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TAXING THE POTENCY OF SIN GOODS: EVIDENCE FROM RECREATIONAL CANNABIS AND LIQUOR MARKETS

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Cannabis is legal to purchase for over 28 percent of U.S. citizens. A central argument used in public campaigns for cannabis legalization has focused on the tax revenue that legal cannabis markets could generate. Recently, some policy makers and politicians have debated switching from traditional ad valorem taxes to taxes on potency, aiming to reduce the potential externalities associated with highly potent products. In this paper, we construct a theoretical model to predict the implications of a potency-based tax in an environment with market power. We then estimate the demand for cannabis potency based on administrative records of sales and potency from Washington state. We finish by conducting counterfactual analyses comparing revenue and potency outcomes from potency-based taxes versus the traditional price-based taxes.

Keywords: cannabis, liquor, potency, externalities, taxation, demand estimation, Pigouvian tax

JEL Codes: D42, D62, H23, H26, H75, L11, L12, L66

I. INTRODUCTION

The median American voter supports legalizing cannabis[1] in some form, and states with nearly one-third of the U.S. population, as well as several jurisdictions around the world, have chosen to legalize the substance for recreational use over the past several years. Advocates for legalization have prevailed, in part, due to the potential

[1] There has been vigorous debate in the popular press and in the academic literature about the choice of words used to describe plants in genus *Cannabis* and the various intoxicating and industrial substances produced from such plants (Dufton, 2017). We use the terms "cannabis" and "marijuana" interchangeably to refer to the spectrum of intoxicating products consumed by humans.

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tax revenue that can be collected from the industry. Washington state, one of the first states to legalize, earned $150 million in cannabis taxes in 2015, the first full calendar year after its market opened.

Lawmakers, however, have disagreed about the optimal way to tax and regulate cannabis. All states except Alaska have implemented ad valorem taxes based on the retail price, and some (including Alaska) have also imposed taxes at production or wholesale based on weight or average prices.[2] In this article, we consider an alternative tax scheme that has been suggested by many in the policy space: using potency as a tax base.

Potency-based taxation schemes — in which a tax is applied to cannabis products based on the amount of psychoactive "cannabinoid" molecules contained within the product such as tetrahydrocannabinol (THC) — may offer policymakers some attractive features. To the extent that consumption of these chemicals generates negative externalities, potency taxes act as a Pigouvian correction mechanism — much as many states tax alcohol products according to the percentage of the product's volume that is ethanol (ABV). Additionally, given that prices have dropped significantly since markets opened, some lawmakers have expressed concerns about the future revenue path of excise taxes — Washington state generated roughly 20 percent less revenue in 2016 than it anticipated pre-legalization (Washington Office of Financial Management, 2013; Miller and Seo, 2019). For these reasons, taxation schemes based on THC content have been seriously considered by California and Washington, among others (Liquor and Cannabis Board, 2019; Sheeler, 2019; Petek, 2019).[3]

This paper aims to evaluate these proposals — in particular, we describe existing evidence on cannabis-related externalities and then provide evidence on the revenue and potency consequences of a potency-based tax in an environment where firms have market power. We also contrast our empirical findings for cannabis with a similar analysis for liquor — a "sin good" that we know much more about. It is important to note at the outset that the two stated goals of policymakers are fundamentally at odds with one another — to the extent that a potency-based tax substantially decreases potency, it will generate less revenue than it would otherwise (although whether it will generate more or less than the current ad valorem tax is a priori uncertain). While the existing evidence on THC-based externalities is too limited to determine the optimal Pigouvian tax rate in this paper, it is unlikely to coincide with the revenue maximizing rate.[4]

In Section II.A, we summarize the research on the personal and public health impacts of cannabis and cannabinoids, which include negative physical effects, such as respiratory and cardiovascular disorders, and increased risks of mental health issues, including depression, psychosis, and suicidal ideation — though these negative consequences are much less likely to lead to death than the consequences of alcohol abuse. There is

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[2] Table 1 summarizes the tax rates in effect as of December 2019.

[3] Indeed, Washington's regulators noted in a report that the origin of the THC tax was based on "the potential to protect public revenues against losses in the event of falling prices."

[4] Moreover, the environment we study features firm market power, and so the optimal Pigouvian tax rate may not be equal to the marginal external cost of substance consumption.

some limited evidence that many of these risks are dose dependent, suggesting that a taxation scheme that successfully reduced the THC content of cannabis products may reduce these risks. We also highlight work identifying an increase in THC content in both black market and legal cannabis over time, which is associated with an increase in cannabis-related emergency room (ER) visits. Given the extensive literature documenting that imposing excise taxes on alcohol leads to increases in prices and decreases in per capita consumption (Cook and Tauchen, 1982; Cordes, Nicholson, and Sammartino, 1990; Ruhm, 1995; Ponicki et al., 1997; Young and Bieli'nska-Kwapisz, 2002; Cook, Ostermann, and Sloan, 2005; Shang, Wang, and Chaloupka, 2018; and many others), and therefore lower social costs from excessive drinking, it may seem reasonable to believe that cannabis potency taxes would have similar effects.

We start our analysis of potency taxes in Section III by introducing a simple monopoly model of supply and demand for sin goods. Our framework highlights that, at least in Washington, firm entry is limited and there is evidence that firms behave as local monopolists (Hollenbeck and Uetake, 2019). In Sections IV and V, we use data from Washington state to estimate the potential impact of potency taxes inspired by this framework. Using the universe of recreational cannabis sales in Washington from June 2016 to June 2017, we estimate a log-log demand model for cannabis as a function of prices and THC content. We focus on "usable marijuana" (i.e., dried flowers of *Cannabis* plants) as it is the largest component of the cannabis market and products feature widely varying potencies (relative to edibles and concentrates, which usually contain fixed amounts of THC). We control for unobservables and potential endogeneity by instrumenting final prices using wholesale prices and including a comprehensive set of fixed effects. In our preferred specification, we find that the demand for cannabis is elastic with respect to prices — the estimated elasticity is –1.20 — and inelastic with respect to THC content — the estimated elasticity is 0.61. We are unaware of any other estimate of the elasticity of cannabis demand with respect to potency.[5] We repeat the exercise with liquor products using data from the Nielsen Retail Scanner Dataset from the same time period, and find that liquor is more elastic with respect to price and potency (measured by alcohol content) than cannabis.

We use our model to analyze the impact of a potency tax in Section V.A. We define a "naive" potency tax rate as the rate that would match the revenue obtained by Washington's current tax regime without considering any supply or demand response. We use the model and our estimated elasticities to predict average prices, potencies, quantities, and tax revenue under this naive rate. We find for both liquor and cannabis that such a policy would reduce revenue. This result is driven, in part, by our assumption of market power: Even though demand for cannabis is inelastic with respect to THC, and so one might think that with the removal of an ad valorem tax and the imposition of a potency tax the net result would be an increase in revenue, changes in any tax rate are filtered through the lens of profit maximization. In other words, the firm's choices exaggerate

[5] Smart et al. (2017) conduct a hedonic price analysis of cannabis products using earlier data that include measures of potency, but they do not estimate demand elasticities.

the consumer response. This result is similar to the results of Hollenbeck and Uetake (2019) and Miravete et al. (2018), who study market power and taxation in the cannabis and liquor markets, respectively, though their work is focused on the interplay between firms within supply chains of both goods.

For both liquor and cannabis, we find that an increase in the proposed potency tax raises revenue relative to the naive version — though only for liquor do we find a potency tax that results in higher revenue relative to the current ad valorem tax. This is, in part, due to our estimates of the marginal cost of potency, which, in the case of cannabis, are roughly equivalent to the naive tax rate (so that the naive rate is "large" relative to the costs of production) and, in the case of liquor, are roughly five times the marginal cost of potency (so that the naive rate is "small").

While our results suggest that a potency tax for cannabis will not raise more revenue than an ad valorem tax, the reduction in potency is substantial. Under the naive tax rate, both the average potency per gram and the total amount of THC consumed decline by about 40 percent relative to the current ad valorem tax. In contrast, the potency decline for liquor is about half as large.

We conclude in Section VI by discussing some of the other challenges facing jurisdictions that wish to impose a potency tax on cannabis sales, including the risks of tax avoidance and the need for effective enforcement that are specific to the cannabis context — a context with substantial noise in and room to manipulate the potency testing process.

II. BACKGROUND

Cannabis consumption was legal in the United States until 1938 — indeed it was listed in the U.S. Pharmacopeia as a treatment for labor pains, nausea, and other conditions. The Marijuana Taxation Act of 1938 prohibited the consumption of the substance, and the Controlled Substances Act of 1970 significantly increased the strength of the prohibition against cannabis, as it was quickly classified a Schedule I substance with a "high potential for abuse and little known medical benefit."[6]

As public views on cannabis consumption have changed, so too has the legal landscape. California legalized cannabis for medical use ("medical cannabis") in 1996 — though the law was eventually struck down by the Supreme Court due, in part, to concerns about cross-border trafficking (Hansen, Miller, and Weber, 2017a) — and several states followed suit thereafter. Voters in Washington and Colorado legalized cannabis for adult use ("recreational cannabis") via ballot measures in 2012 and legal markets opened in 2014. Today, ten states and several countries have legalized recreational cannabis, and more are predicted to follow in the coming years. Since cannabis remains a Schedule I substance, legal cannabis markets operate in a legal gray area created, in part, by an August 2013 memo penned by then Deputy Attorney General James Cole, which instructed U.S. Attorneys to allocate their resources away from prosecuting individuals in legal states whose actions are in "clear and unambiguous compliance" with state law.

Table 1 summarizes the tax rates and bases for all states that have legalized cannabis and were selling recreational cannabis as of December 2019. State retail excise tax

[6] Other Schedule I substances include heroin and methamphetamine.

Table 1
Marijuana Taxes by State

State	Retail Excise Tax Rate (%)	Additional Taxes
Alaska	—	Cultivation tax of $50/oz on dried flowers (unless immature/abnormal; then $25/oz), $15/oz on other plant material, $1 for clones. 5% optional local sales tax.
California	15%	Cultivation tax of $9.25/oz on dried flowers and $2.75/oz on dried leaves. Optional locality taxes.
Colorado	10%	Additional 15% tax applied at wholesale based on average market rate in the state. Optional locality taxes.
Illinois	10%	10% tax applies for products with THC $<$ 35%, 20% tax on edibles, 25% tax for products with THC $\geq$ 35% (mostly concentrates). 7% gross receipts tax (with arms-length transaction rules). Additional optional locality taxes up to 3.5%.
Massachusetts	10.75%	Localities may impose additional 3% excise tax.
Michigan	10%	Additional 15% tax applied at wholesale on "fair market value."
Nevada	10%	Localities may impose additional 3% excise tax.
Oregon	17%	
Washington	37%	

Notes: This table includes every state where recreational cannabis is sold as of December 2019. Vermont, Maine, and Washington, DC have legalized recreational cannabis but have not yet started selling it. States also levy their state and local retail sales taxes on marijuana sold at retail. Washington initially set a tax rate of 25 percent both at retail and for transfers within the supply chain. On July 1, 2015, Washington switched to a single 37 percent tax at retail.

rates range from 10 percent in Colorado, Illinois, Michigan, and Nevada to 37 percent in Washington. Alaska is the only state without a retail excise tax. In addition, state and local retail sales taxes apply to marijuana and some states allow localities to impose an additional local excise tax. Illinois is the only state that varies its retail excise tax rate by product type.[7] More than half the states (including Alaska) also impose taxes at production or wholesale based on weight or average prices. Though Washington's effective tax rate is the highest, even accounting for alternative taxation schemes, there is evidence that Washington's rate is below the revenue maximizing tax rate (Hansen, Miller, and Weber, 2017b; Hollenbeck and Uetake, 2019; Miller and Seo, 2019).

In the following analysis, we focus on Washington because it was an early state to legalize (and, thus, more recent data plausibly represent a mature market), because of the public availability of data on its recreational cannabis market, and because of its policy-makers' interest in potency taxes. Washington's market grew quickly after it opened in July 2014 — while only 26 retail locations opened in the first month of legal sales, 85 stores were open by the end of the year and 352 stores had opened by the end of 2016. Regulators initially capped the number of retail licenses at 334[8] and apportioned those licenses across geographies based on the local population share. As a consequence of restricted entry, retailers are likely to have some market power.

During the ballot process, the State predicted the annual tax revenues from recreational cannabis could be as high as $389 million by using estimates of the marijuana consumption rate produced by the U.S. Department of Health and Human Services and the United Nations Office on Drug and Crime (Washington Office of Financial Management, 2013). However, this estimate did not account for changes in the prices and quantities of other goods and in the price of recreational cannabis products over time. In reality, Washington collected $150 million in cannabis tax revenues in 2015, less than 40 percent of their estimate (Miller and Seo, 2019). It is, in part, due to the substantial fall in cannabis prices since legalization that Washington lawmakers commissioned a report on potency taxes (Liquor and Cannabis Board, 2019).

A. Cannabis Chemistry and Toxicology

To the extent that potency taxes are intended to reduce externalities, it is important to understand the type and extent of such externalities. The externalities of liquor consumption are well known (e.g., Sindelar, 1998; Cook and Moore, 2002; Baumberg, 2006; Sacks et al., 2013; and many others). In this subsection, we summarize medical and public health research on cannabis plants and products with an eye toward describing potential external effects of consumption.

[7] Illinois' excise tax effectively splits the market by product and is 10 percent for usable marijuana, 20 percent for edibles, and 25 percent for concentrates.

[8] Each license entitles a retail firm to open up to three locations. See Thomas (2018) for a description of the licensing process.

Plants of genus *Cannabis* produce a group of molecules called cannabinoids in increasing concentrations as they mature. Many cannabinoids produce psychoactive effects when consumed by acting on cannabinoid receptors in the central and peripheral nervous systems (the "endocannabinoid system"), which alters rates of neurotransmitter release (Atakan, 2012; Donvito et al., 2018). While over 100 cannabinoid compounds have been isolated from *Cannabis* plants, both the industry and the academic literature largely focus their attention on Δ9-THC and cannabidiol (CBD) as they are the most significant substances in terms of percentage of dry weight and in terms of known psychophysiological effects (Amin and Ali, 2019). While a full description of the pharmacokinetics of these molecules is beyond the scope of this paper, we proceed by detailing the most relevant features of these chemicals for public health and policy purposes.

THC is the primary agent responsible for the psychoactive effects of cannabis (Walsh et al., 2017). These psychoactive effects, which are (generally speaking) the reason why people choose to consume cannabis, are dose dependent: the more THC, the stronger the effect (Ashton, 2001; Childs, Lutz, and de Wit, 2017). Thus, THC content is a relevant measure of potency — just as ethanol content (or "proof") is a relevant measure of potency for alcoholic beverages. THC is produced in the plant as tetrahydrocannabinolic acid (THCA), which must be decarboxylated by heat (by, e.g., smoking plant material) to produce bioactive THC. Because THC is fat soluble, it has a long elimination half-life relative to other common recreational drugs and can be detected by drug tests for weeks after consumption (Desrosiers et al., 2014). As a consequence, unlike alcohol, there are currently no reliable procedures or guidelines for determining acute intoxication status through physical sample collection (i.e., for law enforcement purposes).

The acute effects of THC consumption include euphoria and anxiety (Grotenhermen, 2003). While THC has low toxicity — the LD_{50} of THC in rats is 1270 mg/kg[9] (Rosenkrantz, Heyman, and Braude, 1974) and there are very few reports of deaths directly or indirectly attributed to THC overdose (Nedelman, 2019) — it has been associated with several adverse effects including impaired attention and memory, acute psychotic episodes, reduced respiratory function, and cardiovascular events, among others (Hall and Solowij, 1998; Hall and Degenhardt, 2009). These effects are likely dose dependent in the sense that more THC (either through increased consumption or greater potency) produces a greater effect (Niesink and van Laar, 2013). These effects are also more pronounced in youth (Gruber and Sagar, 2017). While cannabis intoxication is associated with decreased driving performance in simulator studies (Bondallaz et al., 2017), early data from Washington and Colorado have shown no evidence of a causal link between cannabis legalization and traffic fatalities (Hansen et al., 2018).

[9] For comparison, in rats, the LD_{50} of cocaine is 96 mg/kg, the LD_{50} of psilocybin is 280 mg/kg, and the LD_{50} of caffeine is 192 mg/kg. These measures alone may be misleading as they do not take into account the dose normally consumed to generate an effect. However, even after accounting for differences in normal consumption, cannabis is less dangerous (in the sense of the risk of acute toxicity through accidental overdose) than other recreational drugs (Lachenmeier and Rehm, 2015).

Longer-term use of cannabis is associated with liver, lung, and cardiovascular disease and is also connected to an increased risk of mental illnesses including dependency disorders, depression, chronic psychosis, schizophrenia, depersonalization disorder, mania, and suicidal ideation (D'Souza, Sewell, and Ranganathan, 2009; Gordon, Conley, and Gordon, 2013; Steenkamp et al., 2017), though causal mechanisms for many of these associations have not yet been established. Cannabis use during pregnancy is associated with lower birth weights, higher rates of miscarriage, and cognitive deficits in children exposed in utero (Wu, Jew, and Lu, 2011; Fonseca, 2013).

In contrast, CBD does not have the same level of psychoactivity as THC and may counter some of the adverse effects of THC (Niesink and van Laar, 2013; Pisanti et al., 2017), though the functional interactions between the two substances are not fully understood. Indeed, some researchers have found evidence that CBD may increase the effects of THC (Boggs et al., 2018), potentially by reducing the body's ability to eliminate THC (Klein et al., 2011). CBD is the primary component of medical cannabis treatments — among other possibilities, CBD may be an effective anti-psychosis treatment (Iseger and Bossong, 2015) and a form of CBD has been approved by the Federal Drug Administration for the treatment of certain forms of epilepsy (Stockings et al., 2018).

Other cannabinoids have received little attention. Industry sources claim that differing concentrations of these molecules, as well as differing concentrations of terpenes (a broader class of hydrocarbons produced by *Cannabis* and other plants), are responsible for much of the variation in the reported effects of consuming different preparations of cannabis plant material or material from different "strains" of the plant.[10] While many cannabinoids have been shown to interact with the endocannabinoid receptor system and terpenes are known to be bioactive, it is currently un- clear how these various molecules interact with each other in the context of cannabis consumption (Russo, 2011; Andre, Hausman, and Guerriero, 2016; Santiago et al., 2019). Non-THC cannabinoids have been found with greater activity on cannabinoid receptors in vivo than THC (Citti et al., 2019). Though the industry markets thousands of different strains, the extent to which these products have different genetics and, therefore, are truly distinct cultivars is unknown (Mudge, Murch, and Brown, 2018). In contrast to other agricultural industries (e.g., apples), producers do not have intellectual property rights over the seeds or names of different products, and so much of the differences in strains may be due to marketing.

Growers can affect the cannabinoid composition of cannabis plant material by modifying growing conditions, including the length of the growing cycle, the amount of water and fertilizer available to the plant at different stages of growth, and the quality and source of light in the growing area (Aizpurua-Olaizola et al., 2016). The potency of cannabis, as measured by the percentage of dry flower weight composed of cannabinoids, has increased substantially over the past several decades. Baker, Taylor, and Gough (1981) analyzed the THC content of cannabis samples from different countries

[10] For example https://www.leafly.com/news/cannabis-101/sativa-indica-and-hybrid-differences-between-cannabis-types; https://www.healthline.com/health/beginners-guide-to-marijuana-strains; https://www.hellodiem.com/education/12-different-strains-of-weed-and-their-effects/

and found concentrations ranging from 1 percent to 10.6 percent. From 1995 to 2014, the average potency of cannabis seized by the U.S. Drug Enforcement Administration increased from 4 percent to 12 percent (ElSohly et al., 2016) and has continued to increase in more recent seizures both in the United States and in Europe (Chandra et al., 2019). In our data, the average potency rose from 15 percent in mid-2014 to over 20 percent by mid-2017 (see Figure 1). This increase has been associated with an increase in the number of adult ER hospital visits with cannabis-related complaints (Monte et al., 2019), though it is possible that changes in social norms or other factors could also explain this increase. High-potency cannabis use has also been associated with an increased severity of dependence, particularly in youth (Freeman and Winstock, 2015; Hall and Degenhardt, 2015), and an increased risk of psychosis beyond the risk coming from consuming cannabis alone (Di Forti et al., 2009; Pierre, Gandal, and Son, 2016).

To summarize, while the full extent of internal and public health effects from cannabis consumption, particularly high-potency cannabis consumption, are unknown, the existing evidence is at least consistent with claims that THC consumption imposes either externalities (i.e., through a user's interactions with others) or internalities (i.e., users unknowingly harm their future health). While a full accounting of externalities and internalities stemming from cannabis is unlikely to be possible for some time (i.e., until natural experiments can be used with populations that have aged sufficiently to reveal the consequences of long-term use), the current evidence is tentatively consistent with the claim (often made by advocates for cannabis legalization) that cannabis consumption is "safer" than alcohol consumption, at least in terms of traffic and overdose fatalities.

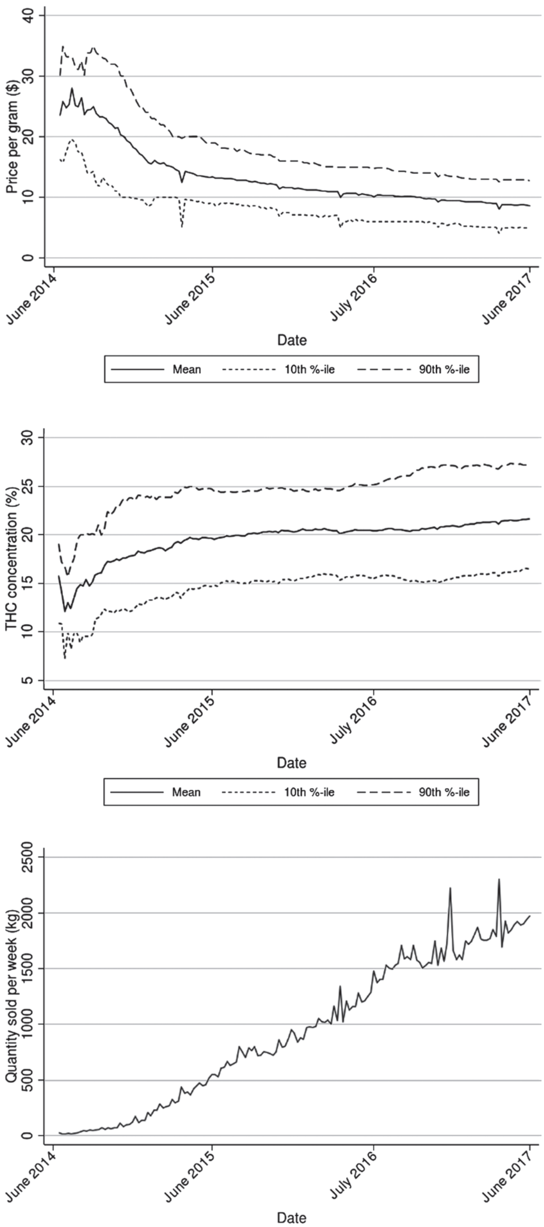
B. Potency Testing

The successful implementation of a potency tax in any state requires effective monitoring of product potency and auditing of test facilities. In this subsection, we describe the variety of rules and regulations surrounding potency testing in current cannabis markets.

Each state with a functioning recreational cannabis market requires potency testing for all cannabis products by an independent accredited laboratory before they can be sold at retail. As cannabis flowers are not homogeneous within or across plants, cannabinoid potency testing is an inherently noisy process as opposed to, for example, testing for alcohol content in containers of well-mixed liquids (GemmaCert, 2018). Common testing procedures, such as liquid chromatography and near-infrared spectrometry, are themselves noisy processes (Hazekamp et al., 2005). As a consequence, each state's laws require potency tests to be performed on a "representative" sample. However, the degree to which the sample selection and testing process is regulated varies widely. Table 2 summarizes the regulatory schemes across different states. California's regime is arguably the most restrictive: The sampling must be done at the production site by an employee of the laboratory who is individually financially independent from the production and retail side of the industry (as opposed to simply requiring that the laboratory itself is financially independent); the law specifies that the sample must be comprised of up to 34 equal-weight "increments" taken from "random and varying locations, both

Figure 1

The Evolution of Washington's Market over Time



Note: Data are aggregated to the weekly level; for example, a point in the top-left graph represents the mean (or 10th percentile, or 90th percentile) price per gram for a flower item sold in that week.

Table 2
Summary of Potency Testing Regulations by State

	AK	CA	CO	IL	MA	ME	MI	NV	OR	WA
Lab employee must obtain sample?	No	Yes	No	Yes	No	Yes	Yes	Yes	Yes	No
Sample size specified by law?	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes
Multiple sub-samples required by law?	Yes	Yes	Yes	No	No	Yes	No	No	Yes	Yes
Sampling methodology specified by law?	No	Yes	No	No	No	No	No	No	Yes	No

Note: This table includes every state where recreational cannabis is sold as of December 2019.

vertically and horizontally" that sum to at least 0.05 percent of the total product weight to ensure the homogeneity and representativeness of the sample (16 CCR § 5707). In contrast, Massachusetts allows firms to collect and submit their own samples and, in the case of solid cannabis plant material (i.e., dry flower), merely recommends (instead of requiring) the use of subsamples to promote homogeneity (935 CMR 500.160). Washington's regime falls somewhere in the middle: While producers collect samples themselves and submit them to laboratories, state regulations require a minimum number of subsamples of a minimum weight that depends on the size of the production batch.

These differing regulations, combined with industry knowledge about factors leading to differential cannabinoid concentrations within and across plants, offer producers seeking to manipulate potency test results a multitude of opportunities. For example, when firms are allowed to choose their own samples, even if some or all of the sample selection procedure is codified by law, operators may be able to manipulate the construction of the product batches to place plant material with greater or lesser than average potency in a physical position that makes them more likely to be sampled. In states where lab employees must obtain the samples themselves, repeated interactions with the same samplers may offer firms the opportunity for similar physical manipulations. All states allow producers to choose the lab that performs the test, and so even if labs are nominally financially independent from producers and retailers, market forces may promote the survival of labs that either directly or indirectly assist producers in obtaining desired potency test results.[11] Firms willing to break additional regulations may be able to mix tested and untested cannabis plant material, or mix material of different known

[11] In our data, average potency varies by the lab performing the test from 17 percent to 24 percent, though this could be explained by a number of alternative factors.

concentrations, before retail sale. Each of the possibilities in this non-exhaustive list may be more or less costly for firms depending on the intensity of monitoring by state regulators.[12] Indeed, if monitoring is sufficiently lax, firms may be able to evade taxes by reporting different potency test results to the government and to retail customers; however, we consider this scenario unlikely given the traceability systems that are typically in place.[13]

III. A FRAMEWORK FOR ANALYZING A POTENCY TAX

In this section, we present a simple framework for analyzing the effects of a potency tax. Our framework focuses on the key institutional details presented in the previous section: namely that firm entry is limited and so retailers have substantial market power (Hollenbeck and Uetake, 2019) and the idea that firms have some capacity to choose the level of potency in their products either through alterations to the production process or by manipulating potency test results.[14] To estimate the effects of a potency tax using data generated in an environment with an ad valorem tax, we include both an ad valorem tax and a tax on potency in this framework.

Consider a monopolist retailer selling a single good. The firm sets the tax-inclusive price of the good p and also a single product "potency" characteristic (i.e., THC or alcohol content) x. The firm faces a per-unit potency tax τ_x (in units of dollars per unit of potency per unit of the good). We define the tax in this way as it is the most commonly proposed form of potency tax.[15] Consumers pay an ad valorem tax τ_p (expressed as a percentage of the tax-exclusive price) and the firm sets the tax-inclusive price p (so that the firm earns $p/(1 + \tau_p)$ per unit sold). Consumer demand $q(p, x)$ is a function of the price and the potency and is assumed to feature constant demand elasticities (ε_p, ε_x) with respect to both characteristics. Marginal costs vary with the potency via

$$(1) \quad mc(x) = c + (\gamma + \tau_x)x.$$

In this equation, c represents marginal costs that are independent of potency and γ is the marginal cost of an additional unit of potency. The marginal costs of additional potency are either costs associated with growing more potent marijuana (e.g., allow-

[12] Monitoring practices vary widely — in Washington, processors are visited by regulators an average of four times per firm per year, whereas in Oregon, only one-third of growers have been visited by regulators post-licensing (Harbarger & Crombie, 2019).

[13] For example, in Washington, labs report potency test results directly to the government. The results can then be linked to any retail inventory containing plant material involved in the test. In other words, assuming some degree of technical sophistication on the part of regulators, an auditor could visit a retail store, scan a product's barcode, and check if the advertised potency matches the potency test result.

[14] We refer to this behavior as avoidance, though evasion behavior is also possible.

[15] Indeed, Washington commissioned a feasibility study of "taxing cannabis products by THC content expressed as a number of milligrams" (Liquor and Cannabis Board, 2019).

ing plants to grow for a longer period of time) or with manipulation during the testing process (e.g., sending in samples that are more likely to give a particular THC reading). We assume marginal costs are independent of q as growers are generally not capacity constrained and can simply add plants to existing grow operations to increase the quantity they produce (Hansen, Miller, and Weber, 2017b).

The firm's profit function is $\pi(p,x)=\left(\frac{p}{1+\tau_p}-mc(x)\right)\cdot q(p,x)$. The first-order conditions for profit maximization, therefore, are

$$(2)\quad \{x\}:0=\left(\frac{p}{1+\tau_p}-c-(\gamma+\tau_x)x\right)\frac{\partial q}{\partial x}-(\gamma+\tau_x)q$$

$$\{p\}:0=\left(\frac{p}{1+\tau_p}-c-(\gamma+\tau_x)x\right)\frac{\partial q}{\partial x}+\frac{q}{1+\tau_p}.$$

A closed form solution to the firm's problem can be found using the fact that the price and potency elasticities of demand are constant. The firm's optimal choices are given by

$$(3)\quad x=-\frac{\varepsilon_x}{\varepsilon_p+\varepsilon_x+1}\cdot\frac{c}{\gamma+\tau_x}$$

$$p=\frac{\varepsilon_x}{\varepsilon_p+\varepsilon_x+1}\cdot c(1+\tau_p).$$

Note that given the assumptions in our model, p is separable from x; changes in the marginal cost of potency or the tax rate on potency do not affect p and changes in the ad valorem tax rate do not affect the choice of x. Furthermore, because the tax-exclusive price is equal to $p/(1+\tau_p)$, it does not rely on τ_p and, therefore, the model features full pass-through from ad valorem taxes to consumers. Conversely, as p is not affected by τ_x, the firm may be thought of as fully internalizing the cost of any potency tax. However, as it reduces potency in response to any increase in the potency tax (the partial derivative of x with respect to τ_x is negative), consumers do "pay" the potency tax in the sense that the price per unit of potency changes in response to the tax. To illustrate this, note that the tax-inclusive price per unit potency p/x depends on the ratio of the two demand elasticities per

$$(4)\quad \frac{p}{x}=-\frac{\varepsilon_p}{\varepsilon_x}(1+\tau_p)(\gamma+\tau_x).$$

This equation also reveals that the pass-through rate of both taxes in terms of the effective cost of potency to consumers is a function of not just the elasticities but the current sizes of both tax types.

Finally, it is straightforward to solve these equations for the two cost parameters as a function of data and demand parameters with

$$(5) \quad c = \frac{\varepsilon_p + \varepsilon_x + 1}{\varepsilon_p} \cdot \frac{p}{1+\tau_p}$$

$$y = -\frac{\varepsilon_x}{\varepsilon_p} \cdot \frac{p}{\left(1+\tau_p\right)x} - \tau_x .$$

Though this model captures key features of substance markets relevant to the imposition of a substance tax, the assumptions we impose create limitations. Chief among these is that the model does not allow for substitution between goods — indeed it assumes that there is only one good of the type being taxed and that the firm is the sole provider of that good. The separability of p and x with respect to the tax rates is a consequence of assuming that the elasticity of demand with respect to both characteristics is constant. If, for example, changes in the price or potency of substitutes change the demand elasticities for this firm's good, our estimates of responses to potency taxes may be biased in either direction depending on the direction of the interaction with the substitute goods.

We proceed in Section IV by estimating a log-log demand equation. After recovering ε_p and ε_x, we use Equation (5) along with the data to back out costs and then use Equation (3) to estimate counterfactual prices and potencies under alternative taxation regimes.

IV. DATA AND METHODS

To examine the role of potency in recreational cannabis markets, we analyze public records from Washington's internal regulatory "traceability" system designed to track each marijuana product from "seed to sale." Broadly speaking, Washington's regulatory system creates a three-step supply chain. Producers grow *Cannabis* plants and harvest the raw plant material. Processors, which may be vertically integrated with producers, convert that material into usable marijuana (i.e., dried flower) and other cannabis products (i.e., edibles and concentrates), package those products, and combine them into homogenous "inventory lots." Usable marijuana must be packaged into units of preset sizes (e.g., 1 gram, 2 grams, or 3.5 grams). Retailers, which must be financially independent from producers and processors, purchase wholesale inventory lots from processors and sell individual products to final consumers. Each inventory lot identifier, therefore, represents a unique combination of strain, manufacturing batch, package size, processor, and retailer.[16]

[16] This means that inventory lot identifiers, while playing the same role within retailers' point-of-sale data systems as a universal product code (UPC) in other retail markets, are far more specific. For example, a 3.5-gram package of usable marijuana from the "Jack Herer" strain produced by "Keaton's Kush Garden" and sold by "Caroline's Cannabis Collective" will have a different inventory lot identifier if the flower comes from plants grown and processed in different batches.

We focus on the retail side of the market. We observe, for each retail transaction, the quantities of each inventory lot sold and the tax-inclusive prices paid by consumers. We link each transaction to product-level data on strain and potency test results.[17] We focus on usable marijuana as the largest category of products (roughly 70 percent of sales revenue) and the category with the greatest variance in potency.

We apply some cleaning steps to our data following the procedure described by Hansen et al. (2018). Most of the details of that paper are focused on the technical features of the administrative data set and the process needed to transform the raw database into a form usable for research. For the purposes of this analysis, the most relevant steps are adjustments to prices that reflect systematic changes in the state's reporting system and third-party tools used by many firms, as well as the cleaning and standardization of user-entered strain names. The first step uses changes in local tax rates and publicly posted menu prices to identify the data entry methodology for each firm, and the second step uses lists of strains from industry websites.[18] We drop observations where we suspect data entry errors (e.g., transactions that exceed the legal limit) and where potency data are unavailable. These exclusions represent 3.8 percent of the raw data. We then aggregate our data to the inventory-lot-week level to avoid cyclical day-to-day variation in sales and idiosyncratic differences in reporting behaviors — the level of our observations, therefore, is similar to demand analyses using Nielsen scanner data aggregated to the UPC-store-week level (DellaVigna and Gentzkow, 2019; Butters, Sacks, and Seo, 2019a,b). Except for Figure 1, where we examine the market over time, we restrict our data set to the most recent year of data we have available — fiscal year 2016 (July 2016–June 2017) — to obtain estimates that are closer to what will happen in the long-run equilibrium of the market.

Table 3 summarizes our data. In total, there are 3.4 million inventory-lot-week observations covering over 773,000 unique inventory lots. The mean and median THC concentration is approximately 20 percent, while the mean CBD concentration is less than 1 percent.[19] On average, 22.8 grams are sold per inventory-lot-week at an average all tax-inclusive price of $10.05 per gram.

These averages obscure the time-varying nature of the data as Washington's market evolved. Figure 1 illustrates features of the distribution of prices and THC concentrations over time, as well as the total weight sold by week. The market has expanded considerably, growing from roughly 500 kg per week in June 2015 to nearly 2,000 kg per week by June 2017. Average THC concentrations hovered near 15 percent in the first six months of retail sales, increased slowly to 20 percent over the next year, and in more recent data reached 22 percent. Average prices have dropped considerably, from approximately $25 per gram in the market's first months to less than $10 per gram in June 2017.

[17] THC concentrations are reported as either percent of dry weight comprised of THC and/or THCA. We convert THCA to THC with $THC_{total} = THC + 0.877 \times THCA$ (Baker, Taylor, and Gough, 1981).

[18] https://www.leafly.com/strains and https://www.allbud.com/marijuana-strains/search.

[19] CBD concentrations are much higher for cannabis sold in the medical market, which is not included in our data. Only 2.4 percent of the observations in our data have CBD concentrations above 1 percent.

Table 3

Summary Statistics

Variable	Mean	10th %-ile	Median	90th %-ile
		Cannabis		
Weight (grams)	22.85	2	10	52.5
Retail price ($/gram)	10.05	5.97	10.00	13.99
Wholesale price ($/gram)	3.27	2	3.33	4.47
Potency				
THC	20.29	15.11	20.47	27.69
CBD	0.285	0	0	0.3
Observations	3,575,345			
Unique inventory lots	773,558			
		Liquor		
Unit sold	3.17	1	2	6
Volume sold (liters)	2.02	0.75	1.5	4.5
Price ($ per unit)	20.62	9.23	18.48	34.30
Price ($ per liter)	30.71	16.59	24.64	51.73
ABV	37.32	33	40	40
Observations	3,243,305			
Unique brands	323			

Notes: An observation in the top panel is an inventory-lot-week (similar to a UPC-store-week). An observation in the bottom panel is a UPC-store-week. Prices include all taxes. Liquor retail taxes are 20.5 percent of sales plus $3.7708 per liter. THC and CBD concentrations are reported as percentages of dry weight on a scale of 0 to 100. Liquor ABV is the percentage of alcohol by volume.

We will compare our marijuana estimates to similarly constructed liquor estimates. We obtain prices, sales, and descriptions of liquor products from the Nielsen Retail Scanner Dataset for Washington from 2012 to 2016. We focus on liquor as it is the only category of alcohol products for which alcohol content information is available. For a subset of stores, the Nielsen Dataset also records whether a product is featured and/or displayed that week at the store. The bottom panel of Table 3 summarizes our 3 million UPC-store-week liquor observations. There are 661 stores selling liquor products with more than 1,800 unique products (UPCs) and 300 brands.[20] We consider brand as an analogue of "producer-processor combination" and UPC as an analogue of "strain-producer-processor combination." The typical product has a package size of 750 ml — we present data and results in per-liter terms. The average alcohol content (in terms of percentage ethanol, or ABV) is 37.32 — the median is 40. On average, there

[20] We define brand as a group of products sharing the first two words in the Nielsen variable brand_descr as brand_descr on its own is too granular. For example, we treat Jack Daniel's Country Cocktail and Jack Daniel's Single Barrel, which have different brand_descr, as one brand, "Jack Daniel." This is analogous to our treatment of strain names in the cannabis data.

are five products in a brand (the median is two) with some but not substantial variation in ABV as the average standard deviation of ABV within a brand is 2.33. A brand in a given week is available at 120 stores, on average, with a median of 25. Each store-week carries about 13 unique brands on average and 11 in the median.

To analyze the relation between potency and demand or prices, we use a log-log specification that follows the demand model of Section III. For some cannabis inventory lot *j* and week *t*, we model our outcome (quantity of grams sold or price per gram) y_{jt} as function of potency and fixed effects via

$$(6) \quad \log(y_{jt}) = \beta_0 + \beta_1 \log(price_{jt}) + \beta_1 \cdot \log(THC_j) + \beta_2 \cdot \log(CBD_j) + FX_{jt} + \varepsilon_{jt}.$$

In this equation, THC_j and CBD_j represent the (fixed) concentration of THC and CBD in inventory lot *j*, respectively, and $price_{jt}$ represents the tax-inclusive price per gram ($price_{jt}$ is dropped as a covariate when it is the dependent variable). FX_{jt} includes retailer-week fixed effects and other fixed effects designed to capture unobservable non-potency product characteristics; in our primary specification, we use retailer-strain and retailer-week fixed effects. We assume that THC and CBD are fixed from the perspective of the retailer at the time of price setting and are, thus, exogenous. We instrument final prices using the wholesale price for that inventory lot.

In our most saturated model, we include retailer-strain, retailer-week, producer, and processor fixed effects. In this model, identification of potency coefficients is coming from variation in potency across inventory lots of the same strain, which are manufactured by the same producer and processor and sold by the same retailer but which come from different harvests of plant material.[21] Given our instrument, the coefficient on price is identified from the same variation.

As a comparison, we estimate the equivalent of Equation (6) for liquor. Let *j* indicate a liquor UPC and *s* be store. We model the quantity of liters sold (or price per liter) y_{jst} via

$$(7) \quad \log(y_{jst}) = \alpha_0 + \alpha_1 \cdot \log(price_{jst}) + \alpha_2 \cdot \log(ABV_{jt}) + FX_{jst} + \varepsilon_{jst},$$

where $price_{jst}$ is the tax-inclusive price per liter (this variable is excluded when prices are the dependent variable) and ABV_{jt} represents the fixed alcohol content for UPC code *j*. We include an extensive set of fixed effects: package size, retailer-week, and brand-retailer; we consider "brand" equivalent to the producer-processor combination.[22] We instrument prices with Hausman-style instruments — the average price for a given UPC-week in stores in non-contiguous counties.[23] Our most saturated model includes retailer-brand, retailer-week, unit size, and in-store advertising fixed effects. The identification of the potency effect, therefore, comes from variation in the alcohol content

[21] This is similar to estimating the demand for wine of different vintages from the same producer (Combris, Lecocq, and Visser, 1997).

[22] We cannot include UPC fixed effects as they are perfectly collinear with ABV.

[23] Nielsen does not reveal the exact location of the store, only the county in which the store is located. Nielsen does not have data on wholesale prices.

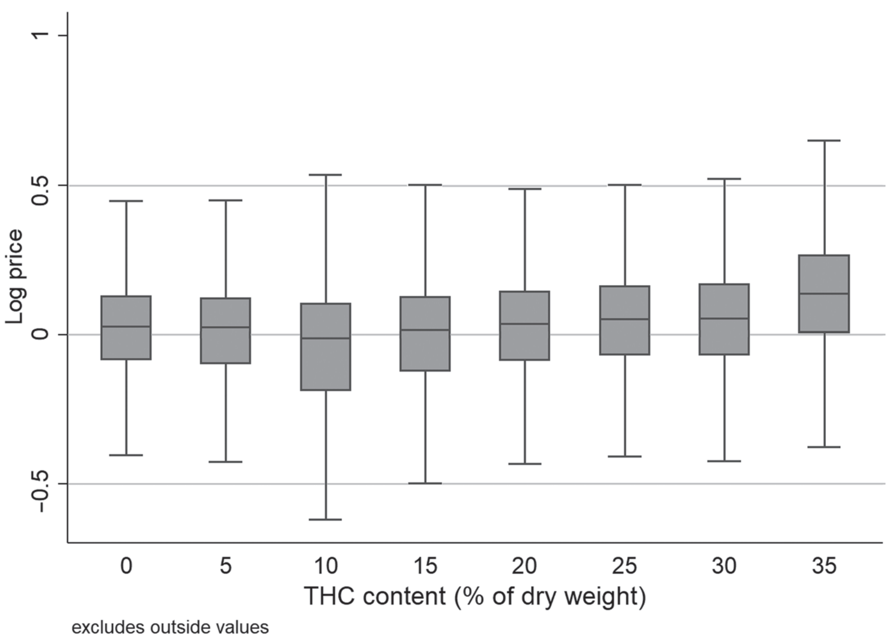
of different products (at one time or over time) offered by the same retailer and brands that are not due to in-store advertising. The coefficient on price is identified through the Hausman assumption of common cost shocks across geographies that are independent of local demand shocks (Hausman, Leonard, and Zona, 1994).

V. RESULTS

In this section, we report our results on the sensitivity of prices and demand for cannabis and liquor to potency. Figure 2 provides a box plot of log prices across values of THC, removing retail-strain and retail-week fixed effects. This figure highlights a weak relationship between THC and prices, suggesting that the assumptions of our framework for analyzing potency taxes are reasonable and that ad valorem taxes may not be very effective at reducing the potency of marijuana in the marketplace. Table 4 echoes the story of Figure 2 by estimating the relationship between prices and THC content after accounting for retail-week and retail-strain fixed effects. We find that a 1 percent increase in THC leads to a 0.20 percent increase in the price per gram of usable marijuana. Once we control for the producer and processor, the estimate is only 0.11. In Table 5, we present

Figure 2

The Distribution of Log-Prices by THC Content



Notes: Log prices are demeaned by retailer-week and retailer-strain fixed effects. Sample restricted to the last year of data.

Table 4

The Association between Prices and THC Content for Usable Marijuana

	Log Price per Gram			
	(1)	(2)	(3)	(4)
Log THC content	0.1984***	0.1169***	0.1133***	0.1083***
	(0.0092)	(0.0065)	(0.0065)	(0.0064)
Fixed effects				
Week × Retailer	Yes	Yes	Yes	Yes
Strain × Retailer	Yes	Yes	Yes	Yes
Producer	No	Yes	No	Yes
Processor	No	No	Yes	Yes
Obs.	3,570,386	3,570,384	3,570,382	3,570,382
R^2	0.5570	0.6272	0.6328	0.6382

Notes: An observation is an inventory-lot-week. The dependent variable is the log of the average price per gram for that inventory lot in that week. THC content is reported as the percentage of dry weight on a scale of 0–100; see Table 3 for summary statistics. All specifications control for CBD concentration. Standard errors, reported in parentheses, are robust to heteroskedasticity and calculated adjusting for clustering at the location level. Estimates obtained via the *reghdfe* package in Stata (Correia, 2014). Observation counts differ across specifications due to dropping singleton observations. ***Denotes significance at the 1 percent level.

Table 5

The Association between Prices and Alcohol Content for Liquor

	Log Price per Liter	
	(1)	(2)
Log alcohol content	0.1647***	0.1668***
	(0.0080)	(0.0201)
Fixed effects		
Unit size	Yes	Yes
Week × Retailer	Yes	Yes
Brand × Retailer	Yes	Yes
Feature, Display	No	Yes
Obs.	3,229,006	506,498
R^2	0.92	0.94

Notes: An observation is product-store-week. The dependent variable is the log price per liter — the log of the average tax- inclusive retail price per liter in each store-week. Liquor retail taxes are 20.5 percent of sales plus $3.7708 per liter. Alcohol content is reported as percentage ethanol by volume on a scale of 0–100; see Table 3 for summary statistics. We consider brand equivalent to producer-processor combination in cannabis. Standard errors, reported in parentheses, are robust to heteroskedasticity and calculated adjusting for clustering at the store level. Observation counts differ across specifications due to singleton observations and Feature and Display variables, which have existed since 2013. ***Denotes significance at the 1 percent level.

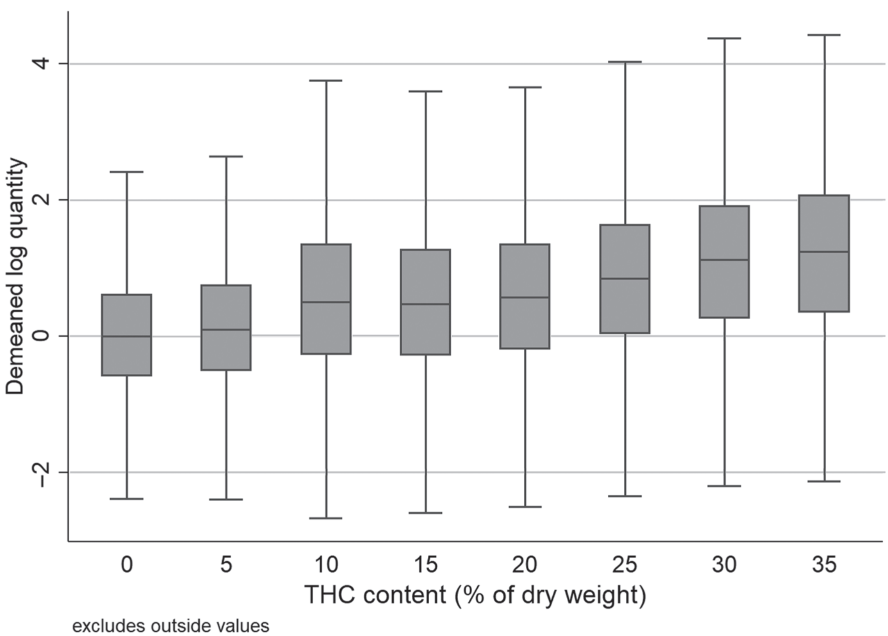
analogous estimates for liquor and find broadly similar results — a 1 percent increase in ABV leads to a 0.16 percent increase in the liquor price per liter.

In contrast, Figure 3 provides a box plot of log quantities across values of THC, again removing retail-strain and retail-week fixed effects. This figure highlights a positive and arguably stronger relation between THC and quantity, suggesting that, even after accounting for differences in strains, consumers prefer more potent products.

Tables 6 and 7 report the findings of regression analysis that further supports this conclusion across both the cannabis and liquor markets. Table 6 presents cannabis results from the estimation of Equation (6). All columns control for CBD concentration, retail-week fixed effects, and retail-strain fixed effects. In Column (1), we estimate the effect of THC and prices on the number of grams sold out of an inventory lot in one week. We find that for a 1 percent increase in THC, the quantity of grams sold in that inventory lot increases by 0.61 percent. Our elasticity of demand with respect to price is –1.2. The remaining columns introduce producer and processor fixed effects to control for unobservable determinants of demand at the processor or producer level. The additional fixed effects do not have substantial effects on either of our reported coefficients.[24]

Figure 3

The Distribution of Log-Quantities by THC Content



Notes: Log quantities are demeaned by retailer-week and retailer-strain fixed effects. Sample restricted to the last year of data.

[24] We have also explored specifications which eliminate the tails of the THC distribution and found similar results.

Table 6

The Association between THC Content, Prices, and Quantities for Usable Marijuana

	Log Grams Sold			
	(1)	(2)	(3)	(4)
Log price	–1.1965***	–1.2059***	–1.1698***	–1.1689***
	(0.0476)	(0.0596)	(0.0609)	(0.0620)
Log THC content	0.6077***	0.5756***	0.5816***	0.5753***
	(0.0223)	(0.0202)	(0.0203)	(0.0201)
Fixed effects				
Week × Retailer	Yes	Yes	Yes	Yes
Strain × Retailer	Yes	Yes	Yes	Yes
Producer	No	Yes	No	Yes
Processor	No	No	Yes	Yes
Obs.	3,570,386	3,570,384	3,570,382	3,570,382
First-stage F-stat.	354.3	279.3	273.9	268.7

Notes: An observation is an inventory-lot-week. The dependent variable is the log of the grams sold from the inventory lot in the week. THC content is reported as the percentage of dry weight on a scale of 0–100; see Table 3 for summary statistics. Prices are instrumented using the wholesale price per gram. All specifications control for CBD concentration. Standard errors, reported in parentheses, are robust to heteroskedasticity and calculated adjusting for clustering at the location level. Estimates obtained via the *ivreghdfe* package in Stata (Correia, 2014). Observation counts differ across specifications due to dropping singleton observations. Reported F-statistics are Kleibergen–Paap Wald statistics, which are robust to heteroskedasticity (Stock and Yogo, 2005). ***Denotes significance at the 1 percent level.

Our estimates of the price elasticity of demand are in line with the literature, given the nature of our specification. Miller and Seo (2019) estimate a multi-stage budgeting model at the county-category-month level and find a price elasticity of demand of usable marijuana products as a category of –1.13 (the reported standard error is 0.22). Hollenbeck and Uetake (2019) estimate a nested logit model of demand at the retailer-category-month level and find own-price elasticities between −2.85 and −3.06. The differences between these estimates largely stem from differences in the treatment of potential substitutes. Following our conceptual framework, we estimate the price elasticity of demand for flower products without considering the set of potential substitutes. As prices of similar products often co-move in our data, our price elasticity estimate can be thought of as an aggregated cannabis-wide estimate. Indeed, Hollenbeck and Uetake (2019) report aggregate price elasticities between −1.08 and −1.13, very similar to our own estimates. Neither of these papers considers the potency of the products under consideration.

Table 7 estimates the analogous model for liquor — Equation (7). All regressions include unit size and retailer-week fixed effects, which control for store specific time varying factors, such as the number of cannabis retailers close to the observed store. The first column in Table 7 is analogous to Column (4) of Table 6. It regresses the log of the quantity sold on log ABV and log price per liter with additional brand-retailer

Table 7

The Association between Alcohol Content, Prices, and Quantities for Liquor

	Log Liters Sold	
	(1)	(2)
Log price	–1.1493***	–1.3343***
	(0.0496)	(0.0636)
Log alcohol content	1.0619***	1.0670***
	(0.0326)	(0.0818)
Fixed effects		
Unit size	Yes	Yes
Week × Retailer	Yes	Yes
Brand × Retailer	Yes	Yes
Feature, Display	No	Yes
Obs.	3,148,163	491,989
First-stage F-stat.	629.61	267.76

Notes: An observation is a retail sale of a product per store-week. The dependent variable is the log of liters sold. Log price is the log of the average tax-inclusive retail price per liter in each store-week, and it is instrumented by non-contiguous Hausman instruments. Liquor retail taxes are 20.5 percent of sales plus $3.7708 per liter. Alcohol content is reported as percentage ethanol by volume on a scale of 0–100; see Table 3 for summary statistics. We consider brand equivalent to producer-processor combination in cannabis. Standard errors, reported in parentheses, are robust to heteroskedasticity and calculated adjusting for clustering at the store level. Observation counts differ across specifications due to singleton observations, lack of instruments for some observations, and Feature and Display variables, which have existed since 2013. ***Denotes significance at the 1 percent level.

fixed effects; we consider brand equivalent to producer-processor. Price is instrumented by non-contiguous Hausman instruments. Column (2) of Table 7 includes Feature and Display fixed effects — indicating whether a product is featured and displayed that week at a store — which control for non-price promotional activities that may be correlated with price. These variables are available for only a subset of stores. Price elasticity is estimated at –1.33 and the elasticity with respect to ABV is close to 1. This estimated price elasticity is close to what Miller and Seo (2019) find (–1.10 with a standard error of 0.12).

Comparing liquor and cannabis, we find that the liquor potency elasticity is significantly larger than the cannabis potency elasticity (almost twice as large in some specifications), suggesting that, all else equal, the average cannabis consumer is less concerned about reported potency than the average liquor consumer. This could be driven by different underlying preferences for potency in the two markets or a recognition by consumers that the potency information received about cannabis products is inherently noisier. This result suggests that liquor firms may have a smaller incentive to change potency, either through altering production processes or engaging in tax avoidance behavior, than cannabis firms. This, in combination with the fact that THC potency is so inherently variable within each batch, giving rise to a number of different ways to engage in relatively low cost tax avoidance, means that it will be particularly important for state governments to set up a regime in which avoidance is more difficult and be vigilant for new forms of tax avoidance that may crop up. We return to the issue of avoidance and monitoring in our conclusion (Section VI).

A. The Effects of Potency Taxes on Cannabis and Liquor Markets

We use the model of Section III along with our preferred specifications (Column (1) of Table 6 for cannabis, Column (2) of Table 7 for liquor) to characterize the consequences of imposing a potency tax on both cannabis and liquor in Table 8. The first column of each panel reflects the average prices, potency, and quantities for each good in our estimation sample. We use Equation (5) to back out the marginal cost of potency production for each good; for cannabis, we estimate that the cost of an additional percentage point of THC is \$0.17 per gram, whereas the cost of an additional percentage point of alcohol in liquor is \$0.55 per liter. For comparison, commodity ethanol prices ranged between \$0.38 and \$0.57 on January 14, 2020.[25]

We consider potency taxes based on a "naïve" policy. We calculate the tax that would be necessary to generate the same level of revenue as the ad valorem tax under the assumption of zero supply or demand response.[26] For cannabis, that tax is \$0.126 per percentage point of THC per gram, whereas for liquor, the tax is \$0.140 per percentage point of alcohol per liter. We then use Equation (3) to predict prices and potencies and our demand results to predict the resulting quantities and tax revenues. For cannabis, the naive tax is roughly equal to the marginal cost of THC production and so the THC content is roughly halved. At the same time, the removal of the ad valorem tax decreases the tax-inclusive price faced by consumers. The net result of these changes is a slight increase in the quantity purchased. However, the decrease in potency more than offsets this change and so the total revenue decreases relative to the baseline. To flesh out the shape of the revenue curve, we also report results for a potency tax that is half of the naive tax and a potency tax that is twice the naive tax. In the "half naive" case, though the potency and quantity are higher than in the naive case, the increase is insufficient to make up for the lower tax rate and so total revenue is lower. In the "twice naive" case, the potency and quantity are lower, but the increase in the tax more than offsets this change and so total revenue is higher than the naive case, though not as high as under current policy. Indeed, according to our model, there is no potency tax for cannabis that earns as much revenue as the current policy.

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[25] See https://grains.org/ethanol_report/ethanol-market-and-pricing-data-january-14-2020/. We are aware of no similar comparison figure for the cost of THC production.

[26] This is calculated by dividing the current ad valorem tax revenue by the current quantity times the current potency.

Table 8

The Effects of a Potency Tax on Cannabis and Liquor Potencies, Quantities, and Tax Revenues

	Cannabis				Liquor			
	Data	Half Naive	Naive	Twice Naive	Data	Half Naive	Naive	Twice Naive
State and local sales tax (%)	8.4	8.4	8.4	8.4	0	0	0	0
Ad valorem tax (%)	37	0	0	0	20.5	0	0	0
Potency tax ($ per % per unit)	0	0.063	0.126	0.252	0	0.070	0.140	0.280
Tax-inclusive price ($ per unit)	10.05	7.49	7.49	7.49	30.71	25.49	25.49	25.49
Potency (%)	20.32	14.89	11.76	8.27	37.32	33.08	29.70	24.67
Tax-inclusive potency price ($ per % per unit)	0.49	0.50	0.64	0.91	0.82	0.77	0.86	1.03
Quantity (per UPC-week)	22.84	26.87	23.27	18.80	2.02	2.28	2.03	1.67
Tax revenue ($ per UPC-week)	71.67	40.79	47.95	50.04	10.55	5.27	8.44	11.51

Notes: Units are grams for cannabis and liters for liquor. Estimates are based on Column (3) of Table 6 for cannabis and Column (4) of Table 7 for liquor. The naive potency tax rate is the tax rate that would earn the same revenue as the ad valorem tax if there was zero potency or demand response: $rate_{naive} = revenue_{data}^{advalorem} / (quantity_{data} \times potency_{data})$.

These results illustrate a key implication of our model. In a perfectly competitive setting with elastic supply given by constant marginal costs, the revenue implications of tax changes are inversely proportional to the elasticity of demand with respect to the characteristic being taxed. One might think that because demand for cannabis is price elastic and THC inelastic, the naive policy should result in more revenue than the current policy. However, in this setting, which features market power, the potency tax is filtered through the lens of the firm's profit maximization problem. Per Equation (3), the degree to which the firm changes potency in response to the introduction of the naive tax depends upon the size of the tax relative to the marginal cost of potency; because the size of the naive tax relative to the cost of production is smaller for liquor than for cannabis, the relative decrease in potency is smaller as well and indeed the revenue under the naive policy is closer to the current policy than for cannabis. The increase in revenue when doubling the potency tax from the naive policy depends, in part, on the incidence of the tax to the tax-adjusted potency price. Per Equation (4), this price changes according to the ratio of the demand elasticities. Both goods are more elastic with respect to price than with respect to potency, and so the incidence of the potency tax on the tax-inclusive potency price is greater than one for both goods. Because the price/potency elasticity ratio is greater for cannabis than for liquor, the incidence is greater as well. These level and percentage effects combine to produce the result that doubling the naive tax for cannabis does not result in sufficient revenue to match the revenue from the current ad valorem tax, while doubling the naive tax for liquor results in revenue exceeding the current policy.

The marginal cost of potency that we estimate for cannabis includes the true cost of increasing potency as well as any manipulation of THC test results through sample selection occurring in Washington's market during our sample period. In the absence of a potency tax, firms have a demand-driven incentive to manipulate tests to generate increases in reported THC content. In the presence of a potency tax, this incentive would be reduced or could potentially change sign — it may be cost minimizing to continue to grow cannabis plants using existing methods and then manipulate tests toward lower THC content. This would be reflected in our model as a decrease in the marginal cost of producing potency. This tax avoidance would result in lower potency for the tax base (though a higher true potency for consumers) and would, unfortunately, both decrease revenue and reduce the impact of the potency tax on negative externalities.

VI. CONCLUSION

Seeking both to provide a bulwark against the impact of falling cannabis prices on ad valorem tax revenues and to dissuade the consumption of high-potency cannabis, which may have higher externalities, lawmakers in several states are considering the imposition of a potency tax. In this paper, we investigate the potential effects of such a tax on recreational cannabis markets. We develop a theoretical model and estimate the demand for marijuana potency using administrative data from Washington state. We also estimate similar models for alcohol, to compare the efficacy of a potency-based tax for an alternative sin good.

We find marijuana demand is more sensitive to price than to potency. Our counterfactual analysis suggests replacing the current ad valorem tax of 37 percent with a naive potency tax of \$0.126 per percentage point of THC per gram — the tax that would generate the same level of revenue as the ad valorem tax under zero demand or supply response — would reduce average potency by 27 percent and increase quantities by 2 percent, while the tax-inclusive retail price of marijuana would fall by 37 percent. Notably, tax revenues fall by 33 percent. The total level of THC consumed would fall by 41 percent. If the level of cannabis externalities is proportional to the total level of THC consumed, the naive potency tax would also reduce these externalities.

Our estimates suggest that increasing the potency tax would reduce potency even further, while marijuana sales would fall below current levels. However, even doubling the potency tax would not increase revenue to the level of Washington State's current ad valorem tax. In short, potency taxes may successfully reduce potency, but our approach suggests even extremely high THC taxes (relative to the cost of production) would fail to generate the revenue traditional ad valorem taxes create. It might seem counterintuitive that taxing potency, which we estimate to be less elastic, generates less revenue than ad valorem taxes. This result is a consequence of market power — the potency tax is filtered through firms' profit maximization problems so demand responses are exaggerated; the firm knows it can easily cut back on THC without losing many sales due to its inelastic nature.

In contrast, we find a potency tax on liquor could exceed the revenue currently obtained from the ad valorem tax. This is, in part, because we find that liquor demand is more elastic with respect to potency (so firms with market power cannot decrease alcohol content as much without losing sales) and because the relevant tax rates are much smaller than the marginal costs of potency production.

To the extent that higher potency products create larger externalities, a potency tax in this context can represent a Pigouvian tax, which adjusts the price of potency to reflect the social costs of consumption. However, Washington's laws specifically allocate a portion of cannabis tax revenues toward alternative avenues for reducing externalities, such as substance-abuse education and treatment programs (RCW 69.50.540). As a potency tax results in less revenue, these programs will need to be funded from other revenue sources, and if this results in less being spent on these programs, the net effect on externalities may be less than anticipated. It is important to note that the existing evidence connecting THC consumption, and in particular consumption of highly potent cannabis products, to negative public health outcomes is limited at best, especially when viewed in the context of the voluminous literature establishing and quantifying the negative externalities of (for example) alcohol and tobacco. For instance, we are aware of only one randomized controlled trial detailing the dose-response curve for some of the effects of THC (Kiplinger et al., 1971). Moreover, because we do not observe individual consumption patterns in our cannabis data, we are also unable to determine whether there is additional optimal tagging by product category as is true for alcohol (Griffith, O'Connell, and Smith, 2019). Future work should also consider the equity consequences of moving to a potency-based tax as the tax-inclusive price per gram changes substantially.

Any potency tax assessed on cannabis products would face additional challenges caused by the inherent noise in the potency testing procedure and the ability of firms to engage in tax avoidance strategies by manipulating the samples used to test cannabinoid content. Tax avoidance strategies may have additional externalities — if reported THC is being altered without changing actual THC levels, it is more likely that consumers will accidentally consume too much and experience the negative effects detailed in Section II.B. Furthermore, potency taxes that are tailored to specific molecules are vulnerable to industry efforts to develop alternative means of delivering psychoactive experiences — one team has recently reported the discovery of a cannabinoid with significantly greater binding activity en vivo than THC (Citti et al., 2019).

Our work is the first step in understanding the heterogeneity in cannabis demand based on observable traits related to quality. It ignores potential substitution patterns that could emerge between alcohol and cannabis (Miller and Seo, 2019), substitution patterns across retailers (Seo, 2017), and the relationships between various cannabis products (Hollenbeck and Uetake, 2019). As such, our approach should be viewed as a lower bound regarding the revenue generating potential of potency-based taxes — or, alternatively, an upper bound of the potential change in cannabis potency as a consequence of potency taxes. Moreover, potency taxes could also push consumers back toward black markets, where marijuana typically has lower prices and higher variability in its potency (Reinarman, 2009; Caulkins et al., 2019). Finally, as legal marijuana access has been shown to decrease the use of opioid pain killers, policymakers seeking to change the regulatory or taxation regime should consider the potential for changes in the demand for these other substances (Powell, Liccardo Pacula, and Jacobson, 2018; Wen and Hockenberry, 2018). Future work could address the demand for potency while more flexibly considering the substitution patterns likely present within sin goods.

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DISCLOSURES

The authors have no financial arrangements that might give rise to conflicts of interest with respect to the research reported in this paper. This article includes analyses calculated (or derived) based in part on data from The Nielsen Company (US), LLC and marketing databases provided through the Nielsen Datasets at the Kilts Center for Marketing Data Center at The University of Chicago Booth School of Business. The conclusions drawn from the Nielsen data are those of the researchers and do not reflect the views of Nielsen. Nielsen is not responsible for, had no role in, and was not involved in analyzing and preparing the results reported herein.

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