but is independent from the other regressors.

The binary variable L_{st} either indicates recreational use of cannabis being legalized, which will be denoted as *legal*, or legal retail sales for cannabis being operated, denoted as *retail*.

State fixed effects correct for systematic variations in prices across states. States featuring easier access to cannabis *ex ante* could be more likely to liberalize cannabis use. In these states, the *pre-legalization* price for cannabis would be relatively low, which would bias estimates downwards. Besides, locations where cannabis is prohibited may be geographically close to areas in which cannabis is either legal, prohibited but more accessible, or largely exported– e.g. British Columbia or Mexico. Controlling for geographical fixed effects enables to rule out this kind spillover effect.

Table 1 describes the average impact of legalization on equilibrium price and quality on the black market for cannabis. Columns 1 and 2 provide such results regarding prices, columns 3 and 4 focus on THC potency, while the two last columns give estimates for price relative to potency. Line 2 reports the coefficient obtained from regressing the outcomes of interest on the binary indicator of recreational cannabis legalization. Line 3 gives the estimates from regressing the outcomes of interest on the binary indicator of operating legal retail sales. Lines 4 to 6 specify the fixed effects used.

Table 1: Difference-in-difference estimates on the effects of legalization on price and THC potency of black market cannabis

	Price		THC		Quality adjusted price	
Main regressor						
legal	-0.100***	-0.0777**	-0.00766	-0.00577	-0.0519**	-0.0361
	(0.0313)	(0.0380)	(0.0142)	(0.0131)	(0.0243)	(0.0264)
retail	-0.186***	-0.169***	0.0162***	0.0185***	-0.155***	-0.142***
	(0.0195)	(0.0236)	(0.00552)	(0.00602)	(0.0210)	(0.0193)
Fixed effects						
State	✓	-	✓	-	✓	-
CSA	-	✓	-	✓	-	✓
Year	✓	✓	✓	✓	✓	✓

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

This table reports OLS estimates of the coefficients for indicators of the legalization of recreational cannabis (*legal*) and the operation of legal retail sales (*retail*) on the logarithm of price, the logarithm of THC potency and the difference between these two variables; as in equation (4) in the text. The estimation of the effect of *legal* is restricted to the sub-sample in which retail sales have not been implemented. Other covariates in the models are geographical and year fixed effects. Geographic entities are either states (line 4) or Combined Statistical Area (CSA) (line 5).

Legalizing recreational cannabis would result in the black-market price to drop by 7% to 10% overall. This effect is strenghened by the implementation of regulated retail sales for recreational cannabis, which would result in the black-market price to decrease by 16.9% to 18.6%. One should keep in mind that these are average effects and that retail sales for legal recreational cannabis are a – direct yet not simultaneous – consequence of legalization. Therefore, the estimates obtained from the evaluation of equation (4) on the whole sample using *legal* as main covariate could be thought as a weighted average of the exclusive effect of the use of recreational cannabis being legalized (i.e. the effect of cannabis legalization without legal sales operating) and the effect of retail sales for legal cannabis. For this reason, I restrict this estimation to the sub-sample such that no legal retail sales have been implemented.

These results suggest both legality and availibility matter. More than 60% of the price variation could be attributed to recreational cannabis being legal (without retail sales being regulated). This could be the result of several phenomena. The illegal retailers could anticipate the upcoming competition from the legal retail market and lower their prices. Alternatively, legalization could decrease the costs of producing black-market cannabis. Lower marginal costs would result in lower prices.

Lower fixed costs could atomize the supply for cannabis on the illegal market and enhance competition.

On quality, THC potency on the black market is not affected by legalization, before retail sales are implemented. However, *retail* results in the THC potency to rise by 1.6% to 1.8%. Once legal retail competition is introduced, the average potency of black market cannabis rises. This could be explained by consumers going to the black market to find high potency products unavailable legally. Another explanation could be that the black market strategically responds to the legal competition by rising the quality of its products.

Once we normalize price with respect to THC potency, the effect of *legal* is more uncertain. If any, this effect seems to be substantially lower (in absolute value) than the effect found on price, without the normalization.

As a check for recreational cannabis causing these market responses, I check for effects of unsuccessful legalization ballots on the black-market price and THC potency; and find none (see Appendix C).

The results regarding the quality adjusted price are in contradiction with the results on price and THC potency. If the average THC potency is unchanged *post-legalization*, while the price for cannabis significantly decreases, one should expect the price normalized to THC potency to decrease in the same proportion as the – unnormalized – price. This suggests the possibility of heterogeneous effects on equilibrium prices and average quality, depending on the type of product, i.e. whether the product is low-quality or *premium*.

To enquire this, I divide observations into 3 categories, depending on their THC potency, following the Ontario Cannabis Store guidelines. This distinction is reported in Table 2.

Table 2: Product classification based on THC potency

Category	Total THC content	Anticipated potency
1	12-16.99%	medium
2	17-20%	strong
3	>20%	very strong

I estimate the following variation from equation (4), which consists in distinguishing the effects of policies on the price of products, depending on their *category*.

$$y_{ist} = \theta_s + \psi_y + \sum_{j=1,2,3} category_{ist,j} + \sum_{j=1,2,3} \beta_{Lj} L_{st} \times category_{ist,j} + \epsilon_{ist} \quad (5)$$

To the notations defined earlier, I add $category_{ist,j}$ which is an indicator of the observation belonging to category $j = 1, 2, 3$. The estimation results are presented in Table 3.

They suggest heterogenous price responses on the black market.

Cannabis liberalization is associated with a decrease in the price of medium to strong potency cannabis. These products observe a moderate drop in price after legalization – of 5 to 14% – which accentuates after legal retail sales are implemented – retail sales being responsible for a drop in price by 18 to 22%. Assuming the demand for these medium range products does not decrease, this feature suggests price is a relatively important differentiation tool in the market for medium range cannabis products.

On the other end, the most potent products see their price rise by 12 to 25% after legalization. [13] This fact, along with the general observation that THC potency rises when the legal market is introduced, suggests that differentiation on premium products would be mostly based on quality.

4 Uncovering consumer preferences for cannabis: evidence from the state of Washington

The first part of the project shows legalization reforms have caused the black-market prices to drop by up to 18.6%. I also observe a – limited yet significant – adjustment in average potency by up to 1.8%, which follows the introduction of a legal retail alternative a year apart. This strategic reaction supports the intuition that legalization atomizes the supply for black market cannabis and reduces its production and distribution costs. Yet, the underlying mechanisms responsible for these effects are not clear and the analysis requires more structure to assess the extent to which legalization weakens the illegal market. Further, the heterogeneity of price responses depending on the product category suggest some selection of the black market products towards higher potency.

[13] This tendancy could persist after the introduction of legal retail cannabis, although the lack of a sufficient number of observations does not allow us to obtain significant results.

Table 3: Difference-in-difference estimates on the effects of legalization on price of black market cannabis by category

	Price	
Main regressor		
legal ×		
medium	-0.0810**	-0.0548*
	(0.0337)	(0.0285)
strong	-0.146***	-0.113**
	(0.0480)	(0.0466)
very strong	0.249**	0.125***
	(0.0993)	(0.0346)
retail ×		
medium	-0.226***	-0.201***
	(0.0397)	(0.0382)
strong	-0.202***	-0.180***
	(0.0227)	(0.0241)
very strong	0.0248	0.0235
	(0.0352)	(0.0389)
Fixed effects		
Category	✓	✓
State	✓	-
CSA	-	✓
Year	✓	✓

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

This table reports OLS estimates of the coefficients for indicators of the legalization of recreational cannabis (*legal*) and the operation of legal retail sales (*retail*), interacted with THC-based categories, on the logarithm of price; as in equation (5) in the text. The estimation of the effect of *legal* is restricted to the sub-sample in which retail sales have not been implemented. Other covariates in the models are category, geographical and year fixed effects. Geographic entities are either states (line 8) or Combined Statistical Area (CSA) (line 9).

Modeling consumers preferences for legal and illegal cannabis, both before and after legalization is necessary to fully understand the effects of legalization on consumption. Under prohibition, consumers who wish to use cannabis necessarily turn to the black market. They purchase cannabis if their indirect utility derived from cannabis consumption is positive. This utility depends on the market price, observed quality – measured by THC potency – and unobserved heterogeneity, as well as individual characteristics. Legalization introduces a new option in the consumers' choice set. Depending on their type and the relative price value of legal cannabis, consumers split into four categories: *never takers*, *always takers*, *switchers* and *new users*.[14] Assuming that the legal product is of sufficient relative quality, under partial equilibrium those categories are characterized as follows.[15]

(i) *Never takers* have low preference, even distaste, for cannabis and never consume, whether under prohibition or legalization. Their utility derived from any cannabis consumption is negative.

(ii) *Always takers* are individuals with moderate taste for cannabis, unwilling to pay the price *premium* associated with the legal market, when this price is too high. They consume cannabis from the black market both *ex-ante* and *ex-post*. If legal cannabis is unexpensive enough, theoretically, *always takers* disappear and the black market is evicted.

(iii) *Switchers*, who have the higher taste for cannabis and value quality, consume black market cannabis under prohibition and turn to the legal market after legalization.

(iv) *New users* appear if the legal product is of relatively good price value. Under prohibition, the utility they derive from – illegal – cannabis consumption is negative. Yet, they have little taste for the commodity, which makes the legal retail market attractive *ex-post* .

This section relies on a random utility discrete choice model, applied to cannabis consumption choices in the state of Washington and specifically accounting for pref-

[14] Auriol et al. (2020) provide a theoretical framework on general equilibrium dynamics and detail consumer selection in partial equilibrium *post-legalization*. In particular, they show that under partial equilibrium, legalization, by introducing a new option and expanding consumers' choice set, increases the overall demand for cannabis.

[15] If the legal commodity is of poor quality, theoretically there should be no *switchers* or *new users*, since the utility derived from illegal cannabis consumption is always higher that the utility derived from black-market consumption.

erences for quality. I estimate own- and cross- elasticities of consumer participation in the legal and the illegal markets with respects to both price and quality. These document substitution patterns and enable to retrieve structural estimates for marginal costs of producing and distributing cannabis on both the legal and the illegal markets. Modeling the competition between these enables me to calibrate the black market's best-response function to changes in price and THC potency of the legal product. This counterfactual exercise highlights the importance of THC potency as a tool to regulate the cannabis market.

4.1 The demand for recreational cannabis

4.1.1 Model

I consider the following discrete choice model, where an agent $i \in \mathcal{I} = \{1, \ldots, N\}$, living in the Metropolitan Statistical Area (MSA) $m = 1, \ldots, M$ at time $t = 1, \ldots, \mathrm{T}$, decides whether to consume cannabis or not. Under prohibition, available products exclusively come from the black market. After legalization, agents who wish to consume cannabis choose between two differentiated products: illegal ($j = 1$) and legal ($j = 2$) cannabis.

The indirect utility derived from cannabis consumption depends on a number of factors, including the price p_{jmt} and the THC potency q_{jmt}, observed for cannabis of type $j = 1, 2$ in market m and period t, as well as individual demographic and health characteristics (represented by the vector X_{imt}).

The value derived by agents when purchasing legal cannabis is different from the value derived when purchasing black-market cannabis. The product fixed effect ξ_j and the random variable $\Delta\xi_{jmt}$ account for these effects. In particular, $\Delta\xi_{jmt}$ relates to shocks in the valuation of consumers in market m and period t for unobserved characteristics of product j.

In my model, the extent to which individual preferences affect the utility derived from illegal consumption are policy invariant. Data limitation, namely the fact that I do not observe the type – legal *versus* illegal – of cannabis consumed *ex-post*, makes this assumption necessary. This implies that the change in consumer choices is solely caused by the birth of a retail market for legal cannabis and market-good specific shocks $\Delta\xi_{jmt}$, as opposed to a change of preferences *per se*.

Time and product specific variables also affect the benefit of consuming cannabis. At the time of its legalization, cannabis had been prohibited for almost a century;

it is still prohibited in most states. While legalization is the result of evolving social norms, it is also likely to have accelerated the change towards acceptance of cannabis consumption; social stigma fading with time. This effect is captured in the the random variable $\Delta\xi_{jmt}$.

Formally, the indirect utility is given as follows.

$$u_{ijt} = \beta_{pj} p_{jmt} + \beta_{qj} q_{jmt} + \beta_{Xj} X_{imt} + \xi_j + \Delta\xi_{jmt} + \epsilon_{ijmt} \tag{6}$$

where ϵ_{ijmt} is some agent-good-market specific idiosyncratic term, known to agent i but unknown to the econometrician. I assume ϵ is an independent Extreme Value Type I variable. $\beta_j = (\beta_{pj}, \beta_{qj}, \beta_{Xj})$ is a vector of parameters to be estimated. The utility derived from choosing the outside option $j = 0$ is normalized to $u_{i0t} = \epsilon_{i0t}$, for all consumers i and on all markets m and periods t.

To ease the exposition, the market-product-specific terms are regrouped under the notation

$$\delta_{jmt} \equiv \beta_{pj} p_{jmt} + \beta_{qj} q_{jmt} + \xi_j + \Delta\xi_{jmt}$$

and the mean conditional valuation of individual i for good j in market m and period t is defined as

$$\bar{u}_{ijmt} \equiv \delta_{jmt} + \beta_{Xj} X_i.$$

Let $y_{it} = j$ if agent i chooses the option j on market m in period t. Then, under the standard logit assumptions, the conditional probability that individual i chooses j, $\mathscr{s}_{ijmt}$, is

$$\mathscr{s}_{ijmt} = P\left(y_{imt} = j | p_{mt}, q_{mt}, X_{imt}; \beta, \xi, \Delta\xi_{mt}\right) = \frac{\exp\left(\bar{u}_{ijmt}\right)}{1 + \sum_{k=1,2} \exp\left(\bar{u}_{ikmt}\right)}. \tag{7}$$

The market share of product j is then the probability that an individual consumes j, averaged over her characteristics X_{imt}; formally $s_{jmt} = \int \mathscr{s}_{ijmt} \mathrm{d}F_X(X_{imt})$. As underlined by Berry et al. (1995), under the logit assumptions, the market-product-specific term δ_{jmt} is equal to $\ln\left(s_{jmt}\right) - \ln\left(s_{0mt}\right)$.

Besides, the conditional own- and cross-price elasticities of these market shares are

$$\eta^p_{ijkmt} = \frac{\partial \mathscr{s}_{ijmt}}{\partial p_{ikmt}} \frac{p_{ikmt}}{\mathscr{s}_{ijmt}} = \begin{cases} \beta_{pj} p_{jmt} (1 - \mathscr{s}_{ijmt}) & \text{if } j = k \\ -\beta_{pj} p_{kmt} \mathscr{s}_{ikmt} & \text{otherwise.} \end{cases} \tag{8}$$

The average price elasticities are therefore given by

$$\eta^p_{jkt} = \begin{cases} \beta_{pj} p_{jmt}(1 - s_{jmt}) & \text{if } j = k \\ -\beta_{pj} p_{kmt} s_{kmt} & \text{otherwise.} \end{cases} \tag{9}$$

Symmetrically, one can define the conditional own- and cross-quality elasticities as

$$\eta^q_{ijkmt} = \frac{\partial s_{ijmt}}{\partial q_{ikmt}} \frac{q_{ikmt}}{s_{ijmt}} = \begin{cases} \beta_{qj} q_{jmt}(1 - s_{ijmt}) & \text{if } j = k \\ -\beta_{qj} q_{kmt} s_{ikmt} & \text{otherwise.} \end{cases} \tag{10}$$

which yields average elasticities given as follows

$$\eta^q_{jkt} = \begin{cases} \beta_{qj} q_{jmt}(1 - s_{jmt}) & \text{if } j = k \\ -\beta_{qj} q_{kmt} s_{kmt} & \text{otherwise.} \end{cases} \tag{11}$$

4.1.2 Estimation

I estimate consumer valuations for black-market and legal cannabis for *pre-* and *post-legalization*. For both periods, I observe whether individuals used cannabis or not. The subset of agents surveyed in the two periods are denoted respectively by $\mathcal{I}_{pre}$ and $\mathcal{I}_{post}$. Analogously, the corresponding time periods belong to the subsets $\mathcal{T}_{pre}$ and $\mathcal{T}_{post}$.

No recreational cannabis is legally available under prohibition. Therefore I assume that any consumer before legalization is provided by the black market. The log-likelihood of the model for all subjects $i \in \mathcal{I}_{pre}$ living in periods $t \in \mathcal{T}_{pre}$ under prohibition is

$$\mathcal{L}\left(\delta_1, \beta_{X1}\right) = \sum_{\substack{i \in \mathcal{I}_{pre} \\ t \in \mathcal{T}_{pre}}} \mathbb{1}_{[y_{imt}=1]} \left(\delta_{1mt} + \beta_{X1} X_i\right) - \ln\left(1 + \exp\left(\delta_{1mt} + \beta_{X1} X_i\right)\right)$$

The BRFSS data does not distinguish legal from illegal cannabis consumption. Directly evaluating equation (7) during the *post-legalization* period does not enable to disentangle s_{i1mt} from s_{i2mt}. Instead, it only allows to estimate the conditional probability that individual i consumes cannabis $s_{i1mt} + s_{i2mt}$. The log-likelihood of the model for all subjects $i \in \mathcal{I}_{post}$ consuming $j = 1, 2$ in periods $t \in \mathcal{T}_{post}$

post-legalization is

$$\mathcal{L}(\delta, \beta_X) = \sum_{\substack{i \in \mathcal{I}_{post} \\ t \in \mathcal{T}_{post}}} \left\{ \mathbb{1}_{[y_{imt}>0]} \times \ln\left(\exp\left(\delta_{1mt} + \beta_{X1} X_i\right) + \exp\left(\delta_{2mt} + \beta_{X2} X_i\right)\right) \right.$$
$$\left. - \ln\left(1 + \exp\left(\delta_{1mt} + \beta_{X1} X_i\right) + \exp\left(\delta_{2mt} + \beta_{X2} X_i\right)\right) \right\}$$

The log-likelihood of the demand for legal and illegal cannabis on the whole sample is simply given by the sum of the log-likelihood functions of the demands for cannabis under prohibition and legalization.

$$\begin{aligned} \mathcal{L}(\delta, \beta_X) = & \sum_{\substack{i \in \mathcal{I}_{pre} \\ t \in \mathcal{T}_{pre}}} \mathbb{1}_{[y_{imt}=1]} \left(\delta_{1mt} + \beta_{X1} X_i\right) - \ln\left(1 + \exp\left(\delta_{1mt} + \beta_{X1} X_i\right)\right) \\ & + \sum_{\substack{i \in \mathcal{I}_{post} \\ t \in \mathcal{T}_{post}}} \left\{ \mathbb{1}_{[y_{imt}>0]} \times \ln\left(\exp\left(\delta_{1mt} + \beta_{X1} X_i\right) + \exp\left(\delta_{2mt} + \beta_{X2} X_i\right)\right) \right. \\ & \left. - \ln\left(1 + \exp\left(\delta_{1mt} + \beta_{X1} X_i\right) + \exp\left(\delta_{2mt} + \beta_{X2} X_i\right)\right) \right\} \end{aligned} \tag{12}$$

The parameters $\{\delta_{1mt}, \delta_{2mt}\}$, β_{X1} and β_{X2} are to be estimated by Maximum Likelihood (ML).

I assume, due to data limitation on consumer choices, that the individual preferences for illegal cannabis are invariant. More specifically, the parameter $\beta_1 = (\beta_{p1}, \beta_{q1}, \beta_{X1})$ remains unchanged after the implementation of legal retail sales. This implies that the choice of consumers – and substitution between illegal and legal cannabis – is solely driven by the introduction of a new option, everything else being equal on the black market. [16] Although this assumption imposes some restriction on consumer preferences, it is necessary to allow for identification of consumer sensitivity to characteristics. This paper is the first to estimate preferences for legal and illegal cannabis simultaneously.

The estimates for β_{pj} and β_{qj}, $j = 1, 2$ are retrieved from a standard two-step estimation procedure, which follows Nevo (2001), where the estimates for δ_{jmt} are

[16] Under the logit assumption, the own-price elasticity of illegal cannabis only changes through price and quantity, β_{p1} remaining identical. Under prohibition, it is indeed given by $\eta^{pre}_{i1t} = \beta_{p1} p_{1mt} \dfrac{1}{1 + \exp(\bar{u}_{i1mt})}$ After legalization, it becomes $\eta^{post}_{i1mt} = \beta_{p1} p_{1mt} \dfrac{1 + \exp(\bar{u}_{i2mt})}{1 + \exp(\bar{u}_{i1mt}) + \exp(\bar{u}_{i2mt})}$ The same applies for quality elasticities.

regressed on the prices p_{jmt} and THC contents q_{jmt}:

$$\hat{\delta}_{jmt} = \beta_{pj} p_{jmt} + \beta_{qj} q_{jmt} + \xi_j + \Delta\xi_{jmt} \tag{13}$$

Potential correlation between prices and unobserved characteristics threaten the consistent estimation of (13). To correct for this source of endogeneity, I therefore use the price on the upstream market as an instrument on the legal price and the proximity to British Columbia as an instrument on the black-market price. Details on instrumental variables are presented in Appendix D.

While strategic responses in prices are immediate, adjustements in quality are delayed by a year (see Section 3.1), which corresponds to the length of the cannabis crop cycle. For this reason, I consider that quality at time t is exogenous and does not require instruments. The ML estimates for the parameters β_{Xj}, $j = 1, 2$ from equation (12) are provided in Table 9. Unsurprisingly, female and older individuals derive less utility from cannabis consumption, while tobacco smokers are more likely to consume cannabis. The coefficients regarding both products are relatively similar. Interestingly, when market definition does not include MSA, individual distaste for black-market cannabis with regards to age and gender is intensified. In this case, observations related to individuals living in relatively rural – and expectedly more conservative – are actually included in the estimated sample; which could explain this result. This underlines the importance of accounting for geographic disparities.

The market shares predicted by model (1) for the sample are generally consistent, although the model seems to over-estimate the extensive margin of cannabis consumption (see Table 9 in Appendix E for more detail).

Table 5 presents the average price elasticities computed using equation (9) and the second-step estimation results (equation 13). I use here the specification (1) of the first-stage model (i.e. with year × MSA fixed effects). Obtained average own-price elasticities for the extensive margin of black-market cannabis consumption are generally between -0.2 and -0.3. Price elasticity of participation to the legal market lies around -0.5. These values are consistent with the existing literature. I also find exacerbated sensitivity to quality on the black market (elasticities around 6) relatively to the legal market. On the illegal market, quality is not certified and hence more volatile than on the legal market, which could explain this result. Finally, subtitution between the legal and the illegal sectors following changes in price is very limited, with cross-price elasticities between 0.02 and 0.03. This is not

Table 4: Estimated coefficients for individual preferences for cannabis (first-stage ML results)

	(1)	(2)	(3)
X_1			
age	-0.0445***	-0.0405***	-0.0545***
	(0.00106)	(0.000937)	(0.000636)
female	-0.556***	-0.546***	-0.646***
	(0.0365)	(0.0356)	(0.0257)
smoke100	1.554***	1.437***	1.483***
	(0.0408)	(0.0394)	(0.0284)
X_2			
age	-0.0435***	-0.0408***	-0.0482***
	(0.00151)	(0.00135)	(0.000914)
female	-0.530***	-0.518***	-0.515***
	(0.0513)	(0.0499)	(0.0319)
smoke100	1.551***	1.447***	1.601***
	(0.0570)	(0.0556)	(0.0348)
Market definition			
MSA × year	✓	-	-
MSA only	-	✓	-
year only	-	-	✓
N	55,100	55,100	80,948

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

the case for changes in quality. In particular, the THC potency on the legal market rising by 10% causes a 5.62% drop in the demand for illegal cannabis. This suggests quality as a viable tool for the legal market to compete against the black market and drive it out of business.

Table 5: Sensitivity of cannabis consumption to price and quality

	(1)	(2)
SENSITIVITY PARAMETERS		
β_{p1}	-0.0291***	-0.0353***
	(0.000790)	(0.000642)
β_{p2}	-0.0353***	-0.0451***
	(0.000821)	(0.000390)
β_{q1}	0.386***	-
	(0.0241)	-
β_{q2}	0.0223***	-
	(0.00556)	-
AVERAGE PRICE ELASTICITIES		
Prohibition		
η^p_{11}	-0.252	-0.305
	(0.0283)	(0.0343)
Legalization		
η^p_{11}	-0.227	-0.275
	(0.0545)	(0.0661)
η^p_{22}	-0.510	-0.565
	(0.249)	(0.245)
η^p_{12}	0.0293	0.0343
	(0.0284)	(0.0320)
η^p_{21}	0.0200	0.02623
	(0.0220)	(0.0273)
AVERAGE QUALITY ELASTICITIES		
Prohibition		
η^q_{11}	6.187	-
	(0.544)	-
Legalization		
η^q_{11}	6.237	-
	(0.682)	-
η^q_{22}	0.419	-
	(0.0349)	-
η^q_{12}	-0.562	-
	(0.521)	-
η^q_{21}	- 0.0244	-
	(0.0254)	-
Quality included	✓	-

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

4.2 The supply for legal and black-market cannabis *post-legalization*

The supply is shared between two sectors: a legal one and an illegal one. The legal sector is composed by a limited number of licensed businesses, which have to comply to local regulations. Prices are affected directly by fiscal requirements, as well as indirectly by licensing, which impacts market concentration. Further, quality and traceability regulations inflate prices by two channels. Resulting cost inflation forces legal retailers to set higher prices. Consumers' willingness to pay for higher quality products enables legal retailers to raise prices. At the other end of the spectrum, the illegal sector abides to no rule. Its price and quality (here measured by THC potency) are set according to the production and distribution costs, the costs related to the business exposure to sanctions, as well as competition dynamics with the legal sector. For the sake of simplicity and due to data limitation, the legal and the illegal sectors are respectively modeled as one representative firm selling a single product. Extensions will account for market concentration within each sector. *Post-legalization*, the legal and the illegal sectors compete playing a two-stage game in which (i) they simultaneously choose their levels of quality q and (ii) given the chosen levels of quality, they choose prices simultaneously. This assumption is consistent with the cannabis one year long crop cycle and the delay in the adjustment of THC potency observed in Section 3.1.

The profit function of sector $j = 1, 2$ on market m in period t is

$$\Pi_{jmt}(p_{jmt}, q_{jmt}) = [p_{jmt} - c_j(q_{jmt})]\, s_{jmt}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right)$$

where $\boldsymbol{q}_{mt} = (q_{jmt}, q_{kmt})$ and $\boldsymbol{p}_{mt} = (p_{jmt}, p_{kmt})$, $k \neq j$. Sector j maximizes its profit with respect to price in the second period, $\frac{\partial \Pi_{jmt}}{\partial p_{jmt}} = 0$.

$$s_{jmt}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) + [p_{jmt} - c_{jmt}(q_{jmt})]\, \frac{\partial s_{jmt}}{\partial p_{jmt}}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) = 0 \tag{14}$$

An equilibrium in quality is such that, for the quality of the other sector being given, sector j maximizes its profit. Thus, the level of quality q_{jmt} that maximizes the profit of sector j is such that

$$-\, c_j'(q_{jmt}) s_{jmt}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) + [p_{jmt} - c_{jmt}(q_{jmt})]\, \frac{\partial s_{jmt}}{\partial q_{jmt}}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) = 0 \tag{15}$$

Retrieving the marginal cost function is necessary in order to analyze counterfactual quality choices. Assume the marginal cost of product j is a function of product quality q_{jmt}, geographical-sector fixed effects θ_{jm}, and a market-time-specific shock ω_{jmt} and can be written as follows[17]

$$c_j\left(q_{jmt}, \theta_{jm}\right) = \theta_{jm} + \gamma_j \exp\left(q_{jmt}\right) + \omega_{jmt} \tag{16}$$

Under this specification and using the results from the demand estimation $\frac{\partial s_{jmt}}{\partial q_{jmt}} = \beta_{qj} s_{jmt}(1 - s_{jmt})$, I evaluate condition (15) which becomes

$$p_{jmt} = \theta_{jm} + \gamma_j \left(1 + \frac{1}{\beta_{qj}(1 - s_{jmt})}\right) \exp\left(q_{jmt}\right) + \omega_{jmt} \tag{17}$$

The estimation results are presented in Table 6. The *post-legalization* estimate

Table 6: Marginal cost functions *post-legalization*

	Black market	Legal market
Prohibition		
γ_0	9.73***	-
	(0.00317)	-
γ_1	5.72e-10***	-
	(1.21e-11)	-
Legalization		
γ_0	7.04***	15.1***
	(0.000239)	(0.119)
γ_1	2.05e-10***	-8.74 e-11***
	(2.40e-12)	(1.30e-12)
Geographical f.e.	✓	✓

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

[17] This is in line with the empirical literature on quality (see Crawford et al., 2019; Fan and Yang, 2020, for example): it specifies quality-convex marginal costs (γ_j is expected to be positive) and hence a profit function concave in quality.

for the baseline marginal cost parameter $\hat{\gamma}_0$ for producing and distributing cannabis is 7.04 USD/g on the black market and 15.1 USD/g on the legal market. The high difference between these estimates reflects the cost burden of the quality and traceability controls implemented by the Washington State Liquor and Cannabis Board. Estimates for $\hat{\gamma}_1$ confirm that the marginal cost on the illegal market is convex in quality. Although it is of small magnitude, the value for this parameter on the legal market being negative is counter-intuitive and requires more investigation. One explanation could be that on the legal market, products with lower THC potency differentiate themselves on other dimensions – e.g. in their composition in other molecules – unobserved here and which could inflate costs. Finally, comparing cost functions for illegal cannabis under prohibition and legalization confirms the intuition of a drop in operation costs *ex-post*, which I impute to changes in risk.

4.3 Policy implications

Throughout the last decade, one of the main objectives of governments legalizing cannabis has been killing the black market. Implementing a legalization policy exclusively aiming at evicting the black market could result in a higher price than under full deregulation and still be successful (Auriol et al., 2020). In this case, the rise in demand subsequent to legalization can be moderated through a price effect. A government willing to control the demand for cannabis would therefore wish for the prices on the legal market to be relatively high.

Using the estimates on consumers' sensitivity and substitution patterns with regards to price and quality, I calibrate the black market best response functions, as well as the variations in the demand for legal and illegal cannabis, to changes in price and quality of the legal good. A wide range of policies enable the government to manipulate the price and quality on the legal market, using the three following tools:

(i) imposing an oligopoly structure for the legal retail market through licensing (and eventually setting a limited number of awarded licenses),

(ii) taxing legal cannabis,

(iii) submitting the legal sector to quality or traceability requirements and controls.

The two first tools have somehow straightforward impacts on the price, while the latter results in a shift in the marginal cost function. Better quality and traceability may also imply higher investments, both before and after the licensing and production phases, resulting in higher cost to enter the legal market. Disentangling entry- *versus* non entry-induced oligopolistic structures is actually a difficult task to undertake. The extent to which state governments limit the number of licenses *per se* is often unclear; so is the cost of complying to the standards imposed on legal retailers prior to being allowed to enter the market.

I model reaction prices from the black market and show that improvements in quality are a reasonable prospect for a government aiming at eradicating the black market.

Cannabis in the state of Washington is heavily taxed. On average, tax rates in this sample, which are a compound of state and local taxes, are around 40%, which heavily inflates prices. As underlined in the previous section, this is amplified by strict quality enforcement driving up marginal costs. Yet, a government might aim at implementing a more liberal policy. Using estimates for demand and cost parameters and differentiating the first order condition (15), I simulate the reaction of the black market when the price on the legal market varies between two extremes, (i) the marginal cost on the illegal market and (ii) its current average price, 15.47$ per gram. I hold the quality of legal cannabis constant at the average observed potency *ex-post*, i.e. approximately 20%. Figure **??** presents the best-response functions of the illegal market in terms of both price and THC potency.

Legal prices left to the vertical green line are such that the best-response price of the black market is at the marginal cost. The legal price such that the black market makes no profit is therefore around 8 USD/g, which is above the marginal cost for producing and distributing uncontrolled cannabis, but well below the estimated marginal cost of current legal retail cannabis. This implies that this price can be reached yet at the cost of quality traceability and controls; which is not necessarily desirable for a number of reasons, including public health and consumer surplus. Further research will include the welfare effect of such a pricing policy.

I reproduce this exercise to simulate best-response functions of the illegal market to improved quality on the legal market, when the legal price remains fixed at 15.47$ per gram. Figure 7 displays the related best-response functions of the black market. Legal rates of THC content right to the vertical green line are such that the best-response price of the black market is at the marginal cost.

The 'eviction potency', holding the legal price constant, is around 29%. This confirms the intuition that quality differentiation is a reasonable strategy to fight

Figure 7: Best-response functions of the black market with respect to changes in the legal retail price

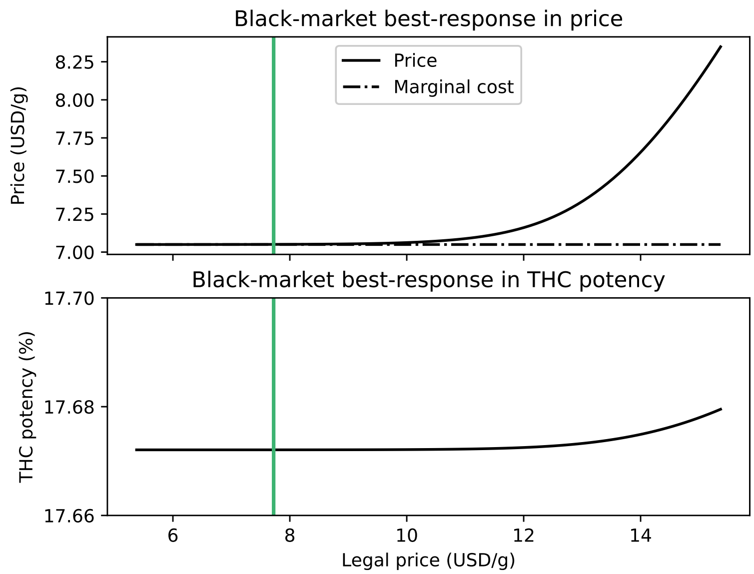
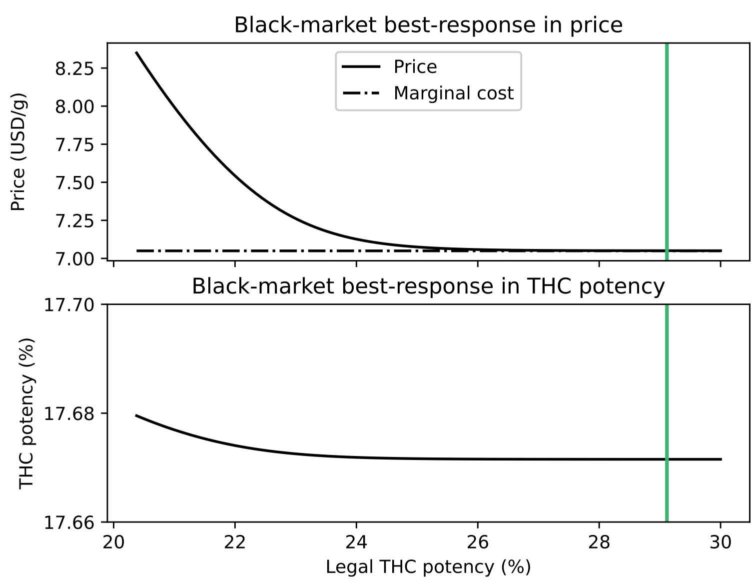


Figure 8: Best-response functions of the black market with respect to changes in the legal THC potency



against the black market.

5 Conclusion

The litterature on cannabis has covered illegal consumption behavior under prohibition. Recent papers have documented the legal sector, covering strategic interactions of legal firms with respect to policy and demand sensitivity to prices. Yet, to my knowledge, no previous work has covered market interactions across the legal and the illegal sectors.

Another contribution of this paper relates to the estimation of preferences with respect to quality; a dimension that has been overlooked by the literature. This second contribution is made possible by the exploitation of original crowd-sourced data on black-market prices, that includes information on cannabis strains.

I first focus on average price and quality responses to legalization policies. Reduced-form estimation highlights equilibrium changes on the black market, where prices decrease by up to 18% while THC potency increases by up to 2%. These results suggest legalization enhances competition on the global market for cannabis; and that retailers' strategy does not only depend on prices, quality matters.

These results motivate the evaluation of a random utility demand model that accounts for quality. Estimation yields measures for sensitivity with respect to both price and THC potency. In particular, it presents substitution patterns between the legal and the illegal sectors with respect to both price and quality. While consumers substitution with regards to price is very low, sensitive substitution based on quality presents it as a viable policy tool. Counterfactual analysis computes the black market best-response functions and show that price competition solely can drive illegal retailers out of business, but at the cost of traceability standards.

Eradicating the black market has been a common objective displayed by governments promoting legalization. Yet, the social optimality of underlying outcomes remains to be discussed in further versions of this work. Besides, as in standard in the literature, this work restricts market prices and levels of quality to single dimensions. Further research should account for quantity discounts in price as well as other dimensions for quality, such as product diversity and availibility.

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Appendix

A Cannabis laws in the U.S.

Along with the societal changes and the increase in cannabis use associated to the seventies, numerous states proceeded to a wave of decriminalization. California, Colorado, Maine, Minnesota, Mississippi, Nebraska, New York, North Carolina, Ohio, Oregon and Washington declassified possession of small amounts of cannabis (usually up to 1 ounce) to a misdemeanor. In 1975, Alaska declared possession of small amounts of cannabis to be protected under state constitutional right to privacy. However, the intensification of the *War on Drugs* in the eighties left this liberalization process stagnating.

The rising concerns about the efficiency of this costly war led to a new wave of policy changes at the edge of the 21st century. Initiated by a second wave of decriminalization laws and the first laws in favor of medical use, this liberalization movement accelerated in the last decade. In 2012, Colorado and Washington states passing bills legalizing recreational use of cannabis after a referendum. From 2014 onward, these states would be imitated by eight other American states and the District of Columbia.

Legalization policies implemented so far are quite diverse. As of 2020, while ten states and the District of Columbia have legalized the use of recreational cannabis, possessing this commodity remains a felony in other states such as Arizona. Not only the legal status differs across states, but sanctions and fine levels are far from uniform between two states having the same cannabis laws. For instance, Arizona state law would not provide any guideline for punishment regarding small amounts of cannabis; possessing up to 2 pounds of cannabis entails a risk of incarceration of up to 2 years and a maximum fine of USD 150,000. In Alabama, possessing any amount of cannabis is punishable by up to 1 year of incarceration along with a maximum fine of USD 6,000. In contrast, Virginia sets a threshold for possession of small amounts at 1/2 oz and sanctions it by no more than 30 days of incarceration and a fine of USD 500 on a first offense. Possessing up to 42.5 g in Minnesota would only entail a risk of a USD 200 fine. Such diversity being observed across a single territory makes the United-States a preferred case of study for analyzing the impacts of cannabis policies.

The table below is borrowed from Auriol et al. (2020). It provides a global overview of the state of american cannabis regulation, highlighting its disparity. For each state, column 2 reports the year during which cannabis was decriminalized. Column 3 provides the year of the first ballot to implement a *Medical Marijuana Law* (MML), while the fourth column records the year during which such a law was passed. Analogously, the year of the first recreational cannabis legalization ballot is recorded in the fifth column; its passing is given in Column 6. The last column reports the year of the first legal retail sales of cannabis. Dashes materialize the absence of the event described in the corresponding column.

State	Decrim.	1st MML ballot	MML	1st rec. ballot	Rec.	Retail
AL	-	-	-	-	-	-
AK	1975[a]	1998	1998	2000	2014	2016
AZ	-	1996	2010	2016	2020	-
AR	-[b]	2012	2016	-[c]	-	-
CA	1975	1996	1996	1972	2016	2018
CO	1975	2000	2000	2012	2012	2014
CT	2011	-[d]	2012	-	-	-
DE	2015	-[d]	2011	-	-	-
D.C.	2014	1998	2010	2014	2014	-
FL	-[e]	2014	2016	-[c]	-	-
GA	-[e]	-	-	-	-	-
HI	2020	-[d]	2000	-	-	-
ID	-	-	-	-	-	-

[a] Alaska issued a cannabis decriminalization bill on May 16, 1975, which is two weeks before the famous *Ravin* decision, protecting the possession of small amounts under constitutional privacy rights, was issued. Decriminalization of cannabis came into effect on June 5, 1975. The timeline of cannabis policy in Alaska then becomes fuzzy: further decriminalization was billed in 1982, then cannabis was recriminalized in 1990, decriminalized in 2003, then recriminalized in 2006; while the *Ravin* caselaw would still interact with the criminal state law (Brandeis, 2012). Legalization approved in 2014 ended this confusion.

[b] Although cannabis use remains a crime under state law, it is decriminalized locally.

[c] A cannabis legalization initiative is expected to be on the ballot in November 2022 ("Marijuana on the ballot", *Ballotpedia*. Retrieved online December 2020, https://ballotpedia.org/Marijuana_on_the_ballot)

[d] *Medical Marijuana* was not on the ballot: instead, it was signed into law after legislative approval.

[e] Although cannabis use remains a crime under state law, it is decriminalized locally.

State	Decrim.	1st MML ballot	MML	1st rec. ballot	Rec.	Retail
IL	2016	- [d]	2013	- [f]	2019	2020
IN	-	-	-	-	-	-
IA	-	-	-	-	-	-
KS	-	-	-	-	-	-
KY	- [e]	-	- [g]	-	-	-
LA	- [e]	- [d]	2015 [h]	-	-	-
ME	1975	1999	1999	2016	2016	2020
MD	2014	- [d]	2013	-	-	-
MA	2008	2012	2012	2016	2016	2018
MI	2018	2008	2008	2018	2018	2019
MN	1976	- [d]	2014	-	-	-
MS	1978	2020	2020	- [c]	-	-
MO	2014	2018	2018	-	-	-
MT	- [e]	2004	2004	2020	2020	-
NE	1979	- [i]	-	-	-	-
NV	2016	1998	1998	2006	2016	2017
NH	2017	- [d]	2013	-	-	-
NJ	-	- [d]	2010	2020	2020	-
NM	2019	- [d]	2007	-	-	-
NY	1977	- [d]	2014	- [f]	2021	- [18]
NC	1977	-	-	-	-	-
ND	2019	2016	2016	2018	[c]	-

[18] Not until 2022. Ferré-Sadurní, Luis. 2021 "New York Legalizes Recreational Marijuana, Tying Move to Racial Equity". *The New York Times*, March 31. https://www.nytimes.com/2021/03/31/nyregion/cuomo-ny-legal-weed.html

[f] The recreational use of cannabis was not on the ballot: instead, it was signed into law after legislative approval.

[g] A *Medical Marijuana* bill was presented to the House of Kentucky in January 2020. It is presently under evaluation by the Senate Judiciary Committee (Kentucky General Assembly, *House Bill 136*; retrieved online 3rd December 2020, url: https://apps.legislature.ky.gov/record/20rs/hb136.html).

[h] Although *Medical Marijuana* was signed into law in 2015, it did not become effective before 2019.

[i] A *Medical Marijuana* ballot is expected to be on the ballot in November 2022 ("Marijuana on the ballot", *Ballotpedia*. Retrieved online December 2020, https://ballotpedia.org/Marijuana_on_the_ballot).

State	Decrim.	1st MML ballot	MML	1st rec. ballot	Rec.	Retail
OH	1975	- [d]	2016	2015	-	-
OK	-[j]	2018	2018	-[c]	-	-
OR	1973	1998	1998	2012	2014	2015
PA	-[e]	- [d]	2016	-	-	-
RI	2012	- [d]	2005	-	-	-
SC	-	-	-	-	-	-
SD	-	2006	2020	2020	2020	-
TN	-	-	-	-	-	-
TX	-[e]	-	-	-	-	-
UT	-	2018	2018	-	-	-
VT	2013	- [d]	2004	- [f]	2018	2020
VA	-	-	-	-	-	-
WA	2012	1998	1998	2012	2012	2014
WV	-	-	2017[k]	-	-	-
WI	-[e]	-	-	-	-	-
WY	-	-	-	-	-	-

B Data cleaning and processing

B.1 Geographical matching and aggregation

Geographical markets were defined using the Metropolitan and Micopolitan Statistical Areas (MMSA) division established by the US Census.

While this information is directly available in the BRFSS data, matching it with the THMQ and the WSLCB data required some processing.

Observations in the THMQ data are given by city – sometimes county or general area – and state. I geocoded these observations and cleaned their associated addresses by scraping Open Street Map's Nominatim. The cleaned, detailed, addresses provided me with the county for each location.

To match geographical areas with prices listed in the WSLCB *seed-to-sale* data, I first follow the same procedure as in Hollenbeck and Uetake (2021); which consists in retrieving the list of license applications from the Washington State Liquor and Cannabis Board website, as well as their history though the Internet Wayback Machine. As previously, I then clean the addresses obtained and assign them to

[j] A cannabis decriminalization initiative is expected to be on the ballot in November 2022 ("Oklahoma State Question 812, Marijuana Decriminalization Initiative (2022)", retrieved online on Ballotpedia; url: `https://ballotpedia.org/Oklahoma_State_Question_812,_Marijuana_Decriminalization_Initiative_(2022)`).

[k] Although a bill regulating medical use of cannabis was signed in April 2017, Medical Marijuana Laws have not been implemented yet in West Virginia.

counties by scraping Open Street Map's Nominatim.

The lists of detailed locations obtained was then merged with the US Census list of statistical divisions.

B.2 Associating strains with THC potencies

The THMQ data provides information on strains. The dataset I collected accounts for more than 2,000 different values of *strain*. To exploit this information, I scraped the strain repertory of `leafly.com` from which I recovered the THC potency, plant type (indica, sativa or hybrid), as well as the different appellations of each strain. I matched this list with the THMQ data. When possible, I used exact matching on strain names and alternative appellations. I paired remaining observations to the repertory items to which they were the closest, in terms of Jaro-Wrinkler distance. I discarded pairs for which the Jaro-Wrinkler metric was less than 75%.

C Averted cannabis reforms

Section 3 shows that legalizing cannabis and regulating its market yields a sustainable decrease of the black-market price and a rise in product THC potency. To support the argument of a causal effect of legalization and retail sales for recreational cannabis on the black-market equilibrium price and potency, I provide event-study and difference-in-difference results on averted legalization attempts.

These attempts are modeled usnig two variables:

- *no successful ballot* describes a situation where a state has put the legal use of recreational cannabis on the ballot but this initiative never resulted in legalization;
- *failed ballot* describes a ballot initiative that was not followed by the legalization of recreational cannabis within two years.

Figure 8 describes the results of an event-study on the effect of *failed ballot* initiatives. It shows that these unsuccessful attempts have no effect on the black-market price for cannabis.

Table 8 is built analogously as Table 1 in the main text. Columns 1 and 2 provide results regarding prices, columns 3 and 4 focus on THC potency, while the two last

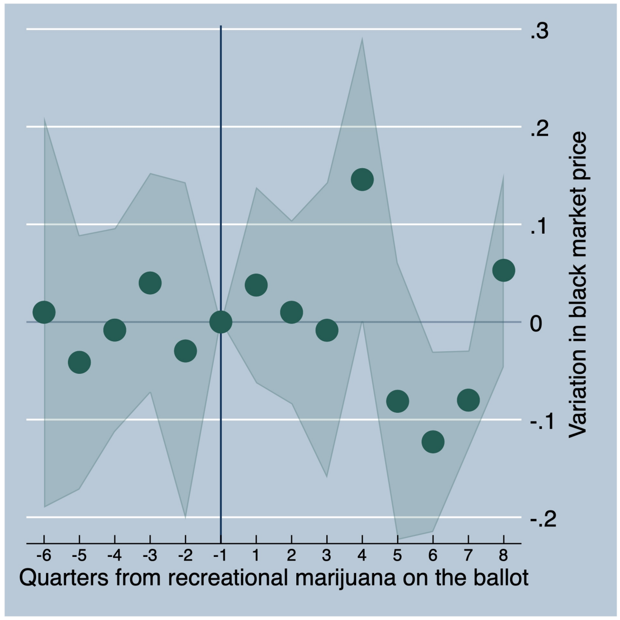

Figure 9: Dynamic effect of failed ballot initiatives on the black market-price for cannabis

columns give estimates for price relative to potency. Line 2 reports the coefficient obtained from regressing the binary indicator *no successful ballot* on the outcomes of interest. Line 3 gives the estimates from regressing *failed ballot* on the outcomes of interest. Lines 4 to 6 specify the fixed effects used.

I find no significant effect of failed cannabis ballots on the black market price for cannabis. Although effects on THC potency and normalized price are mostly not significant, some results on THC potency are in contradiction with the general findings and require further investigation.

D Instrumental variables

Estimating equation (13) requires instruments on prices, which are likely correlated to the unobservable heterogeneity $\Delta\xi_{jmt}$ and thereby endogenous.

Instruments on black-market prices To evaluate equation (**??**), I exploit the geographical proximity between the State of Washington and British Columbia. The instrumental variables on the black-market prices are the driving distance to the nearest border point in British Columbia, computed using Google Maps API,

Table 8: Difference-in-difference estimates on the effects of unsuccessful legalization attempts on price and THC potency of black market cannabis

	Price		THC		Quality adjusted price	
Main regressor						
no successful ballot	0.0326	-0.00805	0.000496	0.0111**	0.0608***	0.0154
	(0.0222)	(0.0204)	(0.00366)	(0.00528)	(0.0168)	(0.0165)
failed ballot	-0.121	-0.0957	-0.0113	-0.00252	-0.0707	-0.0528
	(0.112)	(0.0683)	(0.0118)	(0.0131)	(0.0926)	(0.0514)
Fixed effects						
State	✓	-	✓	-	✓	-
CSA	-	✓	-	✓	-	✓
Year	✓	✓	✓	✓	✓	✓

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

This table reports OLS estimates of the coefficients for indicators of legalization ballots that never resulted in legalization (*no successful ballot*) and were not followed by legalization within two years (*failed ballot*) on the logarithm of price, the logarithm of THC potency and the difference between these two variables; as in equation (4) in the main text. Other covariates in the models are geographical and year fixed effects. Geographic entities are either states (line 4) or Combined Statistical Area (CSA) (line 5).

the annual exchange rate between the US and the Canadian dollars, as well as an interaction between these two variables. The Canadian province has indeed been a significant cannabis producer, the sector especially thriving at the turn of the 21st century, in terms of both size and sophistication (Diplock et al., 2013). Assume the composition of local markets are subject to their distance to British Columbia. In this case, relative geographical position affects local black-market prices. Further, as highlighted by the results of Section 3.2 and Table 3, the reaction of black-market prices to policy changes varies across product categories.

Instruments on legal prices The WSLCB data includes information on upstream transactions. Each retail item is associated with detailed information on the wholesale batch from which it originates. I use the upstream price associated to p_{2t}, denoted p_{2t}^{up}, as an intrument on the price p_{2t}. The upstream price p_{2t}^{up} directly affects the retail price p_{2t} and is exogenous to consumer i's choice.

E First-stage estimation: predicted market shares

Table 9: Observed and estimated extensive margins of cannabis consumption

Good	Under prohibition		After legalization	
	s_j	$\hat{s}_j$	s_j	$\hat{s}_j$
0	94.29%	94.12%	89.29%	85.58%
1	5.712%	5.885%	10.71%	7.213%
2	-	-		7.210%

F Best responses and static comparatives

Differentiating equation (15) yields

$$\alpha_{qj}\mathrm{d}q_{jmt} + \alpha_{qk}\mathrm{d}q_{kmt} + \alpha_{pj}\mathrm{d}p_{jmt} + \alpha_{pk}\mathrm{d}p_{kmt} = 0$$

where

$$\begin{aligned}
\alpha_{qj} =& - c_j''(q_{jmt})s_{jmt}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) - c_j'(q_{jmt})\left[\frac{\partial s_{jmt}}{\partial q_{jmt}}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) + s_{jmt}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right)\right] \\
&+ \left[p_{jmt} - c_{jmt}(q_{jmt})\right]\frac{\partial^2 s_{jmt}}{\partial q_{jmt}^2}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) \\
\alpha_{qk} =& - c_j'(q_{jmt})\frac{\partial s_{jmt}}{\partial q_{kmt}}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) + \left[p_{jmt} - c_{jmt}(q_{jmt})\right]\frac{\partial^2 s_{jmt}}{\partial q_{jmt}\partial q_{kmt}}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) \\
\alpha_{pj} =& - c_j'(q_{jmt})\frac{\partial s_{jmt}}{\partial p_{jmt}}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) + \frac{\partial s_{jmt}}{\partial q_{jmt}}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) \\
&+ \left[p_{jmt} - c_{jmt}(q_{jmt})\right]\frac{\partial^2 s_{jmt}}{\partial q_{jmt}\partial p_{jmt}}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) \\
\alpha_{pk} =& - c_j'(q_{jmt})\frac{\partial s_{jmt}}{\partial p_{kmt}}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) + \left[p_{jmt} - c_{jmt}(q_{jmt})\right]\frac{\partial^2 s_{jmt}}{\partial q_{jmt}\partial p_{kmt}}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right)
\end{aligned}$$

The best-responses adjustments of sector j to price and quality changes in sector k are hence given by the table below.

Using the observed *post-legalization* equilibrium, best-responses can then be simulated using the estimates for the sensitivity parameters[19] and the marginal cost

[19]Recall that under logit assumptions, the first derivatives of market shares are simply given as

	Reaction in price p_j	Reaction in quality q_j
Change in price p_k	$-\frac{\alpha_{pk}}{\alpha_{pj}}$	$-\frac{\alpha_{pk}}{\alpha_{qj}}$
Change in quality q_k	$-\frac{\alpha_{qk}}{\alpha_{pj}}$	$-\frac{\alpha_{qk}}{\alpha_{qj}}$

function.

$\frac{\partial s_{jmt}}{\partial q_{jmt}} = \beta_{qj} s_{jmt}(1 - s_{jmt})$, $\frac{\partial s_{jmt}}{\partial q_{kmt}} = \beta_{qj} s_{jmt} s_{kmt}$, $\frac{\partial s_{jmt}}{\partial p_{jmt}} = \beta_{pj} s_{jmt}(1 - s_{jmt})$, $\frac{\partial s_{jmt}}{\partial p_{kmt}} = \beta_{pj} s_{jmt} s_{kmt}$.