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Essays on the Regulation of Sin Goods

par

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Résumé

Cette thèse explore la capacité des marchés légaux à lutter contre les marchés noirs par mécanisme de compétition. Les deux premiers articles s'intéressent au marché du cannabis. Le troisième examine comment des visas de travail temporaires peuvent lutter contre l'immigration irrégulière.

En quoi un gouvernement peut-il légaliser le cannabis et pousser les dealers hors du marché ? Le premier article propose un environnement théorique pour modéliser les choix des consommateurs de cannabis en situation de risque, avant et après la légalisation. La légalisation affaiblit le marché noir mais induit un *boom* de la consommation, principalement à travers des effets liés au risque et à la disponibilité des produits. Une telle hausse de la consommation n'est pas nécessairement désirable d'un point de vue politique. Associer la légalisation à des sanctions contre le marché noir permet de dépasser le compromis entre les politiques prohibitives coûteuses et l'accroissement de la consommation associé à la légalisation. Cet article propose une stratégie d'éviction aux gouvernements souhaitant évincer le marché noir en régulant un marché de détail du cannabis. Des applications numériques soulignent l'importance d'instaurer de hauts standards de qualité et investiguent la compatibilité de divers objectifs politiques considérés par les politiques de légalisation existantes. En proposant un cadre et des outils pour réflechir aux politiques de régulation du cannabis, ce projet vise à mieux comprendre les politiques d'aujourd'hui – et leurs échecs – ainsi qu'à construire consciencieusement celles de demain.

Le deuxième article s'inscrit dans la continuité de ce travail. Il porte un regard empirique sur les réponses stratégiques du marché noir à la suite de la légalisation, ainsi que sur les conditions selon lesquelles le marché légal peut le contrecarrer en entrant en compétition contre lui. Cet article tire profit d'une base de données nouvellement assemblée pour documenter les réponses d'équilibre du marché noir aux politiques de légalisation et estimer l'influence des prix et de la qualité (mesurée par la teneur en THC) sur les choix des consommateurs. Je montre que légaliser l'usage récréatif du cannabis cause une chute des prix de marché noir de 20% et une augmentation de leur qualité de 1.4% en moyenne. Par ailleurs, l'effet de la légalisation sur le prix est hétérogène à travers les catégories de produits à différentes teneurs en THC : il est porté par les produits à teneur moyenne, alors que le prix des produits les plus forts ne décroît pas. Ce résulat est nouveau pour la litérature. Il suggère qu'à la suite de la légalisation, le marché noir ne se différencie pas seulement en termes de prix. Ses réponses stratégiques sont plus complexes et incluent aussi des ajustements en termes de qualité. L'une des inquiétudes résultantes *post-légalisation* serait que le marché noir cible la demande pour les produits les plus forts, qui sont plus dommageables.

Pour mieux comprendre l'influence du prix et de la qualité sur les choix des consommateurs de cannabis légal et illégal, j'utilise un modèle de choix discret pour estimer la sensibilité des consommateurs au prix et à la teneur en THC pour les deux secteurs : légal et illégal. Les élasticités-prix croisées indiquent peu de substitution entre les deux secteurs basée sur des changements de prix. Toutefois, une hausse de 10% de la qualité sur le marché de détail légal induit une baisse de la demande sur le marché noir de 5%. À cet égard, je calcule les fonctions de meilleure réponse du marché noir aux changements du prix et de la qualité du cannabis légal et je présente la qualité comme un outil crédible pour évincer les détaillants illégaux.

Le troisième article utilise un environnement similaire au premier et modélise les choix de migrants potentiels peu qualifiés et l'offre de passage de clandestins. Comment des schémas de visas temporaires peuvent-ils être appliqués pour éradiquer les passeurs ? Ce travail montre que les contrôles – et les sanctions qui leur sont inhérentes – ne sont pas incompatibles avec des politiques plus libérales, mais les complémentent. Ainsi, associer un marché régulé pour des visas temporaires à un contrôle des frontières permet de dépasser l'opposition entre contrôle des flux migratoires et libres frontières. Fixer la durée et le prix de ces visas à des niveaux d'éviction peut mettre les passeurs en faillite. Ces scénarios d'éviction sont calibrés sur deux routes : Sénégal-Espagne et République Démocratique du Congo-Afrique du Sud. Les résultats soulignent les défis impliqués par de telles politiques, en particulier sur des routes Sud-Nord, sur lesquelles les différences de revenu rendent les individus plus sensibles aux variations de risque et plus enclins à dépasser la durée légale de leurs visas.

Mots clés : légalisation, cannabis récréatif, crime, politique publique, réglementation, estimation de la demande, immigration, marchés clandestins

Abstract

This thesis explores the extent to which legal markets can compete against black markets to undermine them. The first two articles analyze the market for cannabis, while the third one investigates how temporary work permits can fight human smuggling.

Can a government legalize cannabis and push the illegal dealers out of the market? The first article proposes a theoretical framework to model the choices of cannabis consumers confronted to risk, both before and after legalization. If legalization harms the black market, it is also at the cost of booming consumption, mostly through risk- and availibility-related mechanisms. Such an increase might not be politically desirable. Combining legalization with sanctions against the illegal market can overcome the trade-off between the cost of prohibitive policies and the rise in consumption associated to legalization. This article proposes an eviction strategy for a government aiming at eradicating the black market by regulating a retail market for cannabis. Numerical applications underline the importance of setting high quality standards and study the compatibility of the diverse policy goals that have been considered by governments while legalizing cannabis. By providing a framework and tools to reflect on cannabis policy, this project aims at enhancing the understanding of current regulations – and their failures – and conscious design of upcoming policies.

The second article follows up on this work and provides empirical insight on the black market strategic responses to legalization, as well as the terms on which a legal market can compete against it and undercut it. Taking advantage of a newly assembled dataset, this paper documents the equilibrium responses of the black market throughout legalization and provides estimates for consumer behavior with regards to changes not only in price, but also in quality (here measured by THC potency).

I show that legalizing recreational cannabis results in illegal cannabis prices dropping by 20% and quality rising by 1.4% on average. Besides, the price effect of legalization is heterogenous across products of different THC potencies: it is driven by low

and medium potency products, whereas the price of more potent products does not neceessarily decrease. This result is new to the literature. It suggests that after legalization, the black market not only differentiates in prices. Strategic responses are more complex and include also adjustments in potency. One concern is that *post-legalization* the black market could target the demand for more potent products, which are more damageable to health.

To better understand the role of price and quality on consumer choices for legal and illegal cannabis, I estimate a random utility model of discrete choice for cannabis and estimate consumer sensitivity to price and THC potency on *both* sectors, legal and illegal. Cross-price elasticities indicate little substitution between the two sectors following changes in price. However, a 10% improvement in quality in the legal retail sector involves a decrease of the demand for black-market cannabis by 5%. In this line, counterfactual analysis derives best-response functions of the black market to changes in legal price and quality and presents high quality provision as a creditable tool to drive illegal retailers out of the market.

The third article uses a similar framework as the first one and models the choices of low-skilled potential migrants and the supply of human smuggling services. How can temporary visa schemes be implemented to eradicate human smugglers? This work shows that controls – and inherent sanctions – are not incompatible with more liberal policies, they are complementary. Here combining a regulated market for temporary visas with border enforcement can overcome the tradeoff between migration control and free borders. Setting visa duration and price at eviction levels can drive smugglers out of business. These eviction schemes are calibrated on two routes: Senegal to Spain and the Democratic Republic of Congo to South-Africa. The results highlight the challenges of such policies, especially on South-North routes where differences in income make individual choices more sensitive to variations in risk and constraints to overstay tighter.

Keywords: legalization, recreational cannabis, crime, policy, regulation, demand estimation, immigration, human smuggling

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First Article.

Weeding out the Dealers? The Economics of Cannabis Legalization

by

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Abstract. We model consumer choices for recreational cannabis in a risky environment and its supply under prohibition and legalization. While legalization reduces the profits of illegal providers, it increases cannabis consumption. This trade-off can be overcome by combining legalization with sanctions against the black market, and improvements to the quality of legal products. Numerical calibrations highlight how a policy mix can control the increase in cannabis consumption and throttle the illegal market. In the US, the eviction prices we predict to drive dealers out of business are much lower than the prices of legal cannabis in most of the states that opted for legalization, leaving room for the black market to flourish. Analyzing the compatibility of several policy goals sheds light on the less favorable outcomes of recent legalization reforms and suggests a new way forward.

Keywords: recreational cannabis, legalization, crime, policy, regulation

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Individual contributions. This article follows up on Tiffanie Perrault's master's dissertation on the legalization of drugs, under the supervision of Emmanuelle Auriol. Tiffanie Perrault adapted the framework of Auriol and Mesnard (2016) [a] to the market for drugs. This article is based on this application. The idea of using the Prospect Theory framework originated from Tiffanie Perrault. Emmanuelle Auriol and Alice Mesnard are responsible for the whole structure of this article, including drafting the propositions and the corollary. The idea and the design of the fifth section is Emmanuelle Auriol's. Tiffanie Perrault helped implementing it. Most of the writing for the introduction, the literature review and the conclusion was Emmanuelle Auriol's and Alice Mesnard's, although Tiffanie Perrault took part in it. The three coauthors shared the drafting of the rest of the paper. Most work on the proofs, which are described in detail in the theoretical appendix was done by Tiffanie Perrault. These proofs were systematically cross-checked by Emmanuelle Auriol and Alice Mesnard. Tiffanie Perrault is responsible for the computations relating to the numerical applications in the main text as well in the numerical appendix.

a. Auriol, Emmanuelle, and Alice Mesnard. "Sale of visas: a smuggler's final song?." *Economica* 83.332 (2016): 646-678.

1. Introduction

Prohibition policies, which target suppliers or consumers of illegal cannabis, are not very effective at controlling demand. With 192 million users, cannabis is the most popular illegal recreational drug on earth (UNODC, 2018) and accounts for half of global drug seizures and represents a black market worth 142 billion dollars (UNODC, 2017). Prohibition has failed to curb consumption and has fueled criminal activities - drug dealing being the first source of revenue for organized crime. At the same time cannabis is less addictive and less deadly than other psychotropic substances.[1] Governments from advanced and developing countries have decided to legalize the recreational use of cannabis. These legalization reforms have varied widely

1. According to a 2017 meta analysis study of more than 10,000 articles, there are no proven serious adverse effects of moderate cannabis use on the health of adults. It is almost impossible to overdose with cannabis (see Nat. Ac. of Sc., 2017).

from one country/state to the next, reflecting different priorities, such as protecting the youth, improving the quality of the products consumed by adults, creating new legal jobs, or raising taxes. However, all reforms share the common goal of reducing criminal activity. We investigate theoretically the different ways legalization can be implemented to reach this objective and analyze how the objective of defeating crime may conflict with other objectives, such as raising taxes or decreasing consumption. The various trade-offs are illustrated with the help of calibrations based on US data.

Prohibition feeds an international market for drugs, which destabilizes the political economy of drug-producing countries and generates criminality in drug-consuming ones. Yet the costs of violence, instability and repression are generally overlooked by prohibitionists. Barro (2003) argues that legalizing and taxing drugs in advanced economies is a more effective way of controlling the drug market than prohibition. This paper explores a policy of legalization designed to strangle the illegal cannabis market and studies its impact on several outcomes, including price and drug consumption. We model the demand for cannabis from risk averse individuals in a general framework encompassing Expected Utility and Prospect Theory. If the sale of cannabis is illegal, consumers must weigh the benefits of consumption against the costs of participating in an illegal trade. Price is determined by illegal providers who maximize their profits. Our analysis highlights a policy trade-off: although a smart legalization policy may undermine the profits from illegal providers, it also increases cannabis use, which might be a sensitive issue politically. In contrast, prohibition decreases cannabis consumption but strengthens the cartelization of criminal networks and the price paid by their customers.

By illuminating the trade-offs inherent in legalization, our analysis warns policy makers against the unintended consequences of legalization if they neglect the black market responses or if they pursue incompatible objectives. Past reforms have often been disappointing. Canada [2] and Uruguay [3] fell short of eradicating the black market, which was their main objective. In both cases, the willingness of the governments to control consumption led to a severe underestimation of the consumers needs, in terms

2. Beaulieu, Marie-Cristina. 2020. "Cannabis Black Market". *Special Committee on the COVID-19 Pandemic - Hot Issues Notes – June 2020*. June 15. `https://www.publicsafety.gc.ca/cnt/trnsprnc/brfng-mtrls/prlmntry-bndrs/20200930/026/index-en.aspx`

3. González, Enric. 2018. "Uruguay loses momentum in the marijuana legalization stakes". *El País*. October 17. `https://english.elpais.com/elpais/2018/10/16/inenglish/1539687522_144922.html`

of both quantity and quality.[4] In California, the legalization reform even fueled the black market while generating only a fraction of the expected tax revenue. Confronted with high prices, due to high taxes in the legal market and new requirements for getting a medical card, many users have turned to illegal cannabis - in total contradiction with the initial objectives of the reform.[5] Our paper provides a general framework to analyze these failures.

We start from the simple idea, advocated recently by several policy makers, which is to sell legal cannabis at a price that competes with the black market. The analysis shows that this will not be sufficient to eliminate the black market. Prohibition creates barriers to entry, which foster cartelization of the sector by criminal organizations. These networks are able to respond to the legal competition by lowering their price and still make a profit, as demonstrated in Canada and Uruguay. Hence, implemented at a competitive price, cannabis legalization may instead increase consumption of "low-cost" illegal cannabis, with all the negative externalities this entails for society. Next we examine a policy mix that combines pricing tools through the sale of legal cannabis – to push the criminals out of the market – and sanctions against illegal trade – to limit any subsequent increase in consumption.

We show that the eviction price of legal cannabis, which is set to drive illegal providers out of business, can be adjusted with sanctions and marketing tools. Based on evidence from cannabis markets in the U.S., the policy simulations highlight the complementarities between these different instruments, if a government's objective is to limit the increase in consumption *post-legalization*. For instance, with a 0.1% probability of arrest and a USD 1000 fine for illegal purchase, a legal price around USD 98 per ounce would evict illegal suppliers and increase consumption by 53% to 91%, depending on the elasticity of demand. If the probability of arrest reaches 2%, the eviction price goes up to USD 287 and consumption only increases by 20% to 32.5%. These results are in line with the legalization experiences of Colorado and

4. In Uruguay, by the end of 2017, only two producers were approved for an annual volume of one ton each, while the market is estimated at between 35 and 40 tons. In addition, the hostility of pharmacists, charged by the State to sell cannabis, has made it even more difficult for users to obtain supplies. Similarly in 2019 in Quebec, public stores were only open from Wednesday to Sunday, "due to the current supply shortages (...) until product availability is more stable" (SQDC's website, `https://www.sqdc.ca`, March 19, 2019). Quantity has since increased but not quality. Consumers therefore continue to purchase on the black market.

5. See `https://www.nytimes.com/2019/04/27/us/marijuana-california-legalization.html` Thomas Fueller "Getting Worse, Not Better: Illegal Pot Market Booming in California Despite Legalization" *New-York Times* 04 27 2019.

Oregon, where relatively low prices for legal cannabis – around USD 135 per ounce – diverted consumers from the black market but increased consumption by almost 60%.

Interestingly, the eviction price can be further adjusted by improving the quality of legal cannabis relative to illegal products. Doubling its relative valuation by consumers would enable a government to set the eviction price at around USD 186 and to limit the rise in consumption to 37% to 63%. This "quality" channel has been neglected by most authorities, including in Canada and Uruguay. Yet, our simulations show that it is quite effective to modulate the eviction price and, thereby, to control consumption *post-legalization*.

Finally, we embed in our theoretical framework a larger set of policy objectives to provide further insight about current policies. We show that prohibition policies are optimal only if a government seeks to minimize total consumption of cannabis and neglects other objectives, such as minimizing the enforcement costs of prohibition. We also show that reducing crime through a regulated market of cannabis sold at the eviction price is compatible with the maximization of consumers' surplus, the minimization of enforcement costs of repression measures, and with the minimization of negative externalities from illegal cannabis consumption. In contrast, the maximization of tax revenues would lead to the co-existence of legal and illegal markets.

The rest of the paper is organized as follows. In Section 2 we describe the evolution of the regulation of recreational cannabis markets and review the empirical literature on the impact of legalisation measures. In Section 3 we present the set-up of the model, which explains the illegal market structure under *status quo* (prohibition). In Section 4 we analyze the effects of introducing pricing strategies combined with measures targeting consumers and suppliers to drive smugglers out of business and regulate the (legal) sale of cannabis. In Section 5 we calibrate the model based on evidence from the U.S. cannabis market and study its implications in terms of price and increase in consumption *post-legalization*. In Section 6 we enlarge the set of policy objectives to shed more light on current policies before concluding in Section 7.

2. Legalization of recreational cannabis: an overview of policy impacts

In response to an increase in cannabis use, the seventies were characterized by a wave of decriminalization measures. In the United-States, possessing small amounts (usually up to 1 ounce) of cannabis was declassified to a misdemeanor in eleven states [6] and Alaska declared possession of small amounts of cannabis to be protected under the state constitutional right to privacy (see Appendix A for a chronology of cannabis laws across states in the US). Across the Atlantic, the Netherlands took a bold step by making cannabis available for recreational use in coffee shops. However, the attempts to legalize cannabis more generally stalled with the *War on Drugs* launched by Ronald Reagan in the eighties. Rising concerns about the legitimacy and efficacy of this war led to a second wave of decriminalization and the first laws in favor of medical use in the U.S. at the end of the nineties. This liberalization movement accelerated in the last decade.

In 2012, the Uruguayan government announced plans to legalize and control sales of recreational cannabis to counter drug-related crime. This initiative occurred as Colorado and Washington states passed bills legalizing recreational use of cannabis, following popular referendums. From 2014 onward, thirteen other American states and the District of Columbia followed, and in 2018 Canada, South Africa and Georgia also changed their legislation. [7] Legalization policies implemented so far are diverse. In Colorado and Washington states, the reforms have been market oriented, with a clear focus on consumers' needs and taxation. In Canada, retail sale of cannabis is legal although the policies vary across provinces, from Québec's government monopoly to Alberta's privately run stores. In Uruguay the market is under tight public control, which led to sluggish implementation and penury. [8] Based on these examples, a flourishing literature studies the impacts of legalization policies.

2.1. Impacts of legalization on crime and violence

The first strand of the literature highlights the costs, in term of criminal activities and violence, of drug prohibition. Resignato (2000) shows that most drug-related violent crimes are the consequence of systemic factors linked to the *War on Drugs* rather than of psycho-pharmacological effects of drug use on crime. Indeed, prohibition

6. California, Colorado, Maine, Minnesota, Mississippi, Nebraska, New York, North Carolina, Ohio, Oregon and Washington

7. Bills in favor of legalizing recreational cannabis have been passed in Alaska (2014), Oregon (2014), California (2016), Maine (2016), Massachusetts (2016), Nevada (2016), Michigan (2018), Vermont (2018), Illinois (2019), Arizona (2020), Montana (2020), New-Jersey (2020) and South Dakota (2020) (see further detail on the US states legislation in Appendix A).

8. Although Uruguay was officially the first country to legalize recreational cannabis in 2012, public skepticism slowed the process and distribution was delayed until July 2017. Licensed farms are allowed to grow cannabis for the local market, citizens could run cannabis cooperatives, and selected pharmacies acted as dispensaries for both medical and recreational cannabis.

increases incentives to engage in criminal behavior (MacCoun and Reuter, 2001). It promotes violence as almost the only way to resolve conflicts and secure market power, encouraging market strategies based on violence (Miron, 1999, 2003). This strengthens cartelization and leads Miron and Zwiebel (1995) to the conclusion that a free market for drugs would probably outperform prohibition in terms of social costs. The social costs linked to prohibition are exacerbated by "zero-tolerance" policies, which may encourage users to hold higher quantities (Caulkins, 1993).

In line with these arguments, Dills et al. (2017) show that liberalizing cannabis across US states did not lead to a rise in crime. Other evidence by (Brinkman and Mok-Lamme, 2019) shows that overall crime in Colorado decreased in areas where cannabis dispensaries were added. In particular, cannabis legalization could be responsible for a drop in local rapes and property crimes (Dragone et al., 2019).

The benefits of legalization policies extend to organized crime. In the states bordering Mexico, legalization of cannabis for medical purposes has decreased drug-trafficking related crime (Morris et al., 2014; Gavrilova et al., 2019; Chang and Jacobson, 2017). Furthermore legalization policies have shrunk criminals' profits, weakening their power. In Italy, a legislative loophole leading to an unintended liberalization of cannabis decreased revenues from cannabis sales on the black market by 90-170 million euro (Carrieri et al., 2019).

2.2. Impacts of legalization on drug consumption

Due to their prohibited nature, illicit drugs are difficult to access and of uncertain quality, adding a substantial searching cost for consumers (Galenianos et al., 2012). Using a structural approach, Jacobi and Sovinsky (2016) explore the idea that cannabis legalization reduces this cost and removes the stigma of illicit consumption. They find that legalizing recreational cannabis would increase its use by around 48%. This is supported by Miller et al. (2017), who use survey data on undergraduate students at Washington State University to show that cannabis legalization induced a rise in consumption early after being implemented. Moreover, the ease of access to licit drugs encourages individuals to start consuming cannabis earlier, as shown in the Netherlands by Palali and van Ours (2015).

As consumers react to the risk of being caught while buying cannabis illegally (Jacobson, 2004), legalization is likely to affect consumer behavior by lowering their risk. Experiences of medical and recreational cannabis legalization, involving lower sanctions, are correlated with rises in cannabis use. This is suggested by Hunt et al. (2018), who find Marijuana Dispensary Laws in California to be associated with a significant increase in driving under influence arrests. This effect on demand contributes to explain why the reduction in risk faced by consumers following legalization of recreational use has driven up prices for illegal cannabis in the US (Pacula et al., 2010). In this, cannabis is a normal good, with consumers sensitive to variations in prices and risk. [9]

Finally legalization does not seem to lead to the feared socially undesirable gateway effects to other substance use (Dills et al., 2017). On the contrary, cannabis seems to act as a substitute for more powerful and addictive opioids (Powell et al., 2018).

2.3. Legalization and taxation

From a public policy viewpoint, legalization creates a new source of revenue along with the option of controlling consumption levels using tax instruments. Since consumers are price sensitive -with price elasticities of demand between -0.5 and -0.79 (Davis et al., 2016; van Ours and Williams, 2007)-, a government may use taxes to regulate the increase in cannabis use following legalization. Becker et al. (2006) show that policies controlling drug use by taxes are more efficient than quantity reductions through prohibition. Taxing cannabis consumption may discourage early initiation into cannabis use by younger users, who are very responsive to low prices (van Ours and Williams, 2007).

Moreover, cannabis legalization could generate substantial public resources through taxation (Caputo and Ostrom, 1994, 1996). For instance the states of Colorado and Washington collect between USD 200 million and USD 300 million a year in taxes through the cannabis industry. In the state of Washington, this tax revenue is secured by a substantial degree of market concentration, which results itself from the high taxes set by the authorities (Hollenbeck and Uetake, 2021). In the US, Jacobi and Sovinsky (2016) estimate at around USD 12 billion the tax revenue, which could be raised from country-wide cannabis legalization.

9. Although increasing consumption among the adults, legalizing cannabis seems to decrease consumption among the young, provided legal retailers refuse to sell it to underage consumers. DiNardo and Lemieux (2001) do not find any effect of cannabis decriminalization on consumption among high school students, a result confirmed by a recent study in Oregon Kerr et al. (2017). Furthermore, consumption of cannabis by teenagers is estimated to have decreased by 12% following legalization in the states of Washington and Colorado (SAMHSA, 2014).

The literature on cannabis legalization is mainly empirical. The review shows that, while prohibition fuels criminality and violence, it also helps contain cannabis consumption. In contrast, legalization leads to a decrease in overall criminality and generates tax revenue but at the cost of increasing cannabis consumption. By their empirical focus the papers reviewed cannot explain these trade-offs in a comprehensive way. They are limited by data availability and focus on specific geographic areas and topics (e.g. violence, youth consumption, public finance, etc.). Yet, getting a clear view of the trade-offs inherent to legalization of recreational cannabis is important for policy makers, before they embark into such important and controversial reform. We complement this literature by studying the theory behind the policy trade-offs. We set up a general environment, encompassing both expected-utility theory and prospect theory, which ensures the robustness of our results.

3. Prohibition equilibrium

We start our analysis by studying the illegal market under prohibition. In the absence of a legal option, consumers can only purchase illegal cannabis from dealers, who charge the price p.

3.1. Demand under prohibition

Potential customers for illegal cannabis are heterogeneous. They have different "taste" for the commodity, θ, which is drawn from the distribution $G(\theta)$, twice differentiable, with support $\mathbb{R}$ and density function $g(\theta)$. Individuals who like cannabis are characterized by a positive θ, and those who dislike it, by a negative one. When the illegal cannabis is of quality $v \geq 0$, its value for individual θ is given by θv. In other words, cannabis is vertically differentiated (i.e., a higher v corresponds to a better quality cannabis). This assumption is an improvement over the existing literature, in which cannabis is generally modelled as a uniform product.

Since illegal activities entail risk, a consumer who purchases black market cannabis is subject to a probability $q \in [0,1]$ of being caught by the police. If caught, he/she loses the benefit of the commodity, the price paid for it, p, and faces a legal punishment $F \geq 0$ (e.g. fine, prison term). The net payoff of a consumer caught by the police while purchasing illegally is: $-p - F$; while the net payoff for an individual who is not caught is $\theta v - p$. Therefore, choosing to consume cannabis illegally is a lottery $\mathcal{L}_{\text{illegal}} = [-p - F, \theta v - p; q, 1 - q]$. For an individual with characteristic $\theta \in \mathbb{R}$, this lottery has an expected value of

$$w^{+}(1-q)u(\theta v - p) + w^{-}(q)u(-p - F), \tag{1.1}$$

where the utility function $u(x)$ is continuous, strictly increasing in $x \in \mathbb{R}$ and such that $u(0) = 0$,[10] while the probability weighting functions $w^+(x)$ and $w^-(x)$ are increasing in $x \in [0, 1]$, so that $w^+(0) = w^-(0) = 0$ and $w^+(1) = w^-(1) = 1$.

This framework is general. It encompasses the standard Expected Utility approach by setting $w^+(1-q) = 1-q$ and $w^-(q) = q$ and considering an increasing, concave utility function (e.g., CARA). It also encompasses Tversky and Kahneman (1992)'s Cumulative Prospect Theory (CPT), where attitudes towards risk are reference-dependent, probability weighting functions are not linear and the value function $u(x)$ is S-shaped, with an inflection point at zero.[11] Reference-dependent models are more realistic (see Post et al., 2008). So is the S-shaped value function, allowing for diminishing sensitivity and loss aversion. It accounts for the facts that "perceptions are a concave function of the magnitudes of change" and that "people dislike losses significantly more than they like gains"(Rabin, 1998). This attitude towards risk has been largely documented empirically and in the lab (see DellaVigna, 2009, for a review of the literature).

Moreover, CPT is particularly adapted to our context as it is reference dependent and thereby models framing effects, i.e. the effects of the environment on decision-making. This is key when comparing the *pre-* and *post-legalization* equilibria.

The consumer of type θ^I, indifferent between illegal consumption and no consumption, is characterized as follows:

$$w^+(1-q)u(\theta^I v - p) + w^-(q)u(-p-F) = 0 \tag{1.2}$$

We show in Appendix C.1 that, under our assumptions, $\theta^I > 0$ exists and is unique. Any consumer of type $\theta \geq \theta^I$ purchases illegal cannabis, while consumer of type $\theta < \theta^I$ does not. Without loss of generality, the demand for the illegal commodity can then be written:

$$D^I(p) = \int_{\theta^I}^{+\infty} g(\theta)d\theta = 1 - G(\theta^I) \tag{1.3}$$

where θ^I is the solution of equation (1.2).

The following static comparative results regarding the marginal consumer and the price elasticity of demand for illegal cannabis are also derived in Appendix C.1.

First, θ^I increases with q: the demand for the illegal commodity decreases with the probability of arrest, which is the desired effect of prohibition policies. It discourages individuals from purchasing illegally, which leads to a more positive selection of consumers. Second, θ^I increases with p so that a higher price reduces the demand.

10. This is a normalization, intuitively reflecting that losses lead to a negative value and gains lead to a positive value.

11. This theory is the most prominent among non-expected utility theories. While expected utility theories focus on final wealth, CPT models variations in outcome from a given *status quo*.

However, this is not a policy instrument under prohibition, since the equilibrium price on the illegal market results from interactions between unregulated (and untaxed) criminals.

Finally, the absolute value of the price elasticity of demand,

$$\epsilon_{D^I,p} = \frac{-D^{I\prime}(p)p}{D^I(p)} = \frac{g(\theta^I)}{1-G(\theta^I)}\frac{d\theta^I}{dp}p, \tag{1.4}$$

increases with $q \in [0,1]$ under the assumption that the distribution $G(\theta)$ satisfies the monotone hazard rate (MHR) property. Since the MHR property is satisfied by most usual distributions, our general framework establishes that, for these distributions, the price elasticity of demand for cannabis increases with the risk of being caught, an intuitive result.

3.2. Cannabis supply under prohibition

We model the oligopolistic market for illegal provision of cannabis as a generalized Cournot competition, where a few criminal networks, $i = 1, ..., N$, operate. Assuming symmetrical cost functions: $C_i(q_i) = cq_i + K$ where $K \geq 0$ is the sunk cost to set up the illegal network and $c \geq 0$ is the constant marginal cost of supplying the commodity, we focus on symmetric equilibrium. The generalized Cournot price p^N with N smugglers is such that (see Carlton and Perloff, 2015 chapter 6):

$$\frac{p^N - c}{p^N} = \frac{1}{N}\frac{1}{\epsilon_{D^I,p}} \tag{1.5}$$

where N is an integer greater than or equal to 1 and $\epsilon_{D^I,p}$ is the price elasticity of demand defined in (1.4). It is easy to check that, all else being equal, the price in (3.1) is increasing in the marginal cost of production, c, an intuitive result, and decreasing in N: the higher the number of competing providers the lower their mark-up. The generalized Cournot competition demand, $D^I(p^N)$, is between two extreme cases: $D^I(p^m) \leq D^I(p^N) \leq D^I(c)$ for all $N \geq 1$ where $p^m \equiv p^1$ in the monopoly case and $p^\infty = c$ in the competitive case when $N \to \infty$.

We have established in the Appendix C.1 that the price elasticity of demand, $\epsilon_{D^I,p}$, increases with q. Using (3.1) we deduce that the oligopolistic price is lower when the risk q increases. Risk-aversion implies that the price charged by smugglers is lower than the price they would impose on risk neutral individuals with the same expected payoff from consumption. [12]

12. Smugglers also face different types of consumers. If they can identify them, they may apply different prices. As is standard with third degree price discrimination, groups with the largest price elasticity get the smallest price. In contrast, captive consumers (i.e., groups with low price elasticity) are charged higher prices.

In a more dynamic setting, one can endogenize N. Since K is the sunk cost to enter the illegal market, the maximal number of criminal organizations N that can operate profitably is the integer part of n such that $\pi(n) = K$, where $\pi(n) = (p^n - c)\frac{D^I(p^n)}{n}$ is the firm rent. Therefore, any repressive measure increasing c or K reduces the number of criminal networks active on the market, N, and increases the price they charge (see equation 3.1).

4. Legalization

To drive the dealers out of business, different policy makers including Québec's Minister of Public Health, Lucie Charlebois,[13] have used the intuitive approach of matching the price of legal cannabis to the black market price: $p^L = p$. We show easily that this policy increases consumption without necessarily eradicating crime.

Let θbv denote the value of consumption for an individual of type θ considering the purchase of legal cannabis of quality bv. The parameter $b \geq 1$, hereafter called "quality differential", captures the fact that, unlike illegal products, legal products are certified and their potency and composition, including pesticide and other chemicals, are known to consumers at the time of purchase.[14] Moreover, purchasing legally alleviates search costs and personal cost in terms of ethics and social stigma. Finally, the purchase experience is usually better in a shop than on the street. So, in general, for the same type of product (e.g., weed), quality is better in the legal sector.

If it is possible to purchase cannabis at price $p^L = p$ without risk of getting caught, the marginal consumer indifferent between consuming legal cannabis or not consuming at all is such that:

$$\theta^0(p) = \frac{p}{bv} \tag{1.6}$$

Comparing the legal threshold, $\theta^0(p)$, with the illegal threshold implicitly determined by (1.2) for a given price p, we show that the legal demand is higher than the demand for the illegal product: $\theta^0(p) < \theta^I(p)\ \forall p > 0$.[15] For a given price, the value of consuming legal cannabis is higher and there is no risk of being sanctioned, such that the demand for cannabis increases.

13. See "Environ '7-8 dollars le gramme' pour du pot légal" by Martin Croteau in *La Presse*, September 21 2017. `https://www.lapresse.ca/actualites/politique/politique-quebecoise/201709/21/01-5135353-environ-7-8-dollars-le-gramme-pour-du-pot-legal.php`

14. Quality certification under legalization usually involves regulating cropping techniques; in particular the use of pesticides, which are shown to be harmful for health (Subritzky et al., 2017).

15. Indeed, when there is no risk of detection (i.e. $q = 0$) then $\theta^I_{q=0}(p) = \frac{p}{v} \geq \theta^0(p) = \frac{p}{bv}\ \forall b \geq 1$. Since θ^I increases with q, we deduce that: $\theta^I(p) > \theta^I_{q=0}(p) \geq \theta^0(p)\ \forall b \geq 1$ and $q > 0$.

Moreover, a government setting a competitive price for legal cannabis such that $p^L = p$, ignores the fact that dealers may lower their price to keep some customers. In addition to increasing consumption, such a policy does not necessarily eradicate crime.

4.1. Response of illegal suppliers to cannabis legalization

To determine a price of legal cannabis that would drive dealers out of business the government, a Stackelberg leader, [16] needs to take into account the impact of response of illegal providers to its policy. As shown in Appendices C.1 through C.5, all our results hold whether we model behavior under Expected Utility Theory or Prospect Theory. Only the way the marginal consumer is derived under legalization differs slightly in these two frameworks. In Prospect Theory, the marginal type, $\theta^L(p, p^L)$, indifferent between legal and illegal consumption, is the solution of : [17]

$$w^+(1-q)u\left(p^L - p - \theta v(b-1)\right) + w^-(q)u\left(p^L - p - \theta bv - F\right) = 0, \tag{1.7}$$

while, if individuals are expected utility maximizers, the marginal consumer is the solution of: $(1-q)u(\theta v - p) + qu(-p-F) = u\left(\theta bv - p^L\right)$. For example, with a CARA utility function $\theta^L(p, p^L)$ is such that $(1-q)u\left(p^L - p - \theta v(b-1)\right) + qu\left(p^L - p - \theta bv - F\right) = 1$, which is similar to (1.7) but not equal. Appendix C.2 shows that, in both cases, there is a range of legal prices such that $\theta^L(p, p^L)$ exists and is unique. Any individual above this threshold prefers to purchase legally rather than illegally.

Recall that θ^I defined in (1.2) is the threshold above which an individual prefers to make an illegal purchase rather than no purchase at all and that θ^0 defined in (1.6) is the threshold above which an individual prefers to purchase legally rather than not purchase. Let $\tilde{p}^L(p)$ be the value of p^L such that

$$w^+(1-q)u\left(\frac{p^L - bp}{b}\right) = -w^-(q)u(-p-F), \tag{1.8}$$

with the probability weighting function being the identity under Expected Utility Theory. Two cases may occur following legalization, as shown in Appendix C.3.1.

(1) $p^L \leq \tilde{p}^L(p)$. The legal price is low enough and legalization shows the intended effect of pushing the illegal providers out of the cannabis market: $\theta^L \leq \theta^0 \leq \theta^I$.

16. This assumption is motivated by the inherent structures of the legal and the illegal markets. Because the legal market is institutionalized – or at least highly regulated – by design, it has the ability to coordinate its strategy, which makes it a creditable first mover.

17. In Prospect Theory individuals deciding between legal and illegal consumption take the certain payoff associated with the legal option, $\theta bv - p^L$, as reference. Engaging in illegal consumption is then modeled as a lottery $[p^L - p - \theta bv - F, p^L - p - \theta(b-1)v; q, 1-q]$ which yields (1.7).

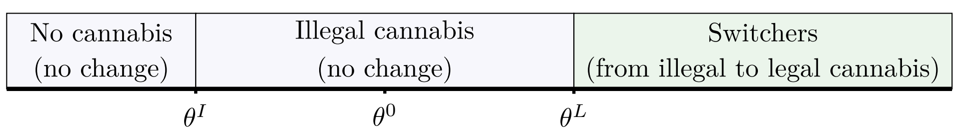
In this case, $\int_{\theta^0}^{\theta^I} g(\theta)\mathrm{d}\theta$ new cannabis consumers appear as illustrated in Figure 1.1.

Figure 1.1. Change in consumers choice *post-legalization* when $p^L \leq \tilde{p}^L(p)$

(2) $p^L > \tilde{p}^L(p)$. The legal price is too high to undermine the dealers and $\theta^I < \theta^0 < \theta^L$. In this case, if the illegal providers maintained the same price as under prohibition, the overall demand for cannabis would not change. Consumers with valuation above θ^L would switch to the legal market as shown in Figure 1.2 and the residual demand for illegal cannabis would become:

$$D^I(p, p^L) = \int_{\theta^I(p)}^{\theta^L(p,p^L)} g(\theta)d\theta. \tag{1.9}$$

Figure 1.2. Change in consumers choice *post-legalization* when $p^L > \tilde{p}^L(p)$



A high-type segment of the former black market customers is captured by the new legal market. Under legalization, individuals with a high valuation for cannabis turn to the legal market and pay attention to quality, while they neglect it under prohibition where products are not certified.

Moreover, to keep some consumers and maximize their profits, illegal providers adjust their price, p. Let $p^N(p^L)$ be the solution of (3.1) computed with $\varepsilon_{D^I,p} = -\frac{\partial D^I(p,p^L)}{\partial p}\frac{p}{D^I(p,p^L)}$, the direct price elasticity of the demand $D^I(p, p^L)$ defined in (1.9), which depends on p^L . The price reaction function of the smugglers is the solution of the following equation:

$$p(p^L) = \begin{cases} p^N(p^L) & \text{if } \; c \leq p^N(p^L) < \frac{p^L}{b} \\ \varnothing & \text{otherwise} \end{cases} \tag{1.10}$$

As long as the illegal providers are active, i.e. have positive profits, their reaction price is increasing in their marginal operating costs, c, and in the price on the legal market, p^L; and is decreasing in the number of active criminal networks in the market, N. Symmetrically, the higher the value of legal cannabis relative to illegal cannabis (the higher b) and the lower the legal price, p^L, the lower θ^L defined in (1.7) and the more difficult it is for criminals to attract consumers by decreasing their prices.[18]

After the illegal providers respond to the sale of legal cannabis, if the value for money of black market cannabis is sufficiently attractive relative to legal cannabis (i.e., if the price differential between the markets is high enough given the quality differential), we have $\theta^I < \theta^0 < \theta^L$, and the black market survives. Facing competition from the legal market to attract the high segment of the consumer distribution, illegal providers push down their prices, which increases the overall demand for cannabis. So far, this has been observed everywhere that cannabis has been legalized (UNODC, 2022).

Proposition 1.1. *Once legal cannabis is introduced to the market, if the costs of operating on the black market and the repression against illegal purchases are held constant, for any level of quality differential,* $b \geq 1$*, the overall demand for cannabis increases.*

PROOF. See Appendix C.3.2. □

This proposition highlights that if policy makers only use one instrument in case of legalization, which is to implement a legal market for cannabis by a price setting strategy, then they have to choose between the objective of controlling cannabis consumption with the help of a cartelized illegal market (the *status-quo* in many countries), or implementing a legal market, which increases cannabis consumption.

The flourishing opium market at the beginning of the 19th century illustrates this policy trade-off. To control the opium market in the East-Indies, the Dutch government imposed a state monopoly and provided licences to consumers in what was called *opium regie*. Although the aim was to regulate the market and tax it better, it had to compromise between imposing low prices (getting lower revenues) and having fewer smugglers on the market, or getting higher revenues with a high regulated price, which allowed smugglers to enter the market and compete on price (van Ours, 1995).

4.2. Eradicating organized crime through legalization

Since many legalization reforms aim to eradicate crime, we now consider a price setting strategy for the legal supply which destroys economic incentives for dealers to operate illegally. The strategy is such that the price of dealers is pushed below their marginal costs after they respond to the policy, i.e. $p(p^L) \leq c$. Let $\theta^I(p)$ be defined in (1.2). We deduce the next proposition.

18. We show in Appendix C.2 that θ^L increases with p^L, while it decreases with b and p.

Proposition 1.2. *To drive illegal suppliers out of business, the legal price of cannabis should be set below the eviction price* $\underline{p}^L = bv\theta^I(c)$*, which, without additional measures, yields the same level of consumption as under perfect competition among illegal suppliers:* $D^L(\underline{p}^L) = D^I(c)$*.*

Proof. See Appendix C.4. □

This result is general. Irrespective of the way we model consumers' behavior (i.e. EUT or Prospect Theory) and the initial market conditions (i.e. monopolist, oligopolistic or competitive), if the government wants to drive out illegal providers, it has to apply a price lower than the threshold price $\underline{p}^L = bv\theta^I(c)$, which is such that their mark-up vanishes after they respond to the policy. We refer to the price $\underline{p}^L$ as the *eviction price*. Since $\theta^I(c)v - c > 0$ it follows that $\underline{p}^L > c$: the threshold price for eliminating illegal suppliers is higher than smugglers' marginal cost, c. Nevertheless, in *post-legalization* equilibrium, the demand, which is now legal, is at the same level as if illegal suppliers were pricing at marginal cost under status-quo.

Compared to the status-quo situation of an oligopolistic illegal market, Proposition 1.2 shows that legalizing the cannabis market through setting the eviction price $\underline{p}^L = bv\theta^I(c)$ would bring the demand of (legal) cannabis to the level of a perfectly competitive illegal market or higher. Public authorities therefore face a trade-off between an increase in cannabis consumption and crime eradication.

4.3. Eradicating organized crime while controlling cannabis use

Increases in drug consumption following legalization may not be desirable for the society, nor politically sustainable. In fact, to date, not a single politician proponent of legalization has disputed this. The increase in cannabis consumption, if anticipated, will prompt opposition to legalization by many citizens, health workers and anti-drug associations. Policy makers need more sophisticated tools to regulate the demand for cannabis *post-legalization*. Our theoretical framework shows that the price that drives criminals out of business can be adjusted.

Corollary 1.1. *The eviction price* $\underline{p}^L$ *increases with the marginal costs of illegal providers* c*, the probability of arrest of illegal consumers* q*, the associated fine amount* F*, and the quality differential between legal and illegal cannabis* b*.*

Proof. See Appendix C.5 □

Intuitively, additional measures affecting c, q, F and b make competing with the legal provision of cannabis more difficult for illegal providers. Combining these four instruments helps contain the increase in cannabis consumption following legalization.

This is either because consumers have higher relative expected payoffs if they consume legally, or because illegal providers operate with increased costs. Their economic activities can be throttled more easily such that the eviction price can be set higher. This dampens the increase in demand following legalization. The optimal combination of these instruments is discussed with the objectives of the reforms in Section 6.

5. Policy Implications

In this section we illustrate the implications of the theory, which combines legalization, sanctions, and investments in quality differentiation, in order to drive illegal providers out of business. The calibration exercise is based on the CPT functional forms derived by Tversky and Kahneman (1992). Our use of CPT is consistent with agents' behavior while considering risky gambles (for a literature review see Rabin, 1998; Barberis and Thaler, 2003; Barberis, 2013). In particular, this theory provides realistic predictions for individual behavior when confronted to risky choices, both inside (Glöckner and Betsch, 2008; Baltussen et al., 2016) and outside (Barberis et al., 2016; Post et al., 2008) the lab.

Tversky and Kahneman (1992) generalize the seminal paper by Kahneman and Tversky (1972), which was one of the first to show that individuals have a poor ability to assess probabilities. They tend to overestimate the odds of rare salient events, while they underestimate the odds of more common events. Criminal behavior is not exempt from this cognitive bias: the general public overestimates the probability of getting arrested (Chalfin and McCrary, 2017). Probability weighting functions account for individuals' distorted perceptions of probabilities.[19] In our framework, individuals choosing to purchase cannabis on the black market face a binary lottery, with a low probability q of being arrested (Nguyen and Reuter, 2012). The weighting function $w^{+}(1-q)$ (respectively $w^{-}(q)$) applied to probabilities associated with positive (respectively negative) outcomes, proposed by Tversky and Kahneman (1992) is:

$$w^t(q) = \frac{q^{\gamma^t}}{\left(q^{\gamma^t} + (1-q)^{\gamma^t}\right)^{\frac{1}{\gamma^t}}} \qquad \text{with } t = +, -. \tag{1.11}$$

and the value function is

$$u(x) = \begin{cases} x^{\alpha} \text{ , if } x > 0 \\ -\lambda(-x)^{\alpha} \text{ , if } x \leq 0 \end{cases} \qquad \text{with } \alpha \in (0,1) \text{ and } \lambda \geq 1. \tag{1.12}$$

19. These functions are simply increasing mappings $w : [0,1] \mapsto [0,1]$, such that $w(0) = 0$, $w(1) = 1$, and for x in the neighborhood of 0 (respectively 1) $w(x) \geq x$ ($w(x) \leq x$).

Substituting (1.11) and (1.12) in (1.2), the marginal consumer is characterized by (see Appendix D.1):

$$\theta^I(p) = \frac{1}{v}\left[\left(\lambda\frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}}(F+p)+p\right]. \tag{1.13}$$

The legal price threshold $\underline{p}^L = bv\theta^I(c)$ is then such that:

$$\underline{p}^L = b\left[\left(\lambda\frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}}(F+c)+c\right]. \tag{1.14}$$

Below we calibrate the eviction price $\underline{p}^L$, as well as the increase in (legal) cannabis consumption at this price and compare it to the level of illegal consumption under prohibition.

5.1. Benchmark values

The exogenous parameters calibrated by Tversky and Kahneman (1992) are $\lambda = 2.25$, $\alpha = 0.88$, $\gamma^+ = 0.61$ and $\gamma^- = 0.69$. The remaining relevant policy parameters are q, F, c, and b. Our simulations aim to show how they interact, which is key to inform legalization policies and to set out a consistent set of objectives. For instance, most policy makers tend to frame legalization and repression policies as oppositional. Our simulations show that these two type of policies are complementary.

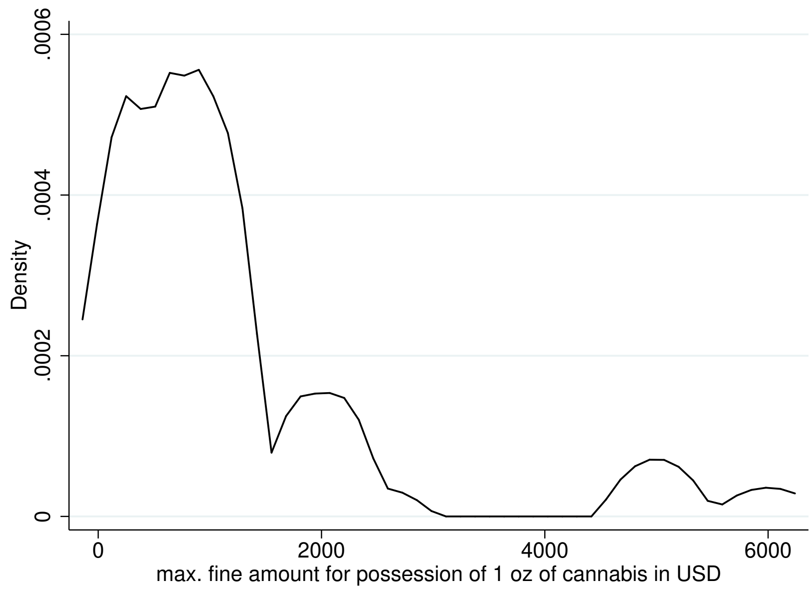
Since most studies so far focus on the US, our calibrations are based on US data. While the current level of fines,F, the marginal costs of production of illegal suppliers, c, and the probability of arrest, q, are documented in several studies, b, the higher valuation of legal cannabis, requires more indirect inference.

The maximum fines applied for possession of illegal cannabis on a first offense vary across states, as represented in Figure 1.3 (NORML, 2020).[20] A non-negligible proportion of states apply fines of USD 1,000. This value is also the median value of the fines applied *on a first offense* across the United States as of March 2020, which we use as a benchmark. Since in some states fines are higher, and in other lower we perform a sensitivity analysis on a range of realistic values described in Figure 1.3.

Using various assumptions, Caulkins (2010) estimates production costs of cannabis *post-legalization* between 70$ and 400$ per pound (i.e. approximately 80$ and 470$ in 2020), depending on the production method used. However, this estimate does not take into account distribution costs under prohibition, which are quite large. The

20. Note that we excluded Arizona from the sample, for this state does not set sanctions for possession of small amounts and features a maximum fine of USD 150,000 for the possession of any amount of cannabis.

FIGURE 1.3. Distribution of state maximum fine amounts for possession of 1 ounce of cannabis across the United States (in states where cannabis is prohibited, as of March 2020)



LSE Expert Group on the Economics of Drug Policy (Quah et al., 2014) estimates the wholesale price of a pound of illegal cannabis under prohibition to be around 3,500$ (i.e. 218.75$ per ounce, or 237.5$ in 2020), and about 10 times smaller under legalization – which is consistent with Caulkins (2010). The LSE Expert Group also reports the typical farmgate price quoted in the media to be around 2,000$ per pound (i.e. 125$ per ounce). Accordingly, the marginal cost for an ounce of illegal cannabis *post-legalization* ranges between 25$ and 125$. We choose 50$ as our benchmark value. This marginal cost of operation by illegal providers is hard to estimate more precisely. Besides, this cost increases with sanctions against black market suppliers, who incur losses and – costly – adapt their behavior. Therefore, a government willing to inflate the equilibrium price of black market cannabis can do so by intensifying repression against illegal producers and retailers. The marginal cost c being a policy tool, rather than an exogenous parameter, motivates our sensitivity analysis using a large range of values.

The probability of being arrested in possession of illegal cannabis in the United States varies across settings. Nguyen and Reuter (2012) highlight that sex, age, and ethnicity influence the probability of being stopped by the police, and therefore of being arrested. The authors argue that in most groups, the average probability of being arrested is around 1%. This characterizes the situation under prohibition. Following the legalization of recreational cannabis, illegal users are more difficult to detect. We therefore set the benchmark value for the probability of arrest at $q = 0.1\%$ *post-legalization.*[21] As this policy parameter varies across settings and groups, and is strongly affected by repressive policies against the residual black market, we perform a sensitivity analysis using a large range of values for q. This includes a 0 probability of being arrested to reflect lax enforcement against the illegal market.

The parameter b describes the higher valuation of legal cannabis relative to cannabis bought on the black market for a similar type of product. This gap is difficult to measure. Not only does it encompass product attributes in terms of chemical composition (e.g. potency, taste), but it also includes quality standards, both at the upstream (cropping and processing) and the retail (shopping experience) levels. To anchor the simulations on quantifiable measures, the benchmark value of the parameter b is set using the relative THC potency of cannabis bought legally or illegally. Taking the potency or purity as a measure of quality is relatively standard in the literature on markets for illicit drugs (see for instance Galenianos et al., 2012; Galenianos and Gavazza, 2017). According to ElSohly et al. (2016), the average THC potency of cannabis seized in the US in 2014 was 11.84%, while around the same time, the THC potency on Colorado's legal market was 18.7%.[22] Based on this difference, a benchmark measure for b could be $\frac{18.7}{11.84} \approx 1.58$. The fact that consumers treat legal cannabis as a superior commodity compared with illegal cannabis is also in line with experimental findings on the substitutability of legal and illegal cannabis in catchment areas where the two types of products are available (Amlung et al., 2019). The sensitivity analysis will consider a large range of values for the parameter b as it can be fine-tuned by public policies.[23] This will also include values below 1, reflecting poor quality of products as initially experienced by consumers in Canada following the legalization reform.

Using the benchmark values $F = 1,000$, $c = 50$, $q = 0.1\%$ and $b = 1.58$, together with the parameters $\lambda = 2.25$, $\alpha = 0.88$, $\gamma^+ = 0.61$, $\gamma^- = 0.69$ estimated by Tversky

21. For instance, in the state of Washington in 2017, 15 percent of adults reported having used cannabis in the past month (BRFSS). Based on a population of 4,380,278 adults, this would mean Washington accounts for around 660,000 monthly consumers. If half of these consumers go to the black market, $q = 0.1\%$ would correspond to around 330 arrests per month.

22. Briggs, Bill. 2015 "Colorado Marijuana Study Finds Legal Weed Contains Potent THC Levels". *CNBC News*, March 23.

23. First, the composition of legal products is certified, which implies that consumers are *able* to choose between different potency, according to their taste. Second, the legal market is subject to quality regulation and controls, including those regarding the use of pesticides and other health-damaging substances. Third, the purchase experience is more pleasant and safer in a shop than under cover in the street.

and Kahneman (1992), we use equation (1.14) to calibrate the eviction price for legal cannabis at around USD 97.79 per ounce (see row 1 of Table 1.2). For comparison, we present in Table 1.1 the illegal and legal prices, p and p^L respectively, observed in 7 states of the U.S., in 2018. We report the number of licensed recreational retailers, which we compare to the number of McDonald's restaurants. We also present each state's share of the U.S. legal market for cannabis. These figures give an idea of the degree of liberalization of the market for recreational cannabis in each state and of the relative position of the black market, which are discussed in Section 6.

With the exception of Colorado and Oregon, our eviction price for legal cannabis is significantly lower than the legal prices on these markets, which helps explaining why the black market is thriving in some of them, especially California. In line with our analysis, consumers in Colorado and Oregon have massively shifted toward the legal market for their purchase of cannabis, thanks to prices in the range of the eviction price.[24] The research firm New Frontier Data (NFD) estimates Oregon's legal market share at 86% in 2020, just behind its share in Colorado, at 87% (New Frontier Data, 2020). In the same report, NFD forecasts that by 2025, 93% of cannabis demand in Oregon will be met with legal products.

This shift toward legal cannabis was accompanied by a bump in overall demand: the National Survey on Drug Use and Health reports cannabis prevalence in Oregon to have increased by almost 60% between 2014 and 2017. Colorado saw a similar evolution of its demand between 2012 and 2015, having preceded Oregon in its legalization reform.[25]

Finally, we want to compute the increase in demand following the legalization at eviction price. This requires an estimate of the price elasticity of demand of cannabis. Van Ours and Williams (2007) estimate that the price elasticity of demand ranges between -0.50 and -0.70, while Davis et al. (2016) find a price elasticity between -0.67 and -0.79. In line with this empirical evidence, our calibrations allow for a range of price elasticities of demand between -0.5 and -0.8. Assuming that the taste for cannabis θ is normally distributed, we calibrate in Appendix D.2.1 the distribution parameters of the Gaussian distribution using our model and the literature on

24. Oregon commission reports from 2019 and 2021 both demonstrate that this state, where legal prices are the lowest and where licences have been flourishing, has been successful in "[offering] the illicit market steep competition" (Oregon Liquor Control Commission, 2021).

25. The NSDUH bases these estimates of prevalence of cannabis use upon the extensive margin of consumption over a 12-month period, for a population aged over 12. In Colorado, the estimated prevalence was 10.41% in 2011-2012 and 16.57% in 2014-2015. In Oregon, it was 12.38% in 2013-2014, 12.73% in 2014-2015 and 19.23% in 2016-2017. These figures were retrieved online using the Substance Abuse and Mental Health Data Archive public data analysis system (`https://pdas.samhsa.gov/saes/state`).

Table 1.1. Legal markets across the U.S.

State	p	p^L	Recreational retailers	McDonald's restaurants	Share of US legal market	Population
AK	298.24	361.57	123	32	0.63%	0.7
CA	256.57	344.45	901	1,279	34.9%	39.5
CO	241.75	143.07	587	209	15.1%	5.6
MA	339.68	354.25	113	170	4.2%	6.9
NV	270.57	295.54	70	134	2.6%	3.0
OR	210.39	127.06	661	130	7.7%	4.2
WA	233.73	≈ 196	512	167	12.8%	7.5

Prices are in USD per ounce, as of fall 2018. The legal price for Washington State is extrapolated from Jeanne Lang Jones and Rob Smith. 2019. "Tight Regulations, High Taxes May Keep Washington State's $1.4B Cannabis Industry from Really Blooming". *Seattle Business*. January. All other legal prices are state averages quoted from New Frontier Data (2019), while state average black market prices were retrieved from the crowd-sourced website `priceofweed.com`, which was accessed using the Internet archive Wayback Machine. Numbers of retailers and testing facilities were retrieved from New Frontier Data's "Cannabis Legalized States" interactive map, as of July 2020. The number of McDonald's restaurants in each state was scraped from Google Places, as of August 2020. Shares of the US legal market are projections quoted from New Frontier Data (2017). Population is expressed in million inhabitants, as of 2018.

cannabis demand. Appendix D.2.1 shows that the mean value of θ varies between -436.4 and -1090.9 when the elasticity varies between -0.8 and -0.5. This negative average "taste" parameter for cannabis is consistent with surveys in the US reporting negative attitudes towards cannabis consumption on average.

The first row of Table 1.2 presents the benchmark values of the policy parameters in columns 1 to 4, the eviction legal price $\underline{p}^L$ around USD 98, and the resulting relative increase in the extensive margin of consumption *post-legalization*. It shows that the increase in demand is predicted to be between 53% and 92% depending on the price elasticity of demand used for the calibrations.

5.2. Effects of policies on post-legalization equilibrium

This section studies the sensitivity of the eviction price and of the *post-legalization* demand to parameters that can be influenced by policies. Several instruments are considered: reinforcing sanctions may increase the marginal cost of operations for illegal suppliers, c, the probability of arrest, q, or fines to illegal consumers, F. Moreover, investing in the quality of the legal cannabis, including the purchasing experience, taste of the product, certification of potency and of the healthiness of the production process, and information/education campaigns about the danger of consuming illegal cannabis will increase the relative valuation of consumption of legal cannabis, b. This aspect is generally overlooked by proponents of cannabis legalization. Yet our simulations show that it is an important instrument of any successful reform.

TABLE 1.2. Sensitivity of legalization price (in USD per ounce) and change in *post-legalization* demand (in percentage)

Policy parameters				Eviction price	Increase in demand			
c	b	q	F	$\underline{p}^L$	$\epsilon = -0.5$	$\epsilon = -0.6$	$\epsilon = -0.7$	$\epsilon = -0.8$
50	1.58	0.1%	1000	97.79	53%	65%	78%	91%
15	1.58	0.1%	1000	41.86	64%	79%	95%	111%
25	1.58	0.1%	1000	57.84	61%	75%	90%	105%
75	1.58	0.1%	1000	137.74	46%	56%	67%	78%
100	1.58	0.1%	1000	177.68	38%	47%	56%	65%
150	1.58	0.1%	1000	257.58	25%	30%	35%	41%
250	1.58	0.1%	1000	417.37	0%	-1%	-1%	-1%
50	0.50	0.1%	1000	30.95	66%	82%	98%	115%
50	0.75	0.1%	1000	46.42	63%	78%	93%	109%
50	1.00	0.1%	1000	61.89	60%	74%	89%	104%
50	2.00	0.1%	1000	123.78	48%	59%	71%	83%
50	3.00	0.1%	1000	185.68	37%	45%	54%	63%
50	1.58	0.0%	-	79.0	57%	70%	84%	98%
50	1.58	0.01%	1000	82.06	56%	69%	83%	97%
50	1.58	0.2%	1000	111.56	51%	62%	74%	87%
50	1.58	0.5%	1000	146.68	44%	54%	64%	75%
50	1.58	1.0%	1000	197.33	35%	43%	51%	59%
50	1.58	2.0%	1000	287.37	20%	24%	28%	33%
50	1.58	0.1%	500	88.84	55%	68%	81%	95%
50	1.58	0.1%	1500	106.74	52%	63%	76%	88%
50	1.58	0.1%	2000	115.68	50%	61%	73%	85%
50	1.58	0.1%	3000	133.58	46%	57%	68%	79%
50	1.58	0.1%	5000	169.37	40%	49%	58%	68%

Notes: Behavioral parameters are set at $\lambda = 2.25$, $\alpha = 0.88$, $\gamma^+ = 0.61$, and $\gamma^- = 0.69$ as estimated by Tversky and Kahneman (1992). Variation in demand relies on the baseline estimates for the parameters of the distribution of θ corresponding to different price elasticities of demand, as described in Table D.1.

Rows 2 to 7 of Table 1.2 present several scenarios regarding the marginal cost of operating on the black market. In the first scenario, the marginal cost for illegal production and distribution of cannabis drops to 15$ per ounce. This captures a situation in which controls are very lax and hence are not inflating the marginal cost of operation for illegal suppliers, which comes close to the estimates given by Caulkins (2010). We then present other cases where increasing and enforcing the sanctions against illegal producers and retailers raises the marginal cost of production on the black market up to 250$.

Another parameter whose evolution is hard to predict is b. Indeed, when retail sales for cannabis are legal, certified products appear, which is likely to increase b. Moreover, legalization decreases search costs, which also contributes to raising b. Meanwhile, being challenged by a newly legalized market, black market producers and retailers may decide to invest in better products and services. For instance, some consumers may not want to be seen coming in person to a dispensary, due to social stigma or professional constraints that strictly forbid them to consume cannabis (in the case of truck drivers for example), and may turn to a black market delivery service. This may reduce the relative value of legal cannabis. Starting from our benchmark value, $b = 1.58$, rows 8 to 12 consider alternative cases, for b increasing to 3.00 or falling to 0.50.[26]

Rows 13 to 18 vary the probability of being caught on the black market, q. Once a legal market is established, it may become more costly to detect consumers of illegal cannabis than it was under strict prohibition, such that q may decrease. On the other hand, it may be politically more feasible to be tough on consumers of illegal cannabis, such that q may increase. Rows 19 to 23 allow for several values of fines, F. For similar reasons, it may or may not be easier to implement higher fines with legalization, which is captured by the range of values chosen for the sensitivity analysis. In particular, it might be politically easier to implement higher fines when a legal alternative exists.

The results highlight that the recommended eviction price, presented in column 4, and the rise in cannabis consumption *post-legalization*, in columns 5 to 8, respond strongly to each policy parameter, c, b, q and F. Yet some are easier to change than others. An intuitive idea to increase the eviction price $\underline{p}^L$, at seemingly low costs, would be to increase the fine F. For example, with a USD 5000 fine for illegal purchase and other parameters set at their benchmark values then a legal price around USD 169 per ounce would evict illegal providers and contain the increase in consumption below 40% to 68%. However, this ignores the fact that high fines are expensive to enforce as they crowd the judicial system. For similar reasons, it is costly to enforce

26. Appendix D.2.4 discusses the case with $b < 1$.

arrests of users of recreational cannabis.[27]

More promising are policies enforcing sanctions against providers, instead of consumers. Our simulations show that marginal costs of production for illegal providers play a large role in the control of cannabis consumption *post-legalization*. For example, not enforcing repression against illegal providers would entail low production costs at around USD 15 per ounce and push the eviction price of cannabis down to USD 42. This would increase consumption *post-legalization* by 64% to 111%. So maintaining pressure on criminal networks is key to the success of any legalization reform, whether the objective is to raise fiscal revenues or to control consumption of psychoactive substance. This shows again that legalization and sanctions against illicit activities are complementary policies.

An under-explored channel highlighted by the calibrations is to strengthen the quality differential between legal and illegal cannabis. From a policy perspective it may seem counter-intuitive to invest in quality control and marketing of legal cannabis to promote the *post-legalization* demand, especially when a large fraction of the population is opposed to the legalization. Yet, the eviction price strongly increases with the differential in quality valuation, b, such that total consumption decreases with it.[28] For example, doubling it from 1.58 to 3 pushes the eviction price of cannabis up to USD 186, limiting the increase in consumption to 37% to 63% *post-legalization*.[29] Although this channel is effective at tilting consumption towards the

27. Yet maintaining the probability of arrest to the prohibition level, $q = 1\%$, entails an increase in the price of legal cannabis up to USD 197 per ounce, which would contain the increase in consumption below 35% to 60%.

28. In this article, we ignore the sensitivity of the demand with respect to quality. In reality, as seen in the Second Article, increases in quality yield higher demand, mitigating this result. In this case, total consumption only decreases if the quality increase yields an increase in the eviction price, such that the price effect on the demand outweighs the quality effect.

29. We model the extensive margin of consumption, not the intensive margin of consumption. The change in demand reported relates to the change in the extensive margin (See Appendix D.2.1). Not being able to capture intensive margins and how these are affected by legalization is one weakness of this model. While legalizing, a government might want to limit either (i) the number of new users or (ii) the potential increase in consumption of those who are already users – or a government might want to prioritize one of these goals over the other. Since new users have lower taste for cannabis, we could expect them to be more price sensitive. Hence, implementing high prices discourages them more than they discourage those who are already consumers. Similarly, these consumers have higher taste for cannabis and should be more sensitive to quality than new users. Hence, implementing lower quality b discourages them relatively more to consume than new users. Therefore, we should expect a policy involving relatively high prices and high quality to favor the policy goal (i), relatively to a policy involving moderate prices, even for low quality. Conversely, a policy for which the price value of legal cannabis is low would favor (ii), yet it would be a more costly policy, as sustaining such prices (high for a low quality) requires high enforcement.

legal sector and controlling it, effort to improve quality of legal products and advertise it has been generally neglected by public authorities. This explains in part some countries' disappointing experience with reform (see more on this in Section 6). It has also been largely overlooked by researchers in economics. To the best of our knowledge we are the first to look into this important aspect of cannabis legalization policies.

The policy scenarios discussed so far only affected one parameter at a time. In practice, these measures can be combined, which, with convex cost functions, is more cost-effective (see Section 6). For instance if the probability of arrest goes up to 0.5% *post-legalization* and fines are set to USD 4000, a quality differential of 2 enables to set the eviction price at USD 422, which maintains consumption at the prohibition level. This is only one illustrative example. Other more realistic examples and a discussion of the sensitivity analysis of eviction price and *post-legalization* consumption to combined measures can be found in Table D.6 in Appendix D.2.3. Both sets of results highlight that, unless significant investments in the quality of legal products and controls against the illegal market are made, the eviction price is around USD 100 USD or below. This implies an increase in demand by more than 50% to more than 100% depending on the price elasticity considered.

6. Enlarging the set of policy objectives

We have focused on policies that try to eliminate the black market while controlling the subsequent increase in consumption, but governments pursue a larger set of objectives when they implement legalization policies. These include restricting access to psychotropic drugs for the youngest users, reducing the negative externalities generated by the consumption of uncertified psychoactive substances, redeploying police forces and relieving congestion in courts and prisons to reduce enforcement costs, increasing consumer surplus, developing a sector that generates legal activities and employment while controlling the quality of products and generating new tax revenues. Although current reforms share most of these objectives, they may have different priorities.

In this section we model a (utilitarian) government's objective function as a linear combination of these objectives and study how they interact. We show that they sometimes reinforce each other, while in other cases they are conflicting. This offers an explanation as to why some reforms have been disappointing in the past.

The timing is as follows.

(1) The government chooses the price of the legal cannabis $p^L = (1+\tau)c^L$, where c^L is the marginal cost of producing the commodity legally and τ is the level of excise tax. [30]

In other words, it chooses the final price paid by consumers by choosing the tax rate. It also sets the level of repression by influencing, on the demand side, the probability of arrest q and the fine F, and on the supply side, the increase in marginal cost to produce illegally due to repression, $\delta \geq 0$, such that $c = (1+\delta)c^L$. Finally, the government takes measures to boost the quality differential between legal and illegal products, $b \geq 1$. [31]

(2) The consumers decide whether to consume or not, and on which market. Depending on the relative prices of legal and illegal products and the quality differential, the black market survives or is eradicated (see Appendix D.3.1 for more details).

Let's note $e = (F, q, \delta)$ the level of enforcement of repression against consumers and producers of illegal cannabis. The government objective function is:

$$W^G(e,b,\tau) = \alpha_T T(e,b,\tau) - \alpha_C C(e,b,\tau) + \alpha_S S^c(e,b,\tau) - \alpha_\xi \xi(e,b,\tau) \qquad (1.15)$$

where $\alpha_T \geq 0$, $\alpha_C \geq 0$, $\alpha_S \geq 0$, $\alpha_\xi \geq 0$ and where

- $T(e,b,\tau) = \tau c^L D^L\left(p,(1+\tau)c^L|b\right)$ is the revenue from excise taxes on legal cannabis.
- $C(e,b,\tau) = E(\delta,q) - qD^I\left(p,(1+\tau)c^L\middle| b\right)F$ is the enforcement cost net of the fines, with the gross cost of enforcement, $E(\delta,q)$, being increasing and convex in δ and q.
- $S^c(e,b,\tau) = \mathcal{S}^L(p,(1+\tau)c^L|b) + \mathcal{S}^I(p,(1+\tau)c^L|b) - \Psi(b)$ is the sum of the consumer surpluses on the legal and illegal markets, net of $\Psi(b)$, the cost of legal cannabis quality improvement, which is strictly increasing and convex.

30. Cannabis is an agricultural product easy to grow as it is highly adaptable to various conditions. When the government encourages competition among the growers and the retailers, they do not make any rent. It can then modulate the final price by imposing an excise tax (e.g. as is widely done for the retail of tobacco). We focus on this case, for the sake of simplicity. More generally, the government may influence the concentration on the legal market by artificially raising its cost of entry (e.g. limiting the number of licenses). Yet, the Cournot price when legal retailers compete among themselves, net of taxes, is proportional to the marginal cost. Our results therefore extend easily to an oligopoly setting. The share of the sector rent captured by the government is simply smaller with an oligopoly.

31. For the sake of simplicity, we assume here that c_L is constant. Yet, in reality it is increasing in b, traceability and controls being costly. Strict regulation on quality could imply that $c < c_L$. In this case, the government should encourage further quality investments on the legal market and enlarge its offer, as solely discriminating in prices would not allow to eradicate the black market. See the Second Article for more detail.

- $\mathcal{S}^L\left(p,(1+\tau)c^L|b\right) = \int_{(1+\tau)c^L}^{\infty} D^L(p,t|b)\mathrm{d}t$ is the net consumer surplus on the legal market.
- $\mathcal{S}^I\left(p,(1+\tau)c^L|b\right)$ $= (1-q)\int_p^{\bar{p}^I} D^I\left(t,(1+\tau)c^L|b\right)\mathrm{d}t - qD^I\left(p,(1+\tau)c^L|b\right)F$ is the net consumer surplus on the illegal market, with $\bar{p}^I$ being the choke-off price on the illegal market. It is defined as the price p such that equation (1.8) holds with equality for $p^L = (1+\tau)c^L$.

- Finally the negative externalities generated by the legal and the illegal sectors are increasing in their respective demands: $\xi(\tau,e,b) = \xi_I D^I\left(p,(1+\tau)c^L|b\right) + \xi_L D^L\left(p,(1+\tau)c^L|b\right)$, with $\xi_I \geq 0$ and $\xi_L \geq 0$.

We consider in turn four different objectives that can be decentralized through the choice of enforcement of sanctions against the illegal sector, $e = (F,q,\delta)$, and regulation of the legal sector (b,τ), and study whether they are compatible with the goal of deflating organized crime by setting an eviction price for legal cannabis.

Minimizing negative externalities: $\alpha_T = \alpha_S = \alpha_C = 0$ and $\alpha_\xi > 0$
Because both legal and illegal consumption of psychotropic substances entail health hazards, a government focusing on such externalities minimizes $\xi(\tau,e,b) = \xi_I D^I\left(p,(1+\tau)c^L|b\right) + \xi_L D^L\left(p,(1+\tau)c^L|b\right)$.

Prohibition corresponds to the case in which legal use of cannabis is perceived as having larger negative externalities than illegal use: $\xi_I \leq \xi_L$. Only in this case does the government minimize total consumption. All else being equal (i.e., for the same investment level in repression) legalization inevitably leads to an increase in demand as shown in Section 4. Therefore, for a given repression budget, prohibition is the policy that minimizes total consumption of cannabis. To limit the (black market) demand for cannabis, the government should invest in repression. Increasing the sunk costs and the marginal cost of producing illegally pushes the number of illegal providers N down and their prices up. The highest price and lowest demand is achieved by a criminal monopolist. It should also increase the repression against users (i.e., q and F) to decrease the number of people willing to purchase the illegal substance (i.e., to increase θ^I in 1.3).

In contrast, a government may consider that illegal cannabis is more harmful than legal cannabis for several reasons. The quality of legal products can be certified and health damages reduced. Illegal cannabis can be sold to minors or vulnerable groups, who are at risk of developing psychosis. The ban of sale to the under-aged cannot be enforced on the black market: many criminals do not mind who is buying their products, as long as they get paid. Finally, it generates a whole range of criminal activities, including violence, corruption and money laundering (see Section 2). This case corresponds to $\xi_I > \xi_L \geq 0$. Clearly if $\xi_L = 0$, the legalization at eviction price $\underline{p}^L = bv\theta^I(c)$ is optimal. Indeed if consumers derive utility from cannabis consumption without incurring, nor generating, any negative externality, then reducing use is a cost, not a benefit. Certain practices, such as driving or working under the influence, should still clearly be prohibited but might be appropriate targets for a different kind of selective policies.[32] If $\xi_L > 0$, the government seeks to annihilate illegal consumption while controlling legal demand, which is achieved through the policy mix described in the corollary 1.1.

Minimizing net enforcement cost: $\alpha_T = \alpha_S = \alpha_\xi = 0$ and $\alpha_C > 0$
A government may want to minimize the burden for tax payers of the net enforcement cost of repression, $C(\tau, e, b) = E(\delta, q) - qD^I\left(p, (1+\tau)c^L|b\right)F$. In practice, $qD^I\left(p, (1+\tau)c^L|b\right)F$, the revenue from arrests, is always lower than the gross cost of enforcement, $E(\delta, q)$. The solution consists in implementing the eviction price $\underline{p}^L = bv\theta^I(c)$. The government avoids investing too much in repression (q and δ should be minimal) as it is costly. It implies that $\theta^I(c)$ in (1.3) will be low in equilibrium. It also implies that the level of taxes will have to be relatively low at $\tau^{\alpha_C} = \frac{bv\theta^I(c)}{c^L} - 1 > 0$ since $v\theta^I(c) > c \geq c^L$. In other words, minimizing the cost of enforcement in a regulated cannabis market is best achieved by implementing a relatively low eviction price, which means that the subsequent increase in demand for cannabis is large. To manage the demand, the government should encourage investment in quality of the legal products, which increases the eviction price and implies a lower increase in *post-legalization* demand. This obviously comes at a cost, which is not internalized in this objective as it is borne by the private sector (i.e., the firms that sell legal cannabis).

A government concerned with the increase in consumption related to legalization at the eviction price may try to minimize the net enforcement cost, while containing consumption. This is typically the objective of most prohibitionist governments, which corresponds to $\alpha_C > 0$ and $\alpha_\xi > 0$ with $\xi_I < \xi_L$. The problem they solve is to minimize $C(e) = E(\delta, q) - qD^I\left(p, (1+\tau)c^L|b\right)F$ subject to $D^I(p) \leq \bar{D}$. Since reducing the illegal demand is only made possible by further – costly – investments, for a given level of fine F, the constraint is binding: $D^I\left(p, (1+\tau)c^L|b\right) = \bar{D}$ and the optimal levels of q and δ then satisfy

$$\frac{\frac{\partial D^I\left(p,(1+\tau)c^L|b\right)}{\partial q}}{\frac{\partial D^I(p,(1+\tau)c^L|b)}{\partial \delta}} = \frac{\frac{\partial E(\delta,q)}{\partial q} - F\bar{D}}{\frac{\partial E(\delta,q)}{\partial \delta}} \tag{1.16}$$

32. We are grateful to Jeffrey Miron for this comment.

Equation (1.16) is a standard result: to optimize the utilization of inputs (here law enforcement resources) the marginal rate of transformation between q and δ in terms of reduction of demand should be equal to their relative marginal cost. Interestingly, everything else being equal, increasing q is more cost effective than increasing δ as the government collects fines when users are arrested. Technically, the Lagrange multiplier of the optimization problem is increasing in the fine amount F. In theory, fixing a very large value for F is a cheap way to control demand. Yet, as mentioned in Section 5, very high fines are not feasible in practice, as most individuals caught would not be able to pay them. This would result in – costly – congestion of the judicial system.

Finally the way repression is targeted and enforced matters too. For the sake of simplicity, we focus on vertically integrated drug dealers, which abstracts from the fine tuning of repression policies. Yet, unpacking the vertical relationship between traffickers and retailers yields interesting and subtle insights (Poret, 2002, 2009). The effects of tougher drug law enforcement policies, depending on whether they target retailers or traffickers, have different effects on wholesale and retail prices of drugs. Poret (2002) hence shows that ill targeted efforts to increase repression can, by disrupting well organized drug cartels, decrease final users' prices and increase the number of consumers.

Maximizing consumer surplus: $\alpha_T = \alpha_\xi = \alpha_C = 0$ and $\alpha_S > 0$

If a government focuses on consumer surplus, it should choose a price p^L lower than (or equal to) the eviction price $\underline{p}^L = bv\theta^I(c)$. Indeed, for the same quantity consumed, the surplus of users is larger with a legal option than an illegal one. The government should therefore implement a legalization policy with a price low enough to shut down the illegal market. In the limit, when it has no other objective, it should set the tax at $\tau = 0$, so that $p^L = c^L$. The government should also aim to improve the quality of cannabis products (notably in terms of variety, availability, marketing and packaging). The quality investment that maximizes consumer surplus equalizes the marginal surplus of consumers with the marginal cost of quality improvement: $\int_{(1+\tau)c^L}^{\infty} \frac{\partial D^L(t|b)}{\partial b} \mathrm{d}t = \Psi'(b)$.

Maximizing tax revenue: $\alpha_S = \alpha_\xi = \alpha_C = 0$ and $\alpha_T > 0$

When focusing on tax revenue, the government will choose $\tau^{\alpha_T} > 0$ such that $\frac{\partial T}{\partial \tau} = 0$, assuming an interior solution exists. This is equivalent to:

$$1 - G(\theta^l) = \tau c^L g(\theta^l) \frac{\partial \theta^l}{\partial p^L}, \tag{1.17}$$

with $\theta^l = \theta^0 = \frac{p^L}{bv}$ if in the initial situation the black market has been eliminated, and $\theta^l = \theta^L$ defined in (1.7) if not. In Appendix D.3.2, we develop an example where

θ follows an exponential distribution on the positive real line so that we can derive closed form solutions. This simple example highlights that the unconstrained solution (i.e., in the absence of competition by the black market) leads to a larger excise tax than the constrained solution: $\tau_0^{\alpha_T} \geq \tau^{\alpha_T}$,[33] which is intuitive. When the government does not have to deal with competition it can impose higher taxes, as the consumers are captive. Unsurprisingly, the price resulting from the tax optimization problem is generally higher than the eviction price $\underline{p}^L = bv\theta^I((1+\delta)c^L)$.

More generally, when the government aims to maximise tax revenue, a portion of the black market will survive. As in Section 5, we run calibrations to compute the prices in both the legal and the illegal markets when the government focuses on maximizing tax revenues. We use the same benchmark values of the policy parameters as in Section 5 and a value for the marginal costs to produce in the legal sector around USD 25 in line with Quah et al. (2014) and Caulkins (2010). Methodological detail, as well as further examples, can be found in Appendix D.3.3. Table 1.3 explores different scenarios in terms of enforcement and quality.

The first column presents the *post-legalization* concentration on the illegal market. Using the Cournot optimality condition with the benchmark black market price and marginal cost valued at USD 320 and USD 50 respectively, yields a concentration on the black market under prohibition of between 0.42 and 0.68, when the price demand elasticity varies between 0.5 and 0.8. We therefore chose 0.55 as a benchmark value for this parameter. Although the concentration on the black market is not a policy parameter *per se*, the legalization may generate changes in the concentration on the black market, which is why we study scenarios where this parameter varies from 0.10 to 1.00. Columns 2 to 5 describe the values of the other policy parameters, whose notations are unchanged. Columns 6 and 7 provide the equilibrium prices on the black market and on the legal market, while columns 8 and 9 give the overall increase in demand $\Delta D(p, p^L)$, as well as the share of the black market in the total demand, $\%D^I$. Column 10 describes the tax revenue in USD *per capita* and *per annum* derived from state cannabis sales for the specified price and demand on the legal market. The last three columns provide the eviction price, as well as the corresponding increase in demand and tax revenue in USD *per capita* and *per annum*.

The results highlight that in most cases, the price on the legal market maximizing the tax revenue from legal sales, roughly USD 300 per ounce, is much higher than the eviction price. This result is consistent with the fact that the state of Washington, where the average legal price for cannabis is around 200 USD per ounce (see Table 1.1), would position itself on the ascending portion of the Laffer curve as argued by

33. They are equal only when $q = 1$.

TABLE 1.3. Legalization price and demand when the government maximizes tax revenue

	Policy parameters				Equilibrium prices		Demand and revenue			Eviction scenario		
$\frac{1}{N}$	c	b	q	F	p	p^L	$\Delta D\left(p, p^L\right)$	$\%D^I$	R	$\underline{p}^L$	$\Delta D\left(\underline{p}^L\right)$	$\underline{R}$
0.55	50	1.58	0.1%	1000	95.33	297.47	33%	35%	341	97.79	104%	151
0.55	25	1.58	0.1%	1000	78.60	292.94	29%	39%	320	57.84	113%	71
0.55	125	1.58	0.1%	1000	146.13	311.84	45%	18%	409	217.63	78%	350
0.55	200	1.58	0.1%	1000	200.42	338.15	54%	0%	491	337.47	54%	490
0.10	50	1.58	0.1%	1000	61.33	288.35	25%	44%	300	97.79	104%	151
0.25	50	1.58	0.1%	1000	75.15	292.01	28%	40%	316	97.79	104%	151
0.75	50	1.58	0.1%	1000	105.23	300.20	35%	32%	353	97.79	104%	151
1.00	50	1.58	0.1%	1000	115.05	302.94	37%	29%	366	97.79	104%	151
0.55	50	1.00	0.1%	1000	56.11	67.85	102%	0%	88	61.89	104%	77
0.55	50	1.10	0.1%	1000	55.20	84.04	76%	15%	103	68.08	104%	90
0.55	50	1.30	0.1%	1000	76.13	173.87	44%	31%	205	80.46	104%	115
0.55	50	1.80	0.1%	1000	105.56	393.40	28%	36%	443	111.41	104%	180
0.55	50	1.58	0.2%	1000	92.88	302.42	33%	33%	351	111.56	101%	177
0.55	50	1.58	0.5%	1000	86.81	314.70	36%	29%	377	146.68	93%	240
0.55	50	1.58	1.0%	1000	78.42	331.60	38%	23%	413	197.33	82%	320
0.55	50	1.58	0.0%	1000	98.73	290.60	31%	37%	327	79.00	108%	115
0.55	50	1.58	0.1%	100	98.65	295.63	31%	37%	333	81.68	108%	120
0.55	50	1.58	0.1%	500	97.17	296.45	32%	36%	336	88.84	106%	134
0.55	50	1.58	0.1%	1500	93.49	298.51	33%	34%	346	106.74	102%	168
0.55	50	1.58	0.1%	2000	91.66	299.55	34%	32%	350	115.68	100%	185

Notes: The above results are based on a price demand elasticity of 0.8 and the corresponding distribution parameters (see Table D.1). The marginal cost on the legal market, c^L, is USD 25 per ounce. The tax revenue in USD *per capita* and *per annum* is given as the product of the difference $p^L - c^L$ with the extensive and intensive margins of consumption. The intensive margin is approximated using Orens et al. (2018) estimates for consumption in Colorado in 2017.

Hollenbeck and Uetake (2021). In the baseline scenario price that maximizes tax revenue is three time higher than the eviction price, which is roughly USD 100 per ounce. In this case, the black market survives and accounts for a third of the overall market. Depending on the setting, it may account for 15% to up to 44% of the market. This result is consistent with the black-market to be responsible for 15% to 50% of the transactions in the state of Washington (Arcview Market Research and BDS Analytics, 2019), as the the average legal price for cannabis is roughly the double of the eviction price. Unless marginal costs are relatively high, the overall extensive margin for cannabis consumption is higher under the eviction price scheme than with a tax maximizing objective.

Interestingly, when the quality on the legal market is not different from the illegal market, the legal price that maximizes tax revenue is relatively close to the eviction price and very little black market survives. This shows a case where maximizing tax revenue and eradicating the black market are compatible. However, with a legal cannabis of low quality, the level of tax revenue is very low. We show in Appendix

D.3.3 that these results are robust to a setting where, post legalization, consumers are not arrested for illegal purchases – i.e. $q = 0$.

Discussion of the implementation of reforms. This review of legalization reform objectives shows that deflating crime through an eviction price is compatible with the maximization of consumer surplus, the minimization of enforcement cost related to the regulation of cannabis market, and the minimization of health hazards and other negative externalities connected with illegal cannabis consumption. Interestingly enough, current dominant policies of prohibition are optimal only when the government wants to minimize total consumption of cannabis. Justifying prohibition based on our general economic framework requires that public authorities consider health hazards due to legal cannabis consumption equal or worse than for illegal cannabis, and that the costs of prohibition enforcement are neglected. Finally, the maximization of tax revenue will generally conflict with the eradication of the black market. Without reinforcing repression, it leads to higher final prices of legal cannabis than eviction prices, leaving room for illegal providers to operate.

Moreover, we have shown that for legalization reforms to succeed, the quantity, quality, and purchasing experience for legal cannabis must be high. An important and generally overlooked tool the government can use to regulate the cannabis market is to improve the quality of legal cannabis relative to illegal cannabis. To fight the black market, an abundant provision of products of good quality is key. This effort should be increased as governments put more weight on health externalities, consumer surplus, enforcement cost or tax revenue. Since the government is generally a poor grower and an even worse retailer of cannabis, the private sector may do a better job of meeting customer demand than civil servants. Since it is a basic agricultural crop, the government should license enough producers to maintain a steady supply of cannabis and avoid high markups by the private sector. Production should be tightly monitored through satellite images and drones to avoid having over-production feed the black market. Sanctions in case of misconduct should be harsh. At the same time, the licensed retailers should be sufficiently numerous to give choices to customers and keep a low pre-tax price (as for tobacco retailers in the EU). The final price should be adjusted by the government by setting the level of the excise tax based on its objectives.

Legalization reforms and their discontent

Following citizens' initiative referendums in November 2012, there was legislative change in Colorado and Washington State to end cannabis prohibition in 2013 and

2014. The reforms gave priority to reducing the costs of prohibition, developing a new sector of activity, and generating tax revenue.[34] Since the initial goal was to meet consumers' needs, production, distribution and sale were entrusted to private operators, who invested in market-driven R&D and quality development. A legal industrial sector has since developed: as of today, each of these states accounts nearly three times more recreational cannabis retailers than McDonald's restaurants (see Table 1.1). This booming legal market generates a substantial revenue, estimated at around USD 1 billion in 2016 in each of these states (for a population of 5.6 million in Colorado and 7.4 million in Washington State).

In Washington State, where the final price is close to USD 200 per ounce, the level of taxes is high, as are quality requirements. This explains why the black market still represents 15 % to 50 % of the cannabis transactions (Arcview Market Research and BDS Analytics, 2019).[35] Nevertheless, a few years after legalization, both states are quite happy with the impact of the reforms on their local finances and economy, while adult consumers enjoy a great variety of high quality cannabis products. These two states had a clear set of compatible priorities that were achieved by combining a market orientation for customers with relatively high taxation.

In a similar line, Governor Cuomo signed legislation S.854-A/A.1248-A on 2021, March 31, legalizing the recreational use of cannabis in the state of New York.[36] This reform was presented as a social measure, putting an end and repairing severe repression disproportionately affecting minorities. It is expected to generate a tax revenue of USD 350 million *per annum* as well as to create 30,000 to 60,000 jobs. The relatively low point of sale retail tax rate – a 9% state tax combined with a 4% local tax – suggests that the state black market is likely to be eradicated fairly quickly.[37]

34. The *Colorado Marijuana Legalization Amendment,* or *Amendment 64*, claims that cannabis legalization is *"in the interest of the efficient use of law enforcement resources, enhancing revenue for public purposes, and individual freedom"*.

35. According to New Frontier Data economist Beau Whitney, cited by Jeanne Lang Jones and Rob Smith. 2019. "Tight Regulations, High Taxes May Keep Washington State's $1.4B Cannabis Industry from Really Blooming". *Seattle Business.* January.

36. See New York State Government, 2021. "Governor Cuomo Signs Legislation Legalizing Adult-Use Cannabis" `https://www.governor.ny.gov/news/governor-cuomo-signs-legislation-legalizing-adult-use-cannabis`

37. Interestingly, this point of sale retail tax is coupled with a THC-potency-based tax on distributors, providing a comparative advantage to low-potency products resembling medical cannabis.

This is in contrast with the legalization reform in California, whose main objective was to raise substantial new tax revenue. In an environment where the Medical Marijuana Laws had made the grey economy prosperous, the introduction price/quality ratio of the legal cannabis was too high compared to the price/quality ratio on the illegal market. Since the cannabis industry was already well established under prohibition, consistently with our predictions, it reacted swiftly to the legal offer by lowering its prices. It has since grown, absorbing customers who previously were purchasing medical cannabis legally. Illicit transactions account for approximately 80% of the Californian cannabis market.[38] The tax revenue is a fraction of what was expected and the government of the state is quite disappointed by the reform. A better policy would have been to fix a lower introduction price of legal cannabis (i.e., lower tax rate, at least initially), combined with investments to raise quality and marketing to give a competitive edge to the legal products, and a stronger push back against illegal cannabis producers and consumers, in line with the policy mix we describe in Section 4.

The reform in Uruguay also failed to reach its main objectives, which were to annihilate the black market and strengthen the protection of minors and the safety of adult users, while controlling total consumption. This led the government to create a state monopoly, which delegated the production of cannabis to strictly regulated private companies. To eradicate the black market, Uruguay had initially set the price of legal cannabis at the same level as the black market. However, the government's attempt to control consumption led to a severe underestimation of the size of the market and rationing.[39] Thus, several years after the official legalization in 2012, a majority of consumers continue to turn to the black market for their consumption, defeating the initial objective of the reform.

With similar objectives of eradicating the black market and drug-related crime, Canada made the same mistake as Uruguay in underestimating the needs of the consumers of cannabis, both in quantity and in quality. This created rationing and the users had to turn to the black market for their consumption. Since the federal government gave the Provinces the responsibility of implementing the new policy by regulating the retail markets, as well as setting possession, use, and cultivation limits

38. Kevin Murphy. 2019. "Cannabis' Black Market Problem". *Forbes.* April 4..

39. By the end of 2017, only two producers were approved for an annual volume of one ton each, while the market has been estimated at between 35 and 40 tons. In addition, the hostility of pharmacists, charged by the State to sell cannabis, has made it more difficult and unpleasant for users to obtain supplies. The authorization of self-cultivation or small producers' clubs, also tightly limited and regulated, has not compensated for the inadequacy of the public offer.

for personal use, the nation-wide legalization policy adopted in 2017 and 2018 took different forms across Provinces.

For instance in Alberta, home-cultivation is allowed [40] and online retail sales are managed by a government monopoly, while retail sales are left to private licensed stores. In Québec, one cannot home-grow cannabis and retail sales are organized by the government. The *Société Québécoise du Cannabis (SQDC)*, a subsidiary of the provincial society for alcohols, provides cannabis both in shops and online. [41] Dried flower products are priced between CAD 8 and 10 per gram by the SQDC, depending on potency and strain type, which is close to the *pre-legalization* black market price ($p^L = p$). As discussed in Section 4, this policy did not anticipate the response of smugglers on the black market and the average black market price in Québec fell to below CAD 6 per gram, as reported Mid March 2019 by the crowd-sourced website priceofweed.com.

It is still too early to assess precisely the effects of legalization on overall consumption and the size of the black market. Using monetary circulation in Canada, Goodhart and Ashworth (2019) show that the need for cash decreased in the country just after the legalization, which they interpret as a decrease in black market cannabis transactions. For them, the country is heading towards one of the goals Trudeau had set in 2015: "[keeping] profits out of the hands of criminals". [42] However, this optimism is contradicted by the recent evolution of the market. Facing a shortage on the supply side, legal providers have focused on increasing their production (i.e. quantity), with no effort to improve the quality of their products, nor the purchasing experience of the consumers (resulting in a low b). As a result of this failure to meet consumers' needs, the black market has survived by lowering its prices, which is consistent with the theory, and the stock market prices of the new legal firms have plummeted. [43] Statistics Canada, the national statistical agency, estimated that about 75% of cannabis users were still using illegal cannabis in 2019. It implies that the overall (legal plus illegal) demand for cannabis has increased in Canada, with a thriving black market. Here again, the failure to anticipate the reaction of the black market to legalization

40. Up to four active plants for personal use.

41. As of March 2019, SQDC stores only open from Wednesday to Sunday, "due to the current supply shortages (...) until product availability is more stable" (SQDC's website, www.sqdc.ca, March 19, 2019). A year later, SQDC stores' schedule covers the whole week and about 40 stores are expected throughout Québec.

42. Liberal Party. 2015. "Real change: a new plan for a strong middle class". `https://www.liberal.ca/wp-content/uploads/2015/10/New-plan-for-a-strong-middle-class.pdf`

43. Levinson-King, Robin. 2019. "Why Canada's cannabis bubble burst". *BBC News*. December 29. `https://www.bbc.com/news/world-us-canada-50664578`

and to internalize consumers' demand for quality led to poorly designed reforms, at least initially.

7. Conclusion

Designing a policy that both eliminates organized crime and limits the increase in cannabis use *post-legalization* is not trivial. Examples of what can go wrong include situations in which cannabis is legal but too expensive (e.g., California) or rationed and of low quality (e.g., Uruguay or Canada). Both scenarios result in flourishing illegal businesses with no significant decrease in crime. We explore how to avoid such unexpected effects of legalization policies. The policy mix we propose enables public authorities to throttle the cannabis black market by implementing a legal alternative and to control the increase in cannabis consumption *post-legalization*.

Our findings highlight the complementarities between legalization of high quality cannabis (in terms of purchasing experience, gustatory quality of the product, potency and purity) and sanctions against illegal trade, providing policymakers with guidelines to overcome the legalization/prohibition trade-off. Legalization will be effective at regulating the demand for cannabis if consumers are compelled to buy on a legal market rather than illegally, and, at the same time, if illegal suppliers are targeted by repressive measures that drive them out of business. Raising the level of punishment and enforcing sanctions not only against users of illegal drugs but more effectively against suppliers, enable authorities to implement higher legal prices for cannabis while undermining dealers.

Although our analysis focuses on how to achieve full legalization by eliminating the black market while containing consumption *post-legalization*, our general framework can be used to study a broader set of objectives. Extensions we discuss show that our policy mix enables governments to reach different objectives, such as the minimization of externalities or of enforcement costs, or the maximization of consumer surplus. Again, the analysis highlights the importance of offering high quality legal products to achieve these objectives. Finally, to shed more light on consumption behavior *post-legalization*, future research should account for the large heterogeneity of consumers, in particular regarding their risk aversion, intensive margin of consumption and liquidity constraints.

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Second Article.

Flying High? Legalization and the Black Market for Cannabis

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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 analyses show that legalization and the introduction of legal retailers yield an immediate and large drop in black-market prices, as well as a limited 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 remains unchanged *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

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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.[44] 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`[45]). Yet, because the black market for cannabis features high vertical differentiation (Červený 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

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

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

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 assemble a novel dataset on city-level crowd-sourced cannabis prices and quality in the US. I digitize 20 years of prices and strains from the Trans-High Market Quotation (THMQ) and match them with their expected THC potency levels, which I webscrape from Leafly's online cannabis consumer guide. These objectively capture quality.[46] 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).[47] 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 20% and THC potency rising by almost 1.4%.[48] 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 necessarily the case for higher potency products, for which reactions are more difficult to predict and which may 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 the First Article of this thesis).

Based on the reduced-form evidence, I propose a structural model of cannabis supply and demand to study the role of price and quality changes induced by legalization.

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

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

48. These average results come from TWFE estimates and are subject to heterogeneity across states and time.

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 of participation [49] to the black market to lie between -0.2 and -0.3. [50] 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). [51] 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. [52] Therefore, since cannabis consumers respond to risk (Jacobson, 2004), they naturally tend to consume

49. 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).

50. This is in line with the results of Jacobi and Sovinsky (2016).

51. 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.

52. 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.

more. Retail sales make cannabis more available, granting easier access 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 the First Article). 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 article 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 its use in the literature has been relatively sporadic [53] – while data on retail transactions from the the WSLCB was recently used in several Industrial Organization 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.

53. Although different extracts of the THMQ data have been used in the economic literature (see for example Jacobson, 2004; Anderson et al., 2013).

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* Biotrack-THC. [54] This requirement 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. [55] I aggregated this data into local price indices, at the Metropolitan Statistical Area level (see Appendix E.1.1).

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, 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.

54. 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.

55. 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.*

FIGURE 2.1. THMQ for the September 2017 issue of *High Times*

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 2.2. THMQ for the December 1999 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.

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 2.1. Older versions, as in Figure 2.2, 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 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`.[56] Appendix E.1.2 provides detail on how the data were cleaned and matched.

3. Reduced-form evidence

This section provides reduced-form results on the black market equilibrium response to legalization reforms. 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.

56. 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.

On quality, estimation of a two-way fixed effects model 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.

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. Average effects of legalization 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.

In the US, unlike in other jurisdictions such as Canada, legalization policies are usually implemented in two steps: first the recreational use of cannabis is legalized, then on average two years later, the first legal retail sales of cannabis are implemented (see Appendix Afor more detail). I therefore consider two treatments: the legalization cannabis use – hereafter called "legalization" – and the operation of legal retail sales for recreational cannabis. The related twoway fixed effects (TWFE) model is given as follows:

$$y_{ist} = \theta_s + \psi_t + \beta_L \mathbf{L}_{st} + \epsilon_{ist} \tag{2.1}$$

where y_{ist} is the outcome of interest for observation i collected in state s during month t, θ_s is a state fixed effect,[57] ψ_t is a time fixed effect, $\mathbf{L}_{st}$ is a vector 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 vector $\mathbf{L}_{st}$ indicates whether recreational use of cannabis is legal, which will be denoted as *legal*, and whether legal retail sales for cannabis are operational, denoted as *retail*.

Two issues here affect the unbiasedness of the TWFE estimator. In the presence of differential timing, the TWFE estimator $\hat{\beta_L}^{fe}$ measures a weighted composite of average treatment effets on the treated (ATT). For instance, Goodman-Bacon (2021) proposes a decomposition of the TWFE estimator into a weighted average of the difference-in-difference estimates resulting from the two-by-two comparisons between all the groups,

57. In this model, 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.

with weights depending on group sizes and variance in treatment. de Chaisemartin and d'Haultfœuille (2020) show the TWFE estimator can be written as a weighted sum of ATT in each group and period. This implies that unless the treatment effect is homogenous across states and time, the TWFE estimator is biased. The other issue comes with retail sales of recreational cannabis being legalized after recreational use. These two policy changes are considered as two treatments dependent on one another, on top on their staggered adoption. By this design, the estimated effect of the implementation of retail sales is likely contaminated by the effect of the legalization of recreational use (Hull, 2018; Goldsmith-Pinkham et al., 2021; de Chaisemartin and d'Haultfœuille, 2022).

To address these issues, I follow de Chaisemartin and d'Haultfœuille (2020) to check the robustness of the TWFE estimator to treatment heterogeneity in my data.[58] The diagnostic tests proposed mainly consist in computing the weights of ATT in each group and period. In this decomposition, weights sum to 1 but some may be negative. In case the TWFE estimator is not a convex combination of the ATTs, then its sign can be opposite to the sign of the actual treatment effect. The tests also provide two statistics: the minimum variance in treatment such that the treatment effect is zero, as well as (should some of the weights be negative) the minimum variance in treatment such that the treatment effect is of opposite sign as the treatment effect.

I consider the three following specifications:[59]

(i) the effect of the legalization of recreational use was computed without controlling for the implementation of retail sales;

(ii) the effect of the implementation of retail sales was computed without controlling for the legalization of recreational cannabis use;

(iii) the effect of the implementation of retail sales was computed controlling for the legalization of recreational cannabis use.

Results of diagnostic tests for these specifications are provided in Appendix E.2. They indicate two things. First, when treatments *legal* and *retail* are taken separately the OLS estimates of TWFE model are a convex combination of the ATTs. However,

58. This diagnostic test method is more suitable in this context than the decomposition proposed by Goodman-Bacon (2021). The latter requires *strictly balanced* panel data. To satisfy this assumption, I would have to aggregate the data at the year level and drop some states, losing a notable amount of information. Further, the decomposition in de Chaisemartin and d'Haultfœuille (2020) can be applied to settings such as this one, in which there are multiple treatments.

59. In Appendix E.2, I conduct similar diagnostic tests for two other specifications in which I restrict the sample to observations such that no more than one treatment – *legal* or *retail* – has been applied. The results from these diagnostic tests indicate a likely problem of sign with the TWFE estimate when the effect of *retail* is analyzed on the subsample that has legalized cannabis, which is why I discard these two additional specifications from the analysis.

should the treatment effect be highly heterogenous, either across time or units, its average could be zero. Second, contamination between the two treatments *legal* and *retail* is very likely.

Tables 2.1 through 2.3 describe the average impact of legalization on the price, quality and quality ajusted price (that is the price normalized by the THC potency) on the black market for cannabis. Columns (1) and (2) of each table provide the results for specification (i) respectively using OLS on the TWFE model specified in (2.1) and the DiD-M estimator introduced by de Chaisemartin and d'Haultfœuille (2020). Column (3) and (4) describes the OLS and DiD-M results for specification (ii). Column (5) gives the result of the DiD-M estimation of the impact of *retail* when controlling for legalization.

Main takeaways comparing the TWFE and the DiD-M estimators. The OLS estimation results of the TWFE model indicate that legalizing recreational cannabis would result in the black-market price to drop by 19.5% overall. This effect seems strenghened by the implementation of regulated retail sales for recreational cannabis, which result in a similar drop in the black-market price. 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 1.4%. The effect of *legal* on the potency-normalized price is lower (in absolute value) than the effect found on price, without the normalization. The treatment *retail* results in a drop in the quality adjusted price by more than 16%.

The DiD-M estimates are very different from the OLS estimates of the TWFE model. Further, they display relatively high standard errors. This result, combined with the OLS results as well as the diagnostic tests suggest a high heterogeneity in treatment effects either across time or units. For example, the DiD-M estimate of the treatment *legal* on the black-market price for cannabis is around -7.7%. Comparing it with model (1) suggests that the TWFE estimates are driven down by some heavily weighted units featuring an outstandingly high decrease in the price. On the effect of *retail*, the DiD-M estimate is even from a different sign as the OLS. Since the diagnostic tests indicate all weights associated to this regression are positive, it suggests that while the price in some heavily weighted units decreases notably, it rises in other units *post-legalization*. The results on the two other outcomes reaffirm this intuition.

These results are not surprising. Legalization policies vary in their implementation and hence can lead to very different legal markets – on thereby different prices and levels of quality. The 15% the tax rate on retail sales for cannabis in Colorado reflects the liberal spirit in which the reforms were implemented. The state of Washington,

Table 2.1. Difference-in-difference estimates of the effects of legalization on the price of black market cannabis

	(i)		(ii)		(iii)
	OLS (1)	DiD-M (2)	OLS (3)	DiD-M (4)	DiD-M (5)
Treatment					
legal	-0.1950***	-0.0774	-	-	-
	(0.0405)	(0.0732)			
retail	-	-	-0.1901**	0.0689	0.0684
			(0.0319)	(0.1451)	(0.1467)
Fixed effects (OLS)					
State	✓	-	✓	-	-
Year	✓	-	✓	-	-
N	9,460	-	9,460	-	-
n	-	115	-	139	139
Switchers	-	10	-	6	6

Standard errors in parentheses are clustered at the state level.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

This table reports OLS and DiD-M 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. Columns (1) and (2) provide the results for specification (i) respectively using OLS and the DiD-M estimator introduced by de Chaisemartin and d'Haultfœuille (2020). Column (3) and (4) describe the OLS and DiD-M results for specification (ii). Column (5) gives the result of the DiD-M estimation of the impact of *retail* without controlling for legalization. Other covariates in the OLS models are state and year fixed effects. DiD-M estimates are robust to dynamic treatment effects. For OLS estimates, N indicates the number of observations. For DiD-M estimates, n gives the number of entities compared in the model while *switchers* is the number of treated entities.

where the cannabis market is more regulated, taxes retail cannabis as high as 37%. Other examples of regulations affecting the legal retail market include – but are not limited to – limits on the number of licenses awarded, stricter or laxer traceability controls at the upstream level or regulations on personal home growing. Section 3.2 provides detail on responses by state.

Price decreases in response to *legal* and *retail* suggest both legality and availibility matter. Almost half 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

TABLE 2.2. Difference-in-difference estimates of the effects of legalization on the THC potency of black market cannabis

	(i)		(ii)		(iii)
	OLS (1)	DiD-M (2)	OLS (3)	DiD-M (4)	DiD-M (5)
Treatment					
legal	0.0038	-0.0581	-	-	-
	(0.0073)	(0.0645)			
retail	-	-	0.0143**	0.0345	0.0345
			(0.0056)	(0.0382)	(0.0331)
Fixed effects (OLS)					
State	✓	-	✓	-	-
Year	✓	-	✓	-	-
N	7,901	-	7,901	-	-
n	-	80	-	119	119
Switchers	-	9	-	6	6

Standard errors in parentheses are clustered at the state level.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

This table reports OLS and DiD-M 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 THC potency. Columns (1) and (2) provide the results for specification (i) respectively using OLS and the DiD-M estimator introduced by de Chaisemartin and d'Haultfœuille (2020). Column (3) and (4) describe the OLS and DiD-M results for specification (ii). Column (5) gives the result of the DiD-M estimation of the impact of *retail* when controlling for legalization. Other covariates in the OLS models are state and year fixed effects. DiD-M estimates are robust to dynamic treatment effects. For OLS estimates, N indicates the number of observations. For DiD-M estimates, n gives the number of entities compared in the model while *switchers* is the number of treated entities.

the legal retail market and lower their prices. Alternatively, legalization could in theory lower the risk for illegal producers of being detected,[60] which would lower the costs of producing black-market cannabis, producers being subject to lower risk of sanctions. This could imply less seizures, resulting in lower marginal costs, as well as lower investment in infrastructures, which need not be as *hidden* as under prohibition, reducing fixed costs. Lower fixed costs would atomize the supply for cannabis on the illegal market and enhance competition.

60. Under prohibition almost any production is illegal, which makes detection relatively straightforward compared to a *post-legalization* environment where law enforcement would have to distinguish illegal from legal businesses.

Table 2.3. Difference-in-difference estimates of the effects of legalization on the quality adjusted price of black market cannabis

	(i)		(ii)		(iii)
	OLS	DiD-M	OLS	DiD-M	DiD-M
	(1)	(2)	(3)	(4)	(5)
Treatment					
legal	-0.1526***	-0.0361	-	-	
	(0.0247)	(0.1335)			
retail	-	-	-0.1622***	0.0509	0.0509
			(0.0193)	(0.1238)	(0.1264)
Fixed effects (OLS)					
State	✓	-	✓	-	-
Year	✓	-	✓	-	-
N	7,029	-	453	-	-
n	-	80	-	119	119
Switchers	-	9	-	6	6

Standard errors in parentheses are clustered at the state level.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

This table reports OLS and DiD-M estimates of the coefficients for indicators of the legalization of recreational cannabis (*legal*) and the operation of legal retail sales (*retail*) on the log-difference between the price and the THC potency. Columns (1) and (2) provide the results for specification (i) respectively using OLS and the DiD-M estimator introduced by de Chaisemartin and d'Haultfœuille (2020). Column (3) and (4) describe the OLS and DiD-M results for specification (ii). Column (5) gives the result of the DiD-M estimation of the impact of *retail* without controlling for legalization. Other covariates in the OLS models are state and year fixed effects. DiD-M estimates are robust to dynamic treatment effects. For OLS estimates, N indicates the number of observations. For DiD-M estimates, n gives the number of entities compared in the model while *switchers* is the number of treated entities.

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.

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 E.3).

The results regarding the effect of *legal* on 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, section 3.3 proposes to analyze the effects of legalization across different product categories, constructed based on their THC potency.

3.2. Heterogeneous effects of legalization on black-market prices and quality

Following the results of the previous section on the disparity between the TWFE and DiD-M, I estimate the effects of legalization policies across states using a stacked difference-in-difference model, as in Deshpande and Li (2019) and Cengiz et al. (2019). It relies on a comparison of each treated unit to its own set of controls. Here each unit of control is a never treeated unit and is only included in one set.

I build the sets of control states based on similarities in terms of electricity prices [61] and climate, which I proxy by the latitude, the average yearly rainfall, as well as the average temperature. [62] Most of the non-labor inputs involved in cannabis growing are electricity and water (Caulkins, 2010; Mills, 2012). Uniform and THC-rich production of cannabis requires stable lighting conditions as well as up to 0.21 gallons of water per square foot per day (Zheng et al., 2021). [63] The variations across states in the quantity of electricity – i.e. lighting, and heating / air-conditioning – required for indoor growing is captured by the latitude and the average temperature. Rainfall does measure the accessibility of water. The local black market for cannabis is also likely to be affected by the proximity to Mexico and Canada, the measure of which is encompassed in the latitude. For the states Colorado, Maine, Massachusetts, [64] Oregon and Washington,

61. As of 2020, in cents per kilowatt hours, retrieved online from the U.S. Energy Information Administration, `https://www.eia.gov/electricity/state/`.

62. Average yearly temperature and rainfall over the period 2000-2020, from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental information, Climate at a Glance: National Mapping, published July 2022, retrieved on July 13, 2022 from `https://www.ncei.noaa.gov/cag/`.

63. For indoor production, at the peak of the growing season. This figure drops to 0.2 gallons for outdoor production. As a comparison, wheat requires 0.19 and maize / corn 0.17 gallons of water per square foot per day at the peak growing season.

64. Since Maine and Massachusetts are very similar neighbors and legalized cannabis the same year, I use the same control group for the two of them.

Table 2.4. Composition of control groups for each treated state

Group of states	Treated	Controls
1	Colorado	Montana, North Dakota, South Dakota, Utah, Wyoming
2	Maine	Connecticut, New Hampshire, New Jersey, New York, Rhode Island
3	Massachusetts	Connecticut, New Hampshire, New Jersey, New York, Rhode Island
4	Oregon	Iowa, Kansas, Minnesota, Nebraska, Wisconsin
5	Washington	Illinois, Indiana, Missouri, Ohio, Pennsylvania, West Virginia

I gather a group of five to six states that are the closest in terms of electricity prices and climate.[65] [66] The composition of these control groups is provided in Table 2.4.

To determine the effects of legalization policies across states, I estimate the following equation:

$$y_{isgt} = \theta_{sg} + \psi_{gt} + \beta_{Lg}\mathbf{L}_{sgt} + \epsilon_{isgt} \tag{2.2}$$

where the notation builds on the notation used in the TWFE model in (2.1). y_{isgt} is the outcome of observation i in state s, which belongs to the group of state g, at time t, θ_{sg} and ψ_{gt} are state and time fixed effects, $\mathbf{L}_{sgt}$ indicates the legalization status in state s of group g at time t. The parameters β_{Lg} are to be estimated and differ across groups of states.

The results of estimating model (2.2) are presented in tables 2.5 through 2.7. In each table, the first column refers to the effects of *legal* and the second to *retail*. The results confirm the intuition from the TWFE and DiD-M effects: the effects of legalization on black-market cannabis prices and THC potency vary sensibly across treated states. While policy entails large drops in prices around 30% in the states of Oregon and Washington, it is not necessarilly the case in other jurisdictions. For instance, the black-market price of cannabis remains stable in Maine after *legal* is implemented. This heterogeneity is reflected in the results on the quality adjusted

65. I compute the average distance in percentage of every potential control state to every treated state in terms of precipitation, temperature, latitude and electricity prices. I then average these distances and

(1) select in the set of controls the states whose average distance to a given treated state are below 15%,
(2) should some states be selected in several control groups, I assign them to the group of the treated unit for which they are the closest.

66. Although being treated in the data, I discard the states which I either do not observe sufficiently *post-legalization* or for which I cannot find comparable controls.

TABLE 2.5. Stacked difference-in-difference estimates of the effects of legalization on the price of black market cannabis

	legal (1)	*retail* (2)
Colorado	-0.146***	-0.196***
	(0.0421)	(0.0549)
Maine	0.0382	-
	(0.0423)	
Massachusetts	0.00397	-0.0480***
	(0.0288)	(9.18e-15)
Oregon	-0.354***	-0.291***
	(0.0118)	(0.0150))
Washington	-0.296***	-0.259***
	(0.0436)	(0.0368)
Average effect	-0.151***	-0.183***
	(0.0188)	(0.0177)
Fixed effects		
State × group	✓	✓
Year × group	✓	✓
N	4,718	4,718

Standard errors in parentheses are clustered at the state level.

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

This table reports the OLS estimates for the stacked difference-in-difference model described in equation (2.2). The first column reports the estimates for the local effects of *legal*, while the second column reports the ones relating to the variable *retail*.

Maine is not observed after the *retail* treatment.

price and THC potency. While *legal* entails a significant rise in THC potency by 10% in Massachusetts, there is no effect in Oregon and a negative effect in Maine.

Responses also feature heterogeneity across time. Appendix E.4 explores this feature.

TABLE 2.6. Stacked difference-in-difference estimates of the effects of legalization on the THC potency of black market cannabis

	legal (1)	*retail* (2)
Colorado	0.0298***	0.0296**
	(0.00806)	(0.0108)
Maine	-0.0567***	-
	(0.00961)	
Massachusetts	0.104***	0.0609***
	(5.30e-14)	(7.82e-15)
Oregon	-0.00678	-0.000304
	(0.0120)	(0.0130)
Washington	0.0217**	0.0249***
	(0.00876)	(0.00829)
Average effect	-0.00735	0.0248***
	(0.00484)	(0.00504)
Fixed effects		
State × group	✓	✓
Year × group	✓	✓
N	3,943	3,943

Standard errors in parentheses clustered at the state level.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
This table reports the OLS estimates for the stacked difference-in-difference model described in equation (2.2). The first column reports the estimates for the local effects of *legal*, while the second column reports the ones relating to the variable *retail*.
Maine is not observed after the *retail* treatment.

3.3. Heterogenous quality responses to legalization

Following the contradictory results on the effects of legalization policies on the black market outcomes, I divide observations into three categories, depending on their THC potency.[67] These are reported in Table 2.8 and enable me to investigate whether responses in price differ between products, based on their THC potency.

67. This classification follows the classification of the Ontario Cannabis Store.

Table 2.7. Stacked difference-in-difference estimates of the effects of legalization on the quality adjusted price of black market cannabis

	legal (1)	*retail* (2)
Colorado	-0.243***	-0.297***
	(0.0210)	(0.0307)
Maine	0.122***	-
	(0.0319)	
Massachusetts	-0.0919***	-0.109***
	(7.24e-14)	(9.54e-16)
Oregon	-0.236***	-0.173***
	(0.0318)	(0.0339)
Washington	-0.215***	-0.205***
	(0.0301)	(0.0289)
Average effect	-0.106***	-0.176***
	(0.0158)	(0.0153)
Fixed effects		
State × group	✓	✓
Year × group	✓	✓
N	3,943	3,943

Standard errors in parentheses clustered at the state level.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
This table reports the OLS estimates for the stacked difference-in-difference model described in equation (2.2). The first column reports the estimates for the local effects of *legal*, while the second column reports the ones relating to the variable *retail*.
Maine is not observed after the *retail* treatment.

Table 2.8. 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 the TWFE model described by equation (2.1), which consists in distinguishing the effects of policies on the price of products, depending on their *category*.

$$y_{ist} = \theta_s + \psi_t + \sum_{j=1,2,3} category_{ist,j} + \sum_{j=1,2,3} \beta_{Lj}\mathbf{L}_{st} \times category_{ist,j} + \epsilon_{ist} \tag{2.3}$$

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 2.9. They suggest heterogenous price responses on the black market.

TABLE 2.9. Difference-in-difference estimates on the effects of legalization on price of black market cannabis by category

	legal (1)	*retail* (2)
medium	-0.107***	-0.155***
	(0.0367)	(0.0338)
strong	-0.149***	-0.136***
	(0.0155)	(0.0278)
very strong	-0.0336	-0.0354
	(0.0672)	(0.0481)
Fixed effects		
State × category	✓	✓
Year	✓	✓
Category	✓	✓
N	7,219	7,219

Standard errors in parentheses are clustered at the state level.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
This table reports the OLS estimates for the TWFE model described in equation (2.3).

Cannabis liberalization is associated with a decrease in the price of medium to strong potency cannabis. Strong potency products observe a moderate drop in price after legalization – 14.9% – which accentuates after legal retail sales are implemented – retail sales being responsible for a drop in price by 13.6%. Medium potency products see their price decrease by 15.5% after the implementation of retail sales. Assuming the demand for these medium range products does not decrease, this feature suggests that price differentiation is relatively important in the market for medium range cannabis products.

On the other end, the most potent products see no significant change in their price after legalization. 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, rather than price.

These results are averages over treated states. To refine them, I estimate the following variation from equation (2.2), which consists in distinguishing the effects of policies on the price of products, depending on their *category*. This requires to further refine the different groups of comparison, classifying observations not only by cohort of states but also product category.

$$y_{isgct} = \theta_{gc} + \psi_{gct} + \beta_{Lgc}\mathbf{L}_{sgct} + \epsilon_{isgct} \tag{2.4}$$

To the notations defined earlier, I add the subscript c which is an indicator of the observation belonging to category $c = 1, 2, 3$.

The estimation results are presented in Table 2.10. Except in Massachusetts and Maine, policies entail decreases in the price of medium and strong potency cannabis products. Treatment effects on very strong potency products are more sporadic and do not seem to follow any general rule.

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

The first part of the chapter shows legalization reforms have caused reactions in the black-market prices and THC potency, the former being subject to large drops while the latter rise moderately. In the state of Washington, legalization policies are associated with decreases in prices for illegal cannabis by 25 to 30%. This decrease is driven by the products of medium to strong potency, while the very strong types of cannabis see their price unchanged *ex-post*. Meanwhile, the THC potency rises by more than 2%. This strategic reaction supports the intuition that legalization atomizes the supply for black market cannabis and reduces its production and distribution costs, through changes in risk. Further, the heterogeneity of price responses depending on the product category suggest some selection of the black market products towards higher potency.

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. This part of the analysis is all the more important since the effects observed are heterogeneous across states, time and product categories: strategic responses of the black market are complex.

Table 2.10. Difference-in-difference estimates on the effects of legalization on price of black market cannabis by state and category

		legal (1)	*retail* (2)
Colorado	medium	-0.164*	-0.216***
		(0.0827)	(0.0693)
	strong	-0.221***	-0.272***
		(0.0404)	(0.0613)
	very strong	0.405***	-0.262***
		(2.63e-09)	(1.32e-09)
Maine	medium	0.201***	-
		(0.0420)	
	strong	0.0312	-
		(0.0372)	
	very strong	-	-
Massachusetts	medium	0.0495	-
		(0.0562)	
	strong	0.0204	-
		(0.0269)	
	very strong	-0.336***	-
		(0.0438)	
Oregon	medium	-0.271***	-0.236***
		(0.0576)	(0.0765)
	strong	-0.177***	-0.119***
		(0.0184)	(0.0207)
	very strong	-1.070***	-1.070***
		(0.225)	(0.225)
Washington	medium	-0.202***	-0.269***
		(0.0483)	(0.0447)
	strong	-0.160***	-0.0900***
		(0.0371)	(0.0297)
	very strong	-0.0265	-0.0815
		(0.231)	(0.222)
Average effect	medium	-0.0773**	-0.240***
		(0.0285)	(0.0375)
	strong	-0.101***	-0.160***
		(0.0171)	(0.0237)
	very strong	-0.206***	-0.471***
		(0.0651)	(0.105)
Fixed effects			
State × group × category		✓	✓
Year × group × category		✓	✓
N		4,820	4,820

Standard errors in parentheses are clustered at the state level.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
This table reports the OLS estimates for the stacked difference-in-difference model described in equation (2.2). The first column reports the estimates for the local effects of *legal*, while the second column reports the ones relating to the variable *retail*.
Maine and Massachusetts are not observed after the *retail* treatment. (Maine is simply not observed, while categories could not be determined in Massachusetts for this period of time).

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. This legal alternative for consuming cannabis is valued differently than black-market cannabis, involving both new potential cannabis consumers and former black-market consumers joining the legal market.[68] Yet, legalization does not automatically pair with the disappearance of the illegal market. Some consumers might remain on the black market *post-legalization*, in particular if the legal market is not attractive (see Chapter 1). Preferences for illegal cannabis are therefore a significant piece of information to understand preferences and choices for legal cannabis.

This section relies on a random utility discrete choice model, applied to cannabis consumption choices in the state of Washington and specifically accounting for preferences for quality. I estimate own- and cross- elasticities of consumer participation in the legal and the illegal markets with respect to both price and quality. These document substitution patterns[69] 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

68. Chapter 1 provides a theoretical framework on general equilibrium dynamics and detail consumer selection in partial equilibrium *post-legalization*. In particular, it shows that under partial equilibrium, legalization, by introducing a new option and expanding consumers' choice set, increases the overall demand for cannabis.

69. Future versions of this work will include random coefficients for the sensitivities to price and quality. One limit of the simple logit model presented in this version relates to the *independence of irrelevant alternatives* (IIA) hypothesis, which forces restriction on substitution patterns. A change in one attribute of a given option yields the same change in the probability of all other options. For example, if the price of legal cannabis decreases, it entails the same decrease in the probability of choosing illegal cannabis and not choosing to consume cannabis, while one could expect a proportion of new users lower than the proportion of illegal cannabis consumers turning to the legal market. Hence, the logit model would overestimate the rise in demand following an improvement in one attribute of the legal option. Following an improvement in one attribute of the illegal option, one should similarly expect a higher decrease in the market share of legal cannabis than in the market share of the outside option. The model is therefore likely to underestimate the share of the outside option, as it is the case in Appendix E.6. For the same reasons, one could also expect the share of the legal market to be overestimated by the model. Expanding the choice set, because of the IIA, clearly affects the ability of the logit to properly predict counterfactual market shares. This lack of precision could be reinforced by the fact that β_1 is constant. Yet, since the predicted market shares in appendix are the result of averaging individual market shares over a large population, this explanation seems less likely to be the main driver.

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. Not consuming cannabis is considered the outside option ($j = 0$). Formally, the indirect utility is given as follows.

$$u_{ijt} = \beta_{pj} p_{jmt} + \beta_{qj} q_{jmt} + \beta_{Xj} X_{imt} + \xi_j + \Delta\xi_{jmt} + \epsilon_{ijmt} \tag{2.5}$$

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.

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. Hence, the change in consumer choices is not caused by a change in preferences *per se*. It is rather the result of the birth of a retail market for legal cannabis, individual (ϵ_{ijmt}) and market-good ($\Delta\xi_{jmt}$) specific shocks, as well as changes in market prices and THC potencies.

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 $\Delta\xi_{jmt}$.

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

$$\mathscr{s}_{ijmt} = P\left(y_{imt} = j | p_{mt}, q_{mt}, X_{imt}; \beta, \xi, \Delta\xi_{mt}\right) = \frac{\exp\left(\bar{u}_{ijmt}\right)}{1 + \sum_{k=1,2} \exp\left(\bar{u}_{ikmt}\right)}. \tag{2.6}$$

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

$$\eta^p_{ijkmt} = \frac{\partial \mathscr{s}_{ijmt}}{\partial p_{ikmt}} \frac{p_{ikmt}}{\mathscr{s}_{ijmt}} = \begin{cases} \beta_{pj} p_{jmt}(1 - \mathscr{s}_{ijmt}) & \text{if } j = k \\ -\beta_{pj} p_{kmt} \mathscr{s}_{ikmt} & \text{otherwise.} \end{cases} \tag{2.7}$$

The average price elasticities are therefore given by

$$\eta^p_{jkt} = \begin{cases} \beta_{pj} p_{jmt}(1 - s_{jmt}) & \text{if } j = k \\ -\beta_{pj} p_{kmt} s_{kmt} & \text{otherwise.} \end{cases} \tag{2.8}$$

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

$$\eta^q_{ijkmt} = \frac{\partial \mathscr{s}_{ijmt}}{\partial q_{ikmt}} \frac{q_{ikmt}}{\mathscr{s}_{ijmt}} = \begin{cases} \beta_{qj} q_{jmt}(1 - \mathscr{s}_{ijmt}) & \text{if } j = k \\ -\beta_{qj} q_{kmt} \mathscr{s}_{ikmt} & \text{otherwise.} \end{cases} \tag{2.9}$$

which yields average elasticities given as follows

$$\eta^q_{jkt} = \begin{cases} \beta_{qj} q_{jmt}(1 - s_{jmt}) & \text{if } j = k \\ -\beta_{qj} q_{kmt} s_{kmt} & \text{otherwise.} \end{cases} \tag{2.10}$$

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 (2.6) during the *post-legalization* period does not enable to disentangle $\mathcal{s}_{i1mt}$ from $\mathcal{s}_{i2mt}$. Instead, it only allows to estimate the conditional probability that individual i consumes cannabis $\mathcal{s}_{i1mt} + \mathcal{s}_{i2mt}$. 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

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

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.

$$\begin{aligned} \mathcal{L}\left(\delta, \beta_X\right) = & \sum_{\substack{i \in \mathcal{I}_{pre} \\ t \in \mathcal{T}_{pre}}} \mathbb{1}_{[y_{imt}=1]} \left(\delta_{1mt} + \beta_{X1} X_i\right) - \ln\left(1 + \exp\left(\delta_{1mt} + \beta_{X1} X_i\right)\right) \\ & + \sum_{\substack{i \in \mathcal{I}_{post} \\ t \in \mathcal{T}_{post}}} \Big\{ \mathbb{1}_{[y_{imt}>0]} \times \ln\left(\exp\left(\delta_{1mt} + \beta_{X1} X_i\right) + \exp\left(\delta_{2mt} + \beta_{X2} X_i\right)\right) \\ & - \ln\left(1 + \exp\left(\delta_{1mt} + \beta_{X1} X_i\right) + \exp\left(\delta_{2mt} + \beta_{X2} X_i\right)\right)\Big\} \end{aligned} \tag{2.11}$$

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

I assume that the sensitivity parameters β_j are policy invariant, i.e. 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.[70] 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 regressed on the prices p_{jmt} and THC contents q_{jmt}:

$$\hat{\delta}_{jmt} = \beta_{pj} p_{jmt} + \beta_{qj} q_{jmt} + \xi_j + \Delta\xi_{jmt} \tag{2.12}$$

Potential correlation between prices and unobserved characteristics threaten the consistent estimation of (2.12). 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 E.5.

While strategic responses in prices are immediate, adjustements in quality take time. A natural cannabis crop cycle is a year long. In artificial environments, heavily controlled with refined hydroponic infrastructures and lighting, plants can flower up to 6 times a year. However, changing plants in crops or improving the quality of one's crops otherwise requires relatively more investment and time. For this reason, I consider that quality at time t is predetermined and does not require instruments.[71]

4.1.3. Results. The ML estimates for the parameters β_{Xj}, $j = 1, 2$ from equation (2.11) are provided in Table 2.6. 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 –

70. 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 $\eta^{pre}_{i1t} = \beta_{p1} p_{1mt} \frac{1}{1 + \exp(\bar{u}_{i1mt})}$ After legalization, it becomes $\eta^{post}_{i1mt} = \beta_{p1} p_{1mt} \frac{1 + \exp(\bar{u}_{i2mt})}{1 + \exp(\bar{u}_{i1mt}) + \exp(\bar{u}_{i2mt})}$ The same applies for quality elasticities.

71. In practice, legal local retailers could adjust the quality of their products by sourcing them from different suppliers. In this case, the assumption of exogeneous quality would be violated. However, the State of Washington does not allow any importation of recreational cannabis, whether at the retail level or upstream. Hence such adjustments in quality are limited to the extent of the existence and availability of higher quality products, whose production should be authorized by the WSLCB. Further, in this version the legal and the illegal sectors are for now each modeled as one representative agent, with average THC potency reflecting the whole panel of products at the grower level. Regarding illegal sellers, these are more likely to be subject to sticky contracts, since most transactions on the black market happen between individuals who are already acquainted (Caulkins and Pacula, 2006).

TABLE 2.11. 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
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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 Appendix E.6).

Table 2.12 presents the average price elasticities computed using equation (2.8) and the second-step estimation results (equation 2.12). 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

Table 2.12. 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

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

lies around -0.5. These values are consistent with the results of Jacobi and Sovinsky (2016) on the elasticity of participation to the black market for cannabis, as well as with Hollenbeck and Uetake (2021) estimating higher sensitivity of individuals to the price of legal cannabis than what the literature had measured on the illegal market (see for example Davis et al., 2016). 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 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.

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 sticky adjustment of THC potency.

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

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

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, $\frac{\partial \Pi_{jmt}}{\partial p_{jmt}} = 0$.

$$s_{jmt}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) + \left[p_{jmt} - c_{jmt}(q_{jmt})\right] \frac{\partial s_{jmt}}{\partial p_{jmt}} \left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) = 0 \tag{2.13}$$

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

$$-c_j'(q_{jmt}) s_{jmt}\left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) + \left[p_{jmt} - c_{jmt}(q_{jmt})\right] \frac{\partial s_{jmt}}{\partial q_{jmt}} \left(\boldsymbol{q}_{mt}, \boldsymbol{p}_{mt}\right) = 0 \tag{2.14}$$

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 [72]

$$\ln c_j\left(q_{jmt}; \theta_{jm}\right) = \gamma_{0j} + \gamma_{1j} q_{jmt} + \omega_{jmt} \tag{2.15}$$

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 (2.14) which becomes

$$\ln p_{jmt} = \ln\left(\frac{1}{\beta_{qj}(1 - s_{jmt})} + 1\right) + \gamma_{0j} + \gamma_{1j} q_{jmt} + \omega_{jmt} \tag{2.16}$$

The estimation results are presented in Table 2.13. Their interpretation in terms of marginal cost for medium, strong and very strong products is provided in Table 2.14.

On the black market, estimates for γ_1 confirm that the marginal cost on the illegal market is convex in quality. Prices for medium to very strong cannabis vary from 7.92 USD/g to 8.45 USD/g on the black market under prohibition. Under legalization, the estimate for the baseline parameter γ_0 decreases, but the quality coefficient γ_1 increases. The former confirms the intuition of a drop in operation costs *ex-post*, which could in theory be due to lower risk for illegal suppliers to be detected and hence arrested. The latter is more difficult to interpret. One explanation could be that more potent products *post-legalization* are further differentiated, which inflates their cost. This possibility is consistent with the results of section 3.3, which suggest that black-marker suppliers differentiate very strong products by improving their quality. [73]

72. 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.

73. While for the sake of simplicity this version proxies quality solely using the THC potency, other aspects might come at play and be paired with increases in THC potency.

On the legal market, the estimated function predicts the marginal cost for medium range cannabis above 19 USD/g. The marginal cost of very strong cannabis would be at 16.7 USD/g. The high difference between these estimates and the ones relating to black-market cannabis reflects the cost burden of the quality and traceability controls implemented by the Washington State Liquor and Cannabis Board. Besides, the value for γ_1 on the legal market being negative is counter-intuitive and requires more investigation. One cause could be the legal market in the State of Washington being subject to heavy traceability regulations. Producing high potency cannabis requires environments where growing conditions are stable and as a result compliance to regulations is easier, hence less costly.

TABLE 2.13. Marginal cost functions

	BLACK MARKET	LEGAL MARKET
Prohibition		
γ_0	1.95***	-
	(0.0211)	-
γ_1	0.00820***	-
	(0.000958)	-
Legalization		
γ_0	0.939***	3.29***
	(0.0780)	(0.0614)
γ_1	0.0595***	-0.0211***
	(0.00454)	(0.00223)
Geographical f.e.	✓	✓
Year f.e.	✓	✓

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

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 (see the First Article). In this case, the rise in

TABLE 2.14. Marginal costs for medium, strong and very strong cannabis

	BLACK MARKET	LEGAL MARKET
Prohibition		
medium (14.5% THC)	7.92	-
strong (18.5% THC)	8.18	-
very strong (22.5% THC)	8.45	-
Legalization		
medium (14.5% THC)	6.06	19.77
strong (18.5% THC)	7.69	18.17
very strong (22.5% THC)	9.75	16.70

Prices in USD/g come from the estimation results presented in Table 2.13.

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 compute 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. 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.

I model reaction prices from the black market and show that improvements in quality are essential for a government aiming at eradicating the black market. I consider the price response of the black market to several legalization scenarios, implying variations in both price and quality of the legal product. Since quality adjustments are sticky, on the short run the black market only reacts in price.[74] Differentiating equation (2.13) yields

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

where

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

The best-responses adjustments of sector j to price and quality changes in sector k are hence respectively given by $-\frac{\alpha_{pk}}{\alpha_{pj}}$ and $-\frac{\alpha_{qk}}{\alpha_{pj}}$. Best-responses can then be interpolated linearly from the observed *post-legalization* equilibrium using the estimates for the sensitivity parameters[75] and the marginal cost function. This equilibrium is such that the price and potency on the black market are 8.41 USD/g and 17.68% on average. The price and potency on the legal market are 15.47 USD/g et 20.28%. These baseline price and potency equilibria on the legal and the black markets correspond to the average price and potency observed in the data, *post-legalization*. The corresponding marginal cost on the black market is 7.32 USD/g. It is computed from the estimated marginal cost function.

74. Further versions of this work will include responses in terms of quality, to investigate long run strategic responses of the black market, which should account for consumers' preferences and substitution patterns with respect to quality.

75. Recall that under logit assumptions, the first derivatives of market shares are simply given as $\frac{\partial s_{jmt}}{\partial q_{jmt}} = \beta_{qj}s_{jmt}(1 - s_{jmt})$, $\frac{\partial s_{jmt}}{\partial q_{kmt}} = \beta_{qj}s_{jmt}s_{kmt}$, $\frac{\partial s_{jmt}}{\partial p_{jmt}} = \beta_{pj}s_{jmt}(1 - s_{jmt})$, $\frac{\partial s_{jmt}}{\partial p_{kmt}} = \beta_{pj}s_{jmt}s_{kmt}$.

Reaction prices of the black market, from the observed *post-legalization* scenario are represented in Figure 2.3 by different colors as functions of the price (on the vertical axis) and THC potency (on the horizontal axis) of cannabis set on the legal retail market. The dashed line represents the isoquant of level 7.32, i.e. combinations of price and THC potency of legal cannabis such that the best-response price of the black-market is at marginal cost. Points in green, South-East of the isoquant, are eviction scenarios: the black market does not survive. The darker the color, the lower the price. In the opposite direction, points in red represent reaction prices above the marginal cost.

To eradicate the black market, the legal sector needs to invest in quality improvements. Even with a price at 5 USD/g, which is well below its current marginal cost, the legal sector cannot eradicate the illegal sector, unless it raises THC potency to 22%. Further, setting a high quality on the legal market – for instance a 24% THC potency – enables to get rid of the black market while setting high prices, and thereby curbing use.

5. Conclusion

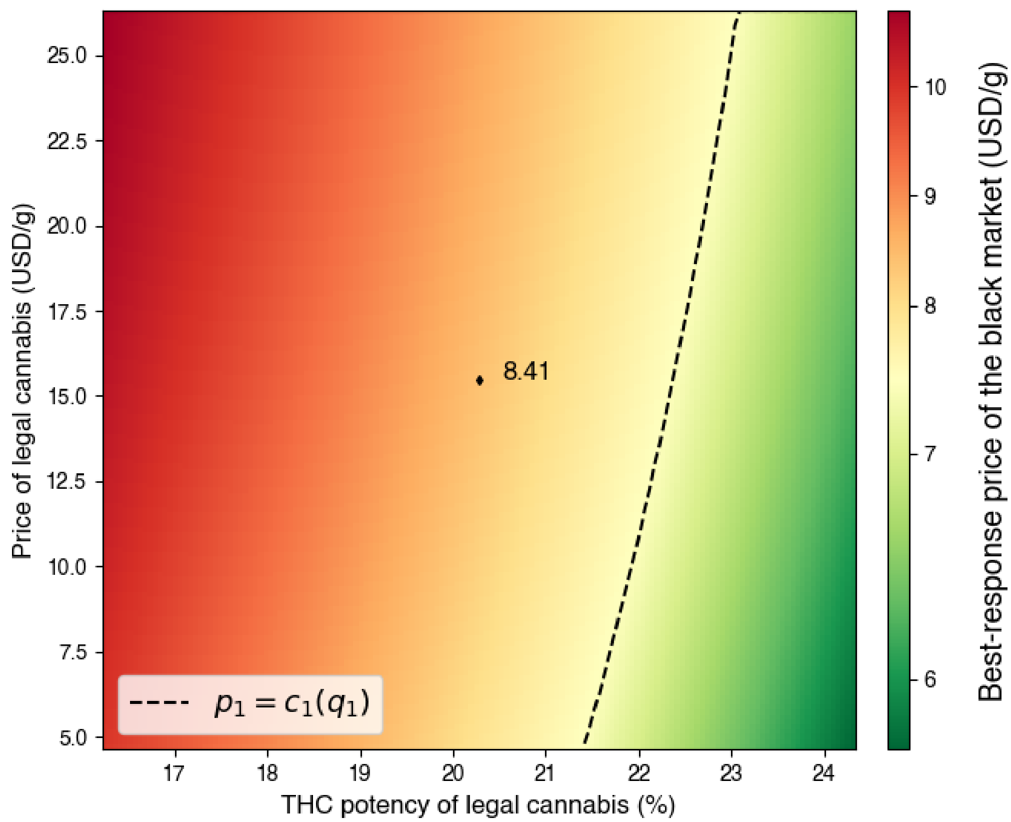
The literature on cannabis has covered illegal consumption behavior under prohibition. Recent papers have documented the legal sector, covering strategic interactions of legal firms with respect to policy and demand sensitivity to prices. Yet, to my knowledge, no previous work has covered market interactions 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 20% while THC potency increases by up to 1.4% on average. This effect in price is heterogenous across different levels of THC potency. These results suggest legalization enhances competition on the global market for cannabis; and that retailers' strategy does not only depend on prices, quality matters.

Understanding the role of quality and how it interacts with price responses 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

FIGURE 2.3. Short-run best-response of the black market with respect to changes in the price and the THC potency of legal retail cannabis



Notes: At equilibrium *post-legalization*, the price and potency on the black market are 8.41 USD/g and 17.68% on average. The corresponding marginal cost is 7.32 USD/g. The price and potency on the legal market are 15.47 USD/g and 20.28%. From this equilibrium, I compute the reaction of the black market to changes in price and THC potency on the legal market. On the short run, the black market responds to the legal market by adjusting its price solely. These reaction prices are obtained iteratively using linear interpolation and differentiating equation (2.13).

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 is 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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Third Article.

Temporary Foreign Work Permits: honing the tools to defeat human smuggling

by

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Abstract. We study how temporary visa schemes can be designed to drive smugglers out of business while meeting labor market demand in host countries. The policy trade-off between migration control and ending human smuggling can be overcome by combining internal and external controls with a regulated market for temporary visas. In this market, visa duration and price are set at "eviction" levels that throttle smuggling activity. We use information on irregular migration from Senegal to Spain and the Democratic Republic of Congo to South Africa to calibrate the eviction prices of visas for these two routes. Our results highlight important constraints for governments seeking to prevent temporary workers from overstaying, especially on South-North routes such as Senegal to Spain. They suggest combining a regulated market for visas with tighter sanctions against employers of undocumented workers as a way forward.

Keywords: immigration, human smuggling, market structure, legalization

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Individual contributions. Emmanuelle Auriol and Alice Mesnard are responsible for the idea of this article as well as its whole structure. It is based on their previous work on long term visas Auriol and Mesnard (2016).[a] Tiffanie Perrault enhanced the theoretical work already in place by generalizing the results to a framework where individuals feature returns to skills and behave according to Prospect Theory; and proved these results. She is responsible for the computations and the graphical representations in the numerical section, which she designed mostly with Alice Mesnard. Most of the writing in the remainder of the paper is Emmanuelle Auriol's and Alice Mesnard's.

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1. Introduction

Concerns about immigration have reinforced populism in most OECD countries and are threatening some core institutions of the European Union such as the Schengen Area.[76] However, when regular and irregular migrants are considered separately, public opinion is much more concerned about irregular migration than about regular migration.[77] Reducing irregular migration is clearly a priority for electorates and the governments.[78] We propose a framework to address jointly two important concerns for the public, which are often considered as policy trade-offs. The first is how to

76. Even outside this area, the perceived lack of immigration control by the public has been one of the main drivers for Brexit, with a majority of citizens in the UK endorsing reducing immigration at the time of Brexit (Blinder and Richards, 2017).

77. For example, in 2013, 80 (70) percent of respondents in the UK (France) are concerned about illegal immigration, compared to 40 (32) percent about legal migration (Transatlantic Trends surveys, cited in Hatton, 2017)

78. The Eurobarometer (May 2015) indicates that, on average, 87% of respondents in Europe support additional measures against illegal immigration, with a minimum support of 72% in Romania and maximum support of 94% in Cyprus (Hatton, 2017).

control migration flows: by this we mean how to control the number of migrants crossing borders to reach a higher wage destination country, as well as their legal status. The second is how to tackle human smuggling. We present a novel system of temporary visas for economic migrants, which competes with the services offered by human smugglers to attract low-skilled migrants.

One way to undermine human smuggling would be to simply open the borders. Although scholars predict large overall economic gains (see for example Clemens, 2011), it is not favored by the majority of citizens, especially in high wage countries. Fears of massive inflows of migrants make such a solution politically unacceptable, at least in the current context. In response to these fears, most OECD countries have been strengthening border controls over the last decades, but current policies, which combine quotas on visas with reinforced border controls, are fairly ineffective at stopping undocumented migration. Their main consequence is to increase demand for smugglers. Strong restrictions on labor mobility mean that migrants seek assistance from smugglers who organize air, sea or ground transportation. They may offer a large range of other services, lending money and helping migrants to find accommodation and jobs at their destination. Such illegal activities cost the lives of thousands of individuals each year and lead to exploitation and abuses of all kinds (for example, forced labor, child trafficking, and sexual coercion). Moreover, with more than 2.5 million people smuggled around the world each year, the human smuggling market brings billions in revenue to powerful criminal networks, which are increasingly organized and, in some countries like Mexico, pose a real threat to the rule of law.[79]

For all of these reasons, ending human smuggling has become an urgent issue. The integration of migrants and migration policies has even found its way in the Agenda for Sustainable Development, with specific reference to ending human trafficking and respecting the labor rights of migrant workers (see UNCTAD, 2018, p. 20).[80] There is also a widespread recognition that controlling migration flows through effective public policies calls for a better understanding of both the supply side and the demand side of the market (OECD, 2015).

79. A low estimate of economic returns worldwide is around USD5.5-7 billion in 2016 (UNODC, 2018).

80. Specifically, target 10.7 of the 2030 Sustainable Development Goals calls on countries to facilitate orderly, safe, regular and responsible migration and mobility of people, including through the implementation of planned and well managed migration policies. Other migration-related targets in the 2030 Agenda include retaining health workers in developing countries; providing scholarships for study abroad; ending human trafficking; respecting the labor rights of migrant workers, in particular women migrants; reducing the costs of transferring remittances and providing legal identity for all.

While information on the operations of smugglers is hard to collect systematically, recent evidence shows that smugglers are prompt to adapt to geo-politic and policy changes. For example, the opening of the central Mediterranean route, following the 2011 fall of the Gaddafi Regime, substantially increased irregular crossings from Lybia to Europe (Friebel et al., 2018). Moreover, investments in border controls between Mexico and the US following the Immigration Reform Control Agreement (1986) pushed smugglers on the Mexico to US route to reorganize their operations. Smugglers increased their cartelisation and the prices they charge to migrants from Mexico (Roberts et al., 2010). On the demand side, enhanced border controls have exacerbated the risks taken by migrants and pushed migrants to more remote routes but they had small deterrence effects on irregular migration to the US (Gathmann, 2008). This is largely driven by the sizable economic opportunities for undocumented workers in high wage countries (Clemens et al., 2019).

Is there a more proactive way to recruit foreign workers than using the labor force of irregular migrants who have either successfully crossed borders undetected, or overstayed their work permits? And can this throttle the market for human smuggling? We discuss whether current and past systems of Temporary Foreign Work Permits (TFWPs), which were not designed with this objective, would reduce human smuggling activity.

Our framework takes into account the response of smugglers, who react to migration policies by adjusting their fees to maximize profits. Simultaneously we model the response by workers of different skill levels who are willing to migrate from low-wage to high-wage countries. In the status quo there is no legal channel to migrate such that they turn to the smugglers' services. This leads to an equilibrium in which smugglers share the illegal market profits. We study what happens to the equilibrium after temporary work permits offering legal channels to migrate are introduced. Workers can choose between legal and illegal channels, which pushes down smugglers' fees. We are particularly interested in policies to drive smugglers out of business. This can be achieved by setting the price of visas low enough, at the "eviction" level, such that smugglers can no longer make positive profits after they compete with low-costs services. An important finding is that a policy mix combining enforcement of internal and external controls with the TFWPs allows adjustment in this eviction price to reach predetermined migration targets. This demonstrates how the joint modeling of the supply and demand sides of the migration market would enable a government to regulate economic migration flows.

Legal channels have the advantage of offering safe journeys to would-be migrants, who may otherwise fail to reach their destination or be deported when they arrive.

Even visas that cost more than smugglers' fees may compete with the services of smugglers. Risk is a key element in the decision to migrate, particularly when there are few legal options, and a growing empirical literature is investigating risk attitudes of migrants (see for example Arcand and Mbaye, 2013; Bah and Batista, 2018). As the considerable risks taken by irregular migrants are sometimes difficult to explain using standard expected utility theory, our framework allows for distortions in how migrants perceive risk and make their decisions in stark contrast to previous literature on visa design.[81]

Another key element in the design of workable temporary work permits is to take into account migrants' incentives to comply with the visa rules, to prevent overstays. This can be achieved by enforcing deportation and embedding economic incentives in the scheme. Our analysis highlights the challenges of enforcing timely return of guest-workers on South-North routes, where economic disparities are typically large, enforcement of deportation is lax and protection of migrants' rights is strong. We show why it is more feasible to regulate migration flows on South-South routes with the help of TFWPs.

By modeling how smugglers interact with migrants and respond to policies, we show that there is not necessarily a trade-off between undermining human smuggling and controlling migration flows. However, this requires enforcing sanctions against illegal activities (especially employment of undocumented workers), which should be carefully combined with the implementation of the legal market for temporary visas. To ensure timely return migration of temporary guest workers, governments in advanced economies may adopt different combinations of enforcement measures, such as harsh punishment against employers of undocumented workers, awarding points towards more settled status in the future, or preservation of future eligibility for visas, as practiced in Canada.

The schemes we propose will support the recruitment of low-skilled workers in short supply in some sectors of the economy, as highlighted during the COVID-19 crisis in the UK and in France.[82] Our schemes can also be fine-tuned to attract missing key workers in a country and meet broader labor market needs. These are hard to meet with current policies that are tilted towards the recruitment of high-skilled economic migrants (Fasani and Mazza, 2020).

81. Our results are qualitatively robust to using expected utility and prospect theory frameworks but their magnitude varies.

82. For example, more than 900 workers from Morocco have been flown to Corsica in October 2020 to rescue Clementine crops. See `https://www.lci.fr/population/travailleurs-saisonniers-en-corse-un-pont-aerien-avec-le-maroc-pour-sauver-la-saison-2166720.html`

The rest of the paper is organized as follows. In section 2 we review different proposals to expand legal channels to migrate and their limits. In section 3 we describe the illegal migration market under the *status quo*, where smugglers compete to maximize their profits and migrants respond by weighing economic opportunities of illegal migration against price and risk factors. In section 4 we describe how the migration market responds to the implementation of temporary visa schemes. In section 5 we study price setting strategies to throttle smugglers' businesses and show how external and internal controls can be optimally combined with temporary visa schemes to reach predetermined economic objectives. In section 6 we present numerical applications on two smuggling routes to discuss the policy implications of the model, before concluding in section 7.

2. Legal channels for economic migrants: a critical review

Globally, 86% of countries in the world have an official migration policy, which in most cases is set to meet labor market needs. [83] In contrast, concerning emigration, the majority of governments have either no explicit policy (36%) or seek to lower current levels (32%). This means that matching demand and supply for immigrants is largely left to individuals' initiative and the unregulated market.

In many high wage countries, immigration policies have increasingly targeted high-skilled migrants with very limited possibilities for low-skilled workers. [84] One unintended consequence of such policies is to feed the illegal markets for non eligible workers. In contrast, large systems of temporary foreign worker permits (TFWPs) have been put in place in the past, then largely dismantled in the US and the EU, following economic downturns and severe criticism. This section is an overview of the policies of the last eighty years, designed to address labor market needs for low-skilled workers in high wage countries. We highlight some of their pitfalls before turning to recent proposals.

83. 61% seek to maintain current levels of legal immigration, while 12% have policies to increase it. Only 13% have policies to lower it, the rest have no official policy or do not seek to influence it (UNDESA, 2017). Among all regions, Europe has the highest proportion of countries seeking to raise immigration levels (32%), followed by Asia (10%). Among countries that aim to decrease immigration, Asia has the highest share of countries seeking to reduce current levels of immigration (23%), followed by Africa (13%).

84. For example, presenting to the UK parliament its new points-based system, the Home Office (2020) states: "We will reduce overall levels of migration and give top priority to those with the highest skills and the greatest talents: scientists, engineers, academics and other highly-skilled workers. [...] We will not introduce a general low-skilled or temporary work route."

2.1. Temporary Foreign Worker Permits

Past experiences show that designing effective policies to meet labor market needs and control immigration is not trivial. After the two world wars (WW), most European countries used TFWPs to meet labor shortages and to reconstruct their economies. For instance in France firms and their representatives set up the General Society of Immigration (SGI) in 1924 to bring in thousands of immigrants in sectors experiencing labor shortage after WWI. In 1945, the French government decided to set up the national office of immigration (ONI) to manage and stimulate immigration to help with the reconstruction of the country after WWII. During WWII the “bracero” program in the US was set up to recruit Mexican workers in the agricultural sector on a temporary basis.

Although most of these systems were dismantled in the 70s, following rising unemployment problems, they have since been replaced by more sector-specific recruitment policies for temporary workers.[85] Some countries rely on issuing large numbers of seasonal and TFWPs. In Canada for example, TFWPs of less than three years duration have in some periods outnumbered other types of work visas, with 338,000 TFWPs granted in 2013 up from 101,000 in 2001 (Gross, 2014). In recent decades in the UK, large numbers of workers have been recruited through temporary visa schemes, such as the now discontinued Seasonal Workers Agricultural Schemes (SAWS) and the Sectors Based Scheme (SBS). The threat posed by post-Brexit restrictions on labor inflows from European countries has revived discussions about how to multiply temporary work permits to recruit foreign workers.[86] However, the recent points-based system proposed by the government does not open a route for low-skilled migrants, apart from a quota of 10,000 seasonal workers in agriculture (Home Office, 2020).

In other countries, the unsatisfied demand for low-wage workers in specific sectors of the economy has led to patchy responses. For example, every year since 2006, France has issued Exceptional Authorizations of Stay (AES) so that workers in the underground economy could legalize their situation. In practice the AES are granted to workers in sectors “sous tension”, where there is a mismatch between the demand for labor and the number of legal workers willing to take "hard" jobs in catering, construction or social care. These AES workers are overwhelmingly men in their thirties

85. See a comparison across European countries in López Sala et al. (2016).

86. In 2018, this led to the Immigration White Paper proposals to create a seasonal workers pilot in agriculture, accompanied by a 12-month temporary migration program to bring workers at any skill level, and a Youth Mobility Scheme (YMS) to admit young people from certain non-EEA countries to work for up to 2 years (UK Government, 2018).

in low wage jobs, coming from African countries such as Mali, Morocco and Tunisia, and having overstayed in France for, on average, 8 to 10 years (OECD, 2017).

Further, there has been an unprecedented expansion of TFWPs in other parts of the world, in the states of the Arabian Peninsula following the increase in the price of oil in 1973 and, more recently, with the rapid economic growth in East Asian countries and the increasing political and economic interconnectedness between states in the ASEAN region (Kaur, 2010).

These systems of TFWPs are subject to two types of criticisms. Firstly, because the 'temporary' aspect of work permits is not enforced, irregular migration by overstaying "guest workers" is higher.[87] Overstaying has been exacerbated by increased migration restrictions, which have the unintended effect of discouraging circular migration and of lengthening the time spent abroad, as documented in Mexico-to-US migration (Angelucci, 2012).

The second criticism relates to the frequent violations of labor and human rights by employers of temporary foreign workers, as identified by non governmental organizations,[88] international organizations (technical report of Palumbo and Sciurba, 2018), as well as scholars in political sciences, sociology and law (Clark, 2017; Cohen, 206; Vanyoro, 2019) and the press.[89]

Forms of bonded labor are more likely to occur when foreign workers rely on their employers for a large range of services such as transport, health care, subsistence and accommodation, and when they do not have enough legal protection or time to be informed of their rights before being repatriated in case of disagreement. There is hence a tension between the arguments of efficiency put forward by economists in favor of foreign temporary work permits, and the rights-based criticisms of the current systems, which are often abused (Sumption and Fernandez Reino, 2018).

2.2. Missing migration markets

Given the very large potential economic gains for migrants to reach high wage countries (Clemens et al., 2019), there has been an increasing recognition that restrictions on international migration generate strong incentives for undocumented migration. There have been several proposals to create a legal market for economic migrants, rather than leaving the market to exploitative smugglers.

87. Noticeable exceptions are the East Asian countries we discuss below, which adopted very strong enforcement policies against undocumented migrants.

88. See for example FLEX (2019); Human Rights Watch (2011).

89. Annie Kelly, 2019. "Rape and abuse: the price of a job in Spain's strawberry industry?" *The Guardian*. April 14. `https://www.theguardian.com/global-development/2019/apr/14/rape-abuse-claims-spains-strawberry-industry`

A much-discussed proposal is to sell visas to regulate migration flows. Following the prominent proposal by Becker to auction visas,[90] different implementations have been debated in the press and blogs (Simon et al., 1999; Freeman, 2006; Saint-Paul and Cahuc, 2009; Orrenius and Zavodny, 2010). The main argument in favor of this idea is that selling visas allows a government to raise revenues that would otherwise be captured by irregular migrants, their employers and smugglers. These revenues can be used to compensate native workers who would lose from the competition with migrants (Weinstein, 2002). Moreover, migrants or their employers with the highest economic gains are likely to win the bids. Lokshin and Ravallion (2019) push this idea one step further by exploring how to complete incomplete immigration markets through the implementation of a decentralized market for work permits. Their original idea is that citizens in high wage countries can rent out their right to work to foreign workers, and spend their time on other activities (e.g., child care, studying, investment in new human capital or in hobbies). This proposal should limit the opposition to immigration from native low-wage workers, who are the most likely to rent their right to work. Other market-based mechanisms have been proposed by Fernández-Huertas Moraga and Rapoport (2014); Fernández-Huertas Moraga and Rapoport (2015) to allocate refugees across destination countries through an efficient tradable system of quotas.

As they are based on the creation of formal migration markets, these proposals require a tight monitoring of informal labor markets, including for natives. They could be difficult to implement in some countries—such as the United States, France, Spain and Italy—where there are large informal labor markets, leaving space for unregulated providers to continue making large profits. There would still be opportunities to undercut the market by attracting poorer migrants via lower-cost services.

It is thus important for the policy design to take the supply-side response into account. Auriol and Mesnard (2016) propose to sell permanent visas at the "eviction" price, such that smugglers can no longer respond to the policy without losing money. However, they show that, in a risk neutral environment, such a price setting mechanism does not limit the increase in migration flows, unless the scheme is accompanied by robust efforts to enforce the sanctions against the smugglers, migrants and their employers, which may be costly to implement. Moreover, regulating migration flows through this policy mix implies selling visas at a relatively high price, which attracts high-skilled economic migrants and leaves unmet the demand for low-skilled workers.

90. Gary S. Becker, 1992. "An Open Door for Immigrants – the Auction". *Wall Street Journal*, October 14. Becker, Gary S., and Edward P. Lazear. 2013. "A Market Solution to Immigration Reform." Wall Street Journal, March 1. and Becker, Gary S. 2010. "The price of entry". *The Economist*, June 24. `https://www.economist.com/finance-and-economics/2010/06/24/the-price-of-entry`

In contrast to previous proposals we depart from the existing legal frameworks of TFWPs and adapt them to defeat human smuggling while controlling the flow of migrants, including those who overstay their visas. We show that these two concerns are intertwined: both require strong measures to fight against smugglers and employment of undocumented workers, which are complementary to the visas scheme we propose. In practice it will also be more feasible for a government to enforce external and internal border controls and to sanction employers of undocumented workers if there are sufficient legal channels to employ foreign workers in the host economy. The way forward we suggest to discourage overstays involves targeting the illegal employment of undocumented workers, and not necessarily the whole informal labor market, which also differs from previous proposals.

3. Smuggling market

When legal migration is restricted under the *status quo*, we assume that workers from poor countries need to hire smugglers to migrate, at price p^I.[91] In line with the literature on criminality applied to the smuggling market (Aronowitz, 2001; Futo and Jandl, 2007; Guerette and Clarke, 2005; Lundgren, 2008; Auriol and Mesnard, 2016), services are provided by N smugglers, who compete *à la Cournot.*[92] This determines the generalized Cournot price, p^I, as solution to the following equation:

$$\frac{p^I - c}{p^I} = \frac{1}{N}\frac{1}{\varepsilon_{D^I,p^I}} \tag{3.1}$$

where c represents their marginal operating costs, ε_{D^I,p^I} is the price elasticity of the demand for smugglers' services and N is an integer greater than 1. The generalized Cournot competition demand, $D^I(p^I)$, is between the two extreme cases: $D^I(p^m) \leq D^I(p^I) \leq D^I(c)$ where p^m is the monopoly price ($N = 1$) and the price under perfect competition is equal to the marginal costs c ($N \to \infty$). Other than this price, the important factors to determine the demand for smugglers' services are the economic

91. Although figures vary a lot across destination countries, reliance on smugglers to enter high wages countries is stronger when it is difficult to migrate through legal channels, when border controls are enforced and when geographical borders do not exist between origin and destination countries. In the UK for example, smugglers are involved in around 75% of detected cases of irregular border crossing (Home Office, 2001).

92. This model is more flexible than Bertrand competition, which, with a fixed entry cost K, always leads to a monopoly. Cournot can yield both a monopolistic equilibrium and a more competitive equilibrium depending on the number of smugglers N, which is easily endogenized in an equilibrium with free entry and a fixed cost K. Other models of imperfect competition, such as horizontal differentiation, lead to the same type of results, as the smugglers end up reaching marginal cost pricing in all cases.

gains from migration and the risk of crossing borders irregularly, which are studied below.

3.1. Economic gains from irregular migration

Potential candidates for irregular migration are heterogeneous according to their labor efficiency (or skill), θ, which is drawn from the distribution $F(\theta)$ with support $\mathbb{R}_+$. It is assumed that the distribution $F(\theta)$ is twice differentiable with a density function $f(\theta) > 0$.

Returns to skills in the home country are given by $\Delta_h(\theta)$, where $\Delta_h : \mathbb{R}_+ \rightarrow [1, +\infty)$ is continuous, increasing and concave. Earnings of individual of type θ are then given by $\Delta_h(\theta)w_h$ where w_h is the expected wage of an unskilled individual in her home country.[93]

When a worker succeeds in crossing a border irregularly, she takes on jobs in the undocumented labour market where she does not benefit from returns to her skills, and receives a discounted wages of the minimum wages in the foreign country, dw_f with $d < 1$[94], which is higher than what she would earn at home w_h.

Assuming no return to skill in the undocumented sector of the destination country, we characterize the demand for workers in labor intensive sectors of the economy such as construction, domestic care, sweatshops, hospitality, or agriculture, where the skills of undocumented workers are not recognized. They are paid at a flat rate, which is lower than minimum wages. As will become clear below, this results in a negative selection of irregular migrants and is in line with recent evidence on irregular flows of workers from non conflict areas in Africa and Middle East to Europe (Aksoy and Poutvaara, 2019).[95]

93. This is consistent with the large body of empirical research on returns to skills (see Lemieux, 2006), where earnings take the form of a Mincer (1970) equation. One would simply postulate $\Delta_h(\theta) = e^{D_h \theta}$, $D_h > 0$.

94. See Kossoudji and Cobb-Clark, 2002 for the US and Monràs et al., 2020 for Spain

95. The model can be extended to the case of a more positive selection of undocumented migrants, which has been observed in other settings with severe liquidity constraints or large positive returns to skills if there is a possibility of obtaining legal status in the host country (Grogger and Hanson, 2011; Orrenius and Zavodny, 2005). To be attractive to higher skilled individuals, the type of visa must give access to jobs with positive returns to skills in the destination country, for example working as middle men on building sites or as health workers, but the pricing mechanism of visas is similar to what we develop below.

3.2. Migration decision under high risk of failure

The way we model migration decisions from risk averse individuals is fairly general and encompasses both advances in cumulative prospect theory (CPT) following Tversky and Kahneman (1992) and the more standard expected utility theory (EUT).[96] CPT postulates that individuals compare lottery outcomes rather than final wealth and allows for them to be risk-seeking for losses and risk-averse for gains through more flexibility in S-shaped value functions. It also leaves flexible the use of non linear weighting functions of risk, which may result in individuals over-estimating the odds of rare salient events – e.g. a successful irregular migration – and under-estimating those of more common events – e.g. a failed migration. This accounts for behavioral traits that are hard to explain using EUT, such as the fact that undocumented migrants take on a high risk of their migration failing, with large sunk costs. This motivated our choice of the CPT framework to present our results, but all results are robust to using either framework, as shown in the appendices.

If irregular migrants are intercepted by border guards, with probability q, we assume that they are sent back to their home country and lose the money paid to smugglers.[97] Earnings in the foreign country are used to pay the smuggler's fee p^I and for consumption $dw_f - p^I$. A worker deciding whether to risk irregular migration faces the following lottery $\mathcal{L}_{illegal} = \left[dw_f - p^I, \Delta_h(\theta)w_h - p^I; 1-q, q\right]$ and compares it with the certain payoff she receives when she does not migrate, $\Delta_h(\theta)w_h$. The migration condition is written as: $\omega^+(1-q)u\left(dw_f - p^I - \Delta_h(\theta)w_h\right) + \omega^-(q)u\left(-p^I\right) > 0$,[98] with the probability weighting functions $\omega^+(.)$ accounting for individuals' distorted perceptions of probabilities.[99]

Studying the threshold such that an individual is just indifferent between an undocumented migration or not migrating, the marginal type θ^I is the solution of the following equation:

$$\omega^+(1-q)u\left(dw_f - p^I - \Delta_h(\theta)w_h\right) + \omega^-(q)u\left(-p^I\right) = 0 \tag{3.2}$$

Since u and Δ_h are monotonous functions, as long as at least one individual (i.e. the type 0) decides to migrate – which is mathematically written as

96. More detail on CPT and on the functions specified and calibrated by Tversky and Kahneman (1992) can be found in appendices B and G.1.

97. In practice, given the large amounts at stake, the final payment may be partially locked in a bank account or under the control of the migrant's network until there is proof of success (UNODC, 2018), but many migrants lose their down-payments.

98. Under EUT it becomes: $(1-q)u\left(dw_f - p^I\right) + qu\left(\Delta_h(\theta)w_h - p^I\right) > u\left(\Delta_h(\theta)w_h\right)$.

99. These functions are simply increasing mappings $w : [0,1] \mapsto [0,1]$, such that $w(0) = 0$, $w(1) = 1$, and for x in the neighborhood of 0 $w(x) \geq x$ (respectively $w(x) \leq x$ for x close to 1). More detail in appendix B.

$\omega^{+}(1-q)u\left(dw_f - w_h - p^I\right) + \omega^{-}(q)u\left(-p^I\right) > 0$ – there exists a unique $\theta^I > 0$.[100] This condition shows that if the risk of failure, q, or the price of irregular migration, p^I, is too high relative to the economic gains, then no worker is willing to migrate irregularly.[101]

Aggregating over the distribution of skills, we obtain the demand for irregular migration as a function of migration price p^I through θ^I, defined implicitly in (3.2):

$$D^I(p^I) = \int_0^{\theta^I} f(\theta)d\theta = F(\theta^I) \tag{3.3}$$

The demand for irregular migration is higher the lower the migration price, p^I, the lower the risk, q, the higher the discounted wages earned abroad as an irregular migrant, dw_f, and the lower the wages in the home country, w_h. These results, shown in appendix F.1, are intuitive since workers compare the costs and economic benefits from irregular migration.

4. Implementing a market for Temporary Foreign Work Permits

In this section we study the equilibrium when a government enters the migration market by selling temporary visas of duration τ, to foreign workers willing to take on low paid jobs. These are designed to attract workers in specific sectors with low returns to skills and labor shortage, such as agriculture in Spain and Canada, or domestic care and hospitality in Cyprus. Foreign workers recruited through these schemes earn $\Delta_f(\theta)w_f$ for a duration τ and spend the rest of their working life $(1-\tau)$ in their country of origin where they earn $\Delta_h(\theta)w_h$ per unit of time.

The function $\Delta_f : \mathbb{R}_+ \to [1, +\infty)$ is continuous, differentiable, increasing and concave. To capture that returns to skills in the destination country are lower than in the origin country with a lower level of economic development,[102] we assume that $\Delta_f(\theta) < \Delta_h(\theta)$ for all $\theta > 0$. We further postulate that the income differential between the home and host country decreases with worker's skill level: $\Delta'_f(\theta)w_f < \Delta'_h(\theta)w_h$. This characterizes low-paid jobs abroad, which are the focus of this paper. These jobs do not recognize foreign workers' skills even though workers can work in jobs where their skills are recognized in their home countries. These assumptions imply that legal migration under the TFWP scheme selects individuals negatively.

100. This result holds both under CPT and EUT (see appendix F.1).
101. Without risk ($q = 0$), this existence condition becomes $dw_f - w_h > p^I$.
102. This is in line with cross-country evidence on returns to education and skills (Psacharopoulos and Patrinos, 2018; Hanushek and Zhang, 2009).

A workable temporary visa market needs to satisfy three constraints. The *individual rationality constraint* is that some workers prefer to migrate temporarily rather than stay in their home country. The *incentive compatibility constraint* is that some workers prefer to migrate temporarily under these schemes than enter a country without a visa. The *enforceability constraint* is that temporary workers do not overstay their visa duration. Moreover, to set the price and duration of temporary visas, the government, a Stackelberg leader,[103] takes into account that the smugglers will adjust their price in response to the legal offer.

4.1. Demand for temporary visas

The *individual rationality constraint* determines the skill threshold θ^L under which a worker prefers to migrate under the temporary visa scheme (p^L,τ) than stay at home, which is the unique solution to:

$$\Delta_f(\theta)w_f - \Delta_h(\theta)w_h = \frac{p^L}{\tau}. \tag{3.4}$$

Individuals under this skill threshold have migration gains, equal to $\tau(\Delta_f(\theta)w_f - \Delta_h(\theta))$, larger than the costs they pay to migrate legally, p^L. For legal migration to occur, this threshold, θ^L must be higher than 0, which is satisfied if and only if $w_f - w_h > \frac{p^L}{\tau}$. This condition guarantees that at least the lowest skilled individual is willing to migrate under the temporary visa scheme (see all proofs in appendix F.2).

The *incentive compatible constraint* determines the skill threshold, θ^{LI}, such that any individual above this threshold prefers to migrate temporarily with work permits rather than illegally. Appendix F.3 shows that θ^{LI} is the unique solution to the following equation:

$$\begin{aligned}\omega^+(1-q)u\left[(d-\tau\Delta_f(\theta))\,w_f-(1-\tau)\Delta_h(\theta)w_h-p^I+p^L\right]\\+\omega^-(q)u\left[\tau\left(\Delta_h(\theta)w_h-\Delta_f(\theta)w_f\right)-p^I+p^L\right]=0\end{aligned} \tag{3.5}$$

Note that this threshold may be below the minimum skill level of workers ($\theta^{LI} < 0$), in which case no worker will migrate irregularly using a smuggling' service following the implementation of the scheme.

Comparative statics in appendices F.2 and F.3 intuitively show that more individuals are willing to migrate legally with a temporary visa than to stay at home or migrate irregularly as the migration duration increases, the price of visa decreases and the income differential between origin and host countries increases. Moreover when irregular migration persists, fewer individuals prefer to migrate illegally than legally

103. Once the government announces its policy, it must stick to it to be credible.

as the benefit of irregular migration decreases (i.e., as the income differential between the legal and illegal sectors increases, the price of smugglers increases, and the risk associated with migrating irregularly increases).[104]

4.2. Enforceable temporary visas

Opponents of guest-worker programs typically question whether temporary visas are enforceable, as workers could be tempted to overstay in the host country and work illegally. To address this, the government could offer incentive compatible guest-worker programs by withholding a share, s, of the income earned abroad and returning it to the worker upon completion of the visa after he/she returns to the home country. Enforcement can be strengthened by deporting workers who overstay and take on undocumented work. We note δ the probability of being deported if a worker overstays.

4.2.1. Overstaying constraint. Migrants facing the decision to overstay to work illegally compare the payoff they derive from the lottery $\mathscr{L}_{overstay} = [\tau(1-s)\Delta_f(\theta)w_f + (1-\tau)dw_f - p^L, \tau(1-s)\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h - p^L; 1-\delta, \delta]$, with their payoff if they comply with the rules of the guest worker program, $\tau\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h - p^L$. They decide to return to work in their origin country upon completion of the visa if and only if:

$$\begin{aligned}\omega^{+}(1-\delta)u\left[(1-\tau)\Big(dw_f - \Delta_h(\theta)w_h\Big) - s\tau\Delta_f(\theta)w_f\right] \\ +\omega^{-}(\delta)u\left[-s\tau\Delta_f(\theta)w_f\right] \leq 0\end{aligned} \tag{3.6}$$

Since the left hand side of the *enforceability constraint* (3.6) decreases with θ, we find that skilled workers have more incentive to comply with the visa rules than low-skilled workers. This is because skilled individuals have higher returns to their skills in their origin country. In other words, giving more incentives for workers to return upon completion of their visas helps to avoid a negative selection of overstayers.[105]

The following proposition establishes that it is always possible, by combining different policy instruments, to set up a program of TFWPs satisfying the "self-enforceability" constraint (i.e. so that workers do not choose to overstay).

Proposition 3.3. *For any $\tau, s, d \in (0,1)$, there exists a minimum deportation rate $\underline{\delta}(\tau, s, d) < 1$, decreasing with the share of wages retained s and the duration of visa*

104. That is, $\partial\theta^{LI}/\partial d > 0$, $\partial\theta^{LI}/\partial w_f > 0$, $\partial\theta^{LI}/\partial p^I < 0$, $\partial\theta^{LI}/\partial\tau < 0$, $\partial\theta^{LI}/\partial w_h < 0$, $\partial\theta^{LI}/\partial q < 0$ and $\partial\theta^{LI}/\partial p^L > 0$ (see appendix F.3).

105. Note that in case a worker decides to overstay, she decides to stay in the foreign country for the rest of her working life. After the visa expires, if she does not make a timely return to her home country, she loses the retained income. Hence overstaying the visa but returning before the end of her working life is even more costly.

τ, and increasing with the benefit of undocumented sector employment d, such that temporary migration visas are self-enforceable.

Proof. See appendix F.4. □

The enforceability constraint (3.6) is easier to satisfy as the relative benefits of overstaying to work in the undocumented sector decrease (through a lower d, a lower $\frac{\Delta_f(\theta)w_f}{\Delta_h(\theta)w_h}$ or a larger visa duration, τ) and as the enforcement instruments are strengthened.[106] The latter can be implemented through workplace inspections (a lower d), through increasing the costs of overstaying, entailed by a larger share s of wages retained abroad or by a longer visa duration τ, and through enforcement of deportation (a larger δ). For example, after replacing $\delta = 1$ in (3.6), it is easy to check that the enforceability constraint is always satisfied. Symmetrically, when $\delta = 0$, the condition (3.6) becomes:

$$(1-\tau)(dw_f - \Delta_h(\theta)w_h) \leq s\tau\Delta_f(\theta)w_f \tag{3.7}$$

so that unless the retention rate s and visa duration τ are very large, the guest worker program will not be self-enforceable when deportation measures are never enforced.

4.2.2. Enforceable short-term visas in practice. Proposition 3.3 shows the complementarities between the policy instruments and the importance of carefully combining the implementation of a market of temporary visas with other policy instruments. In practice, most countries already rely on some of these measures to manage labor migration. They combine sticks and carrots to ensure timely return of guest workers.

Large retention fees (large s) and enforced deportation (large δ): In East Asian countries, low rates of guest workers overstaying are enforced through harsh deportation measures and large retention fees (sticks). Employers can withhold substantial parts of the wages and/or can require a large contract-completion deposit, sometimes up to USD10,000 as in Japan, which is paid back to workers upon timely return (Bélanger et al., 2011; Djajić, 2013). There are other ways to enforce compliance with visa rules, such as fines, sometimes even jail sentences, and an exit tax to migrants who would like to leave the host country after the date of compliance (Djajić and Vinogradova, 2015).

Harsh punishment against undocumented work (low d): Alternatively, strict controls of employers and harsh punishment against firms that would employ undocumented migrants (stick) decrease d and, therefore, ease the enforceability of temporary

106. We assume for simplicity that the discount rate equals the interest rate such that withdrawing a share of wages and giving back later is neutral. If the interest rate is higher than the discount rate one could compensate guest-workers by paying interest on the withheld share.

migration visas. Condition (3.6) is indeed always true when $d = 0$. In countries with very limited economic prospects in informal labor market, such as Luxembourg, Iceland, Norway or Sweden,[107] it is more feasible to design self-enforceable temporary migration visas.

Eligibility for future temporary visas (larger τ): Finally, host countries may put in place a system of credits to gain eligibility for future visa applications if a migrant returns home before the work visa expires (carrot). This additional instrument has been implemented in Canada.

Limits to TFWP self-enforceability: As a corollary, it is not always possible to enforce the temporary stay of workers by retaining a share of earnings abroad. With low deportation rates (low δ) and thriving informal labor markets for undocumented workers (large d), visas need to be unrealistically long and retention shares arbitrarily large to incentivize workers to return to their home country upon completion of the visa. Indeed visa duration and retention share interact to increase financial losses in case of default.[108] As a consequence, with lax enforcement of deportation and the existence of large informal labor markets for undocumented workers, as in Southern Europe and the USA, substantial numbers of migrants may overstay illegally. This problem will be illustrated in section 6, which studies the required levels of enforcement needed for workable temporary visas on two (i.e., South-North and South-South) routes.

For the remainder of this section and section 5, we consider a set of contracts for which the self-enforceability constraint is not binding, such that the exact design of the incentives to prevent overstaying does not affect the results.

4.3. Smugglers' reaction to the sale of temporary visas

When visas can be bought legally, the individual of type θ compares the lottery $\mathcal{L}_{illegal} = \left[dw_f - p^I, \Delta_h(\theta)w_h - p^I; 1-q, q\right]$ with the payoff she retrieves from migrating legally, $\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h$. A constraint for the smugglers is to fix their price low enough relative to the price of a legal permit, to attract the workers of type between 0 and θ^{LI}. This requires that $\theta^{LI} > 0$. Since $\omega^-(q)u\left[\tau\Delta_h(\theta)w_h - \tau\Delta_f(\theta)w_f - p^I + p^L\right] + \omega^+(1-q)u\left[dw_f - \tau\Delta_f(\theta)w_f - (1-\tau)\Delta_h(\theta)w_h - p^I + p^L\right]$ is decreasing in θ, a necessary condition is that the comparison of the lottery must be positive for

107. See https://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/documents/publication/wcms_626831.pdf

108. Equation (3.7) presents this constraint in the extreme case in which the deportation is not enforced.

the lowest skilled worker:

$$\begin{aligned}\omega^{+}(1-q)u\left[(d-\tau)w_f-(1-\tau)w_h-p^I+p^L\right]\\+\omega^{-}(q)u\left[p^L-p^I-\tau\left(w_f-w_h\right)\right]>0\end{aligned}\tag{3.8}$$

This condition is more likely to be satisfied with a higher visa price, a lower smugglers' fee and a shorter visa duration, which all make legal migration less attractive relative to irregular migration.

Under condition (3.8), the demand faced by the smugglers is:

$$D^I(p^I,p^L)=\int_0^{\theta^{LI}}f(\theta)d\theta=F(\theta^{LI})\tag{3.9}$$

Let $p^N(p^L)$ be the solution of (3.1) computed with the direct price elasticity of demand (3.9), $\varepsilon_{D^I,p^I}=-\frac{\partial D^I(p^I,p^L)}{\partial p^I}\frac{p^I}{D^I(p^I,p^L)}$, which depends on p^L. The price reaction function of the smugglers is the solution of the following equation:

$$p^I(p^L)=\begin{cases}p^N(p^L) & \text{if } c\leq p^N(p^L)\\ \varnothing & \text{otherwise}\end{cases}\tag{3.10}$$

This shows that the reaction price of the smugglers is increasing in their marginal operating costs, c and in the price of a visa, p^L, and decreasing in the number of smugglers, N.

5. Eliminating smugglers through a sale of visas

Taking into account the three constraints of workable schemes and the smugglers' response to the implementation of temporary visas, the government can determine its optimal pricing strategy by backward induction, which will depend on its economic priorities.

5.1. Setting the eviction price

We consider schemes designed to eliminate the incentive to smuggle by selling visas at a low price that leaves zero profit for smugglers. This requires that their reaction price is pushed below their marginal cost, i.e. $p^I(p^L)\leq c$.

We establish the following result.

Proposition 3.4. *The eviction price $\underline{p}^L(\tau)$ of temporary visas of duration τ below which smugglers exit the market is implicitly defined by*

$$\begin{aligned}\omega^{+}(1-q)u\left[(d-\tau)w_f-(1-\tau)w_h-c+\underline{p}^L\right]\\+\omega^{-}(q)u\left[\underline{p}^L-c-\tau\left(w_f-w_h\right)\right]=0\end{aligned}\tag{3.11}$$

The eviction price increases with τ, c, q and decreases with d.

Proof. see appendix F.5. □

Appendix F.5 shows that the eviction price is such that $\theta^{LI} = 0$ for $p^I = c$. In other words, a government that wants to push smugglers' reaction price down until their mark-up vanishes has to apply the price $\underline{p}^L(\tau)$, solution to (3.11), hereafter called the eviction price for a visa of duration τ. Note that this result applies to any initial structure of the market for smugglers: monopolist, oligopolist or competitive. Irrespective of the initial market conditions, if a government wants to eradicate smugglers by selling visas it has to apply $\underline{p}^L(\tau)$ such that the smugglers end up reaching their marginal cost pricing.[109]

Intuitively, the eviction price is increasing in the duration of visa τ: as temporary visas become more valuable, it is easier to throttle the smugglers by introducing legal options to migrate. It is also increasing in the marginal operating costs for smugglers c and in the risk associated with irregular migration q, which both make smugglers' services less attractive. Similarly, if pay-offs to work in the illegal sector decrease relative to the legal sector, pushing down d, the eviction price can be set higher.

Furthermore, there is a minimum duration of temporary visas, $\underline{\tau}$, above which the eviction price is positive. This is summarized in the following corollary:

Corollary 3.2. *The minimum duration of temporary visa, $\underline{\tau}$, required to set a positive eviction price decreases with q and c, and increases with d.*

Proof. see appendix F.5. □

If the duration of the temporary visa τ is lower than $\underline{\tau}$, then $\underline{p}^L$ is negative (it is a subsidy). Workers will need to be paid to migrate legally under this scheme as the illegal option, enabling a longer stay in the high wage country, becomes more attractive. This is less likely to be the case when there is a high probability that irregular migration will fail, high marginal costs for smugglers to operate (increasing their fees) and lower economic prospects as working illegally. Occasionally migrants have been subsidized to move to advanced economies to work, for example in the sixties in Europe. However, with higher risks of failing irregular migration, temporary permits become more attractive to migrants and the eviction price can be set higher. In countries that have large temporary work permits programs, such as the Gulf countries, Jordan or East-Asian countries, the cost is generally strictly positive and the programs are accompanied by strict enforcement policies.

109. The same reasoning also holds irrespective of the way the competition between the smugglers is modeled in quantity, as modeled in the present paper, or in price.

As the (legal) migration demand decreases with the visa price (see equation 3.4) it follows that, at the eviction price $\underline{p}^L$, the legal migration demand, $F\Big(\theta^L(\underline{p}^L)\Big)$, decreases with the illegal migration risk, q. In other words, fighting irregular migration by increasing q, the risk of not managing to cross the border, through reinforced controls, can be used as an instrument to control migration flows of temporary workers following the introduction of the visa scheme. Similarly, increasing the marginal operating costs for smugglers, c, through repression against smugglers or decreasing the discounted value of working illegally, d, through enforcement of fines against employment of undocumented workers, can also be used as policy instruments to increase the eviction price and to decrease the flows of legal migrants. As a consequence of corollary 3.2 the flow of temporary workers under this scheme decreases with sanctions against illegal activities.

5.2. Skill diversity of foreign workers

An important aspect of the visa policy aimed at eradicating smugglers is its impact on the skill composition of the migrant population. Voters may, for example, oppose the legalization scheme if it brings workers with a less diverse pool of skills. The next proposition characterizes the visa duration $\tilde{\tau}$ and the associated eviction price $\underline{p}^L(\tilde{\tau})$ such that the pool of migrants' skills remains the same after the sale of visas, compared to the status quo with irregular migration.

Proposition 3.5. *The visa scheme sold at eviction price $\underline{p}^L(\tau)$ increases the skill diversity of migrants if the visa duration τ does not exceed $\tilde{\tau}(q,c,d) \in [0,1]$ solution to*

$$\frac{\underline{p}^L(\tilde{\tau})}{\tilde{\tau}} = \Delta_f(\theta^I)w_f - \Delta_h(\theta^I)w_h \tag{3.12}$$

where θ^I is defined by equation (3.2) and $\underline{p}^L(\tau)$ by equation (3.11). The threshold $\tilde{\tau}(q,c,d)$ decreases with q and c and increases with d.

PROOF. see appendix F.6. □

A shorter visa duration attracts a smaller pool of migrants, the price remaining constant. However, in an eviction framework, it entails a lower eviction price, which increases the demand for legal visas as $\frac{\partial \theta^L}{\partial p} < 0$. This price effect overrides the effect driven by the change in the visa duration.

When introducing a new scheme to meet labor market needs, the government faces a trade-off between the duration of the temporary visas, τ, and the average skill level of migrants recruited: a longer duration implies a pool of temporary migrants with lower skills on average. This result, which as far as we know, is new to the literature, is important for policy purposes. It implies that when a country seeks to recruit migrants to fill positions in low pay jobs (e.g., in agriculture, construction, social care), the longer the work permit, the less qualified the candidates for these jobs will be. For instance a student might wish to travel to a rich country for a few months to pick fruits and vegetables as a way to finance their studies or to accumulate capital to start a business at home. But they might not want to commit to a stay of several years as their human capital would be wasted on such low pay occupation. A relatively short term visa scheme, with low prices, makes it possible to recruit a wider range of workers, enlarging the skill pool of foreign workers.

This establishes that temporary foreign workers on short term visas may come with a larger pool of skills, compared to a pool of undocumented migrants under the *status quo*. However, since they only stay for a limited period, τ, the number of foreign workers living abroad at a given time (i.e. the stock) may decrease following this scheme, provided that the workers do not overstay.[110]

Indeed, such short-stay temporary visas are hard to enforce without substantial investment in deportation combined with wage retention while abroad (sticks) or other incentives, such as giving points to migrants for future visa eligibility or paying them to return to their home country. The latter has been implemented for example in France with "Aides au Retour" or at the EU level with the EU-IOM joint initiative for migrant protection and reintegration (carrots).[111]

5.3. Cost-effective policies to regulate labor migration

Our results so far highlight the very strong complementarities between (external and internal) controls and workable temporary visa schemes against smuggling. As internal and external controls are costly to enforce, we now turn to studying the optimal combination of these policy instruments for a cost-effective regulation of labor migration.

We depart from the *status quo* situation where marginal costs to smuggle is c, the risk of failing irregular migration is q and the wage discount factor for undocumented workers is d, and we determine the government's allocation of additional resources to enforce external and internal controls. We denote $c(I_1)$ the marginal costs that the smugglers face when the government invests $I_1 \geq 0$ additional resources to fight against smugglers and assume that $c'(I_1) > 0$ and $c''(I_1) < 0$. Similarly, the government may

110. The total effect of the policy on the stock of foreign workers in the host country depends on how $F(\theta^I)$ under the *status quo* compares to $\tau F(\theta^L)$ under the new scheme. Computing the variation in the number of migrants in the economy following the introduction of the visa scheme, $\Delta N = \frac{\tau F(\theta^L) - F(\theta^I)}{F(\theta^I)}$, it is easy to show that ΔN is negative if and only if: $\frac{F(\theta^L)}{F(\theta^I)} < \frac{1}{\tau}$.

111. See https://www.migrationjointinitiative.org/

also multiply the controls by investing in additional man hours at the border to prevent irregular border crossings. We denote $q(I_3)$ the probability a migrant fails the crossing when the government invests $I_3 \geq 0$ additional resources and assume that $q'(I_3) > 0$ and $q''(I_3) < 0$. The concave shapes of the functions indicate decreasing returns to scale of external controls. Finally, the government can allocate funds to increase internal controls at work-sites and enforce the sanctions paid by the employers of undocumented migrants. We denote $d(I_2)$ the wage discount factor resulting from these enforcement measures and assume that $d'(I_2) < 0$ [112] and $d''(I_2) > 0$. The convex shape of the function indicates decreasing returns to scale in the fight against illegal employment.

Note that we do not embed in the policy instruments the visa duration τ. The work permit duration is more realistically determined by the type of occupation targeted (i.e. seasonal in agriculture, hospitality, or longer term for personal care jobs) or by other priorities such as the targeted skill diversity of workers – in line with proposition 3.5 – or the legal framework in destination country. [113]

Replacing c by $c(I_1)$, d by $d(I_2)$ and q by $q(I_3)$ in (3.11), we can determine the eviction price of temporary visas of duration τ, $\underline{p}^L$, such that smugglers are pushed out of business given their inflated marginal costs, the reduced payoff to undocumnented employment and the increased risk of border crossings. The demand for temporary visas following this policy mix, combining the sale of temporary foreign work permits with enforced controls, can be written as:

$$D^L(I_1, I_2, I_3) = F\left(\theta^L\right) \tag{3.13}$$

with θ^L solution of :

$$\Delta_f(\theta)w_f - \Delta_h(\theta)w_h = \frac{\underline{p}^L}{\tau}. \tag{3.14}$$

The government chooses the optimal investments I_1, I_2, and I_3 that minimize their overall costs while reaching the target of recruiting T equivalent permanent foreign workers (i.e. T/τ temporary workers), as follows:

$$\min I_1 + I_2 + I_3 \qquad \text{s.t.} \qquad \tau D^L(I_1, I_2, I_3) = T \tag{3.15}$$

Focusing on interior solutions, the optimal allocation of resources is summarized in the next proposition. [114]

112. See Woodland and Yoshida (2006) for a theoretical foundation of this assumption and Cobb-Clark et al. (1995) for empirical evidence.

113. If we consider visa duration to be flexible, it is easy to determine its optimal level simultaneously with the other instruments by adding one first order condition in Proposition 3.6: $\tau f(\theta^L)\frac{\partial \theta^L}{\partial \tau} + F(\theta^L) = 0$

114. Depending on the functions $c(.)$, $d(.)$, and $q(.)$, it may be the case that the optimal solution involves increasing c only (i.e. $I_2 = 0$ and $I_3 = 0$), increasing q only (i.e. $I_2 = 0$ and $I_1 = 0$),

Proposition 3.6. *To dismantle smugglers through a cost-effective sale of temporary visas of duration* τ *and meet the labor market needs for* T *permanent equivalent workers, a government should invest the amounts* $\{I_1^*, I_2^*, I_3^*\}$ *in internal and external controls, solutions of the following equations:*

$$\tau F(\theta^L) = T \tag{3.16}$$

$$c'(I_1)\frac{\partial \theta^L}{\partial c} = d'(I_2)\frac{\partial \theta^L}{\partial d} = q'(I_3)\frac{\partial \theta^L}{\partial q} \tag{3.17}$$

with θ^L *solution of equation (3.14).*

The optimal allocation of resources into different measures to enforce internal and external controls is such that their marginal effects on the migration demand are equalized, as shown by (3.17). In other words, whatever the migration target T, the government should equalize the marginal impact of investments in external and internal controls on migration flows to minimize the enforcement costs of the policy.

Since the demand for visas is a normal good and since $c'(I_1) > 0$, $d'(I_2) < 0$ and $q'(I_3) > 0$ we can check that $\frac{dD^L(I_1,I_2,I_3)}{dI_k} < 0$, for $k = 1, 2, 3$. When repression against smugglers increases, the marginal cost of their activity, c, and the probability of failure when crossing the border, q, increase. This enables a government to price out smugglers through higher eviction prices. Similarly, when sanctions are enforced against employers of undocumented migrants, this is transmitted to irregular migration payoffs through a decrease in d. As a result, a government can set higher eviction prices for visas. These measures, optimally combined to minimize the costs, enable a government to control migration flows and reach its target number of foreign workers recruited through the scheme. In stark contrast to the situation in the *status quo*, the regulation of migration flows is done without relying on the abusive power of smugglers, who are driven out of business.

6. Policy Implications

Our numerical applications focus on two routes: a South-North route from Senegal to Spain and a South-South route from the Democratic Republic of the Congo (DRC) to South Africa. The results are not fully fledged policy simulations, since we abstract from other changes that may occur in the rest of the economy.[115] However they

decreasing d only (i.e.$I_1 = 0$ and $I_3 = 0$) or any combination of the three instruments. However, in other cases there will be an interior solution defined in (3.17) and such that $\tau D^L(I_1, I_2, I_3) = T$.

115. In particular, labor markets may adjust following larger inflows of documented workers, which may dampen the initial incentives to migrate and, in turn, lead to smaller changes in migration flows than the ones we calibrate. However, Clemens et al. (2018) show very limited effects of the withdrawal of the BRACERO program on the US labor market.

do illustrate the complementarities between selling temporary visas and other policy instruments in the fight against irregular migration and the constraints of the policy mix.

Estimates of the fees paid by irregular migrants, the marginal costs for smugglers to operate, the risk of failure of irregular migrants and the discounted wage to work as an undocumented worker are retrieved from different surveys and testimonies (see in table 3.1). The minimum wage in Spain is from ILO statistics, while we use GDP and Gini coefficients of the World Data Indicators to calibrate low-skill wages in the DRC, Senegal and South Africa (see detail in appendix G.1.1).

Table 3.1. Benchmark parameter values

Parameter	Value		Year	Source
Wages (monthly)				
DRC	36 PPP	32,806 FC	2020	20th percentile of computed distribution
Senegal	88 PPP	21,666 Fcfa	2007	20th percentile of computed distribution
South Africa	155 PPP	1,074 R	2020	20th percentile of computed distribution
Spain	857 PPP	694 €	2007	International Labour Organization (2008)
d	0.8			Monràs et al. (2020); Rivera-Batiz (1999); Kossoudji and Cobb-Clark (2002)
Marginal costs				
Senegal to Spain	1,150 PPP	266,666 Fcfa	2007	Mbow and Tamba (2007)
DRC to South Africa	830 PPP	408 USD	2020	inferred from Tshimpaka and Inaka (2020)
Smuggling prices				
Senegal to Spain	1,690 PPP	391,981 Fcfa	2007	Mbaye (2014)
DRC to South Africa	1,220 PPP	600 USD	2020	Tshimpaka and Inaka (2020)

Conversion rates between PPP and LCU, for private consumption, were retrieved from World Bank (2020).

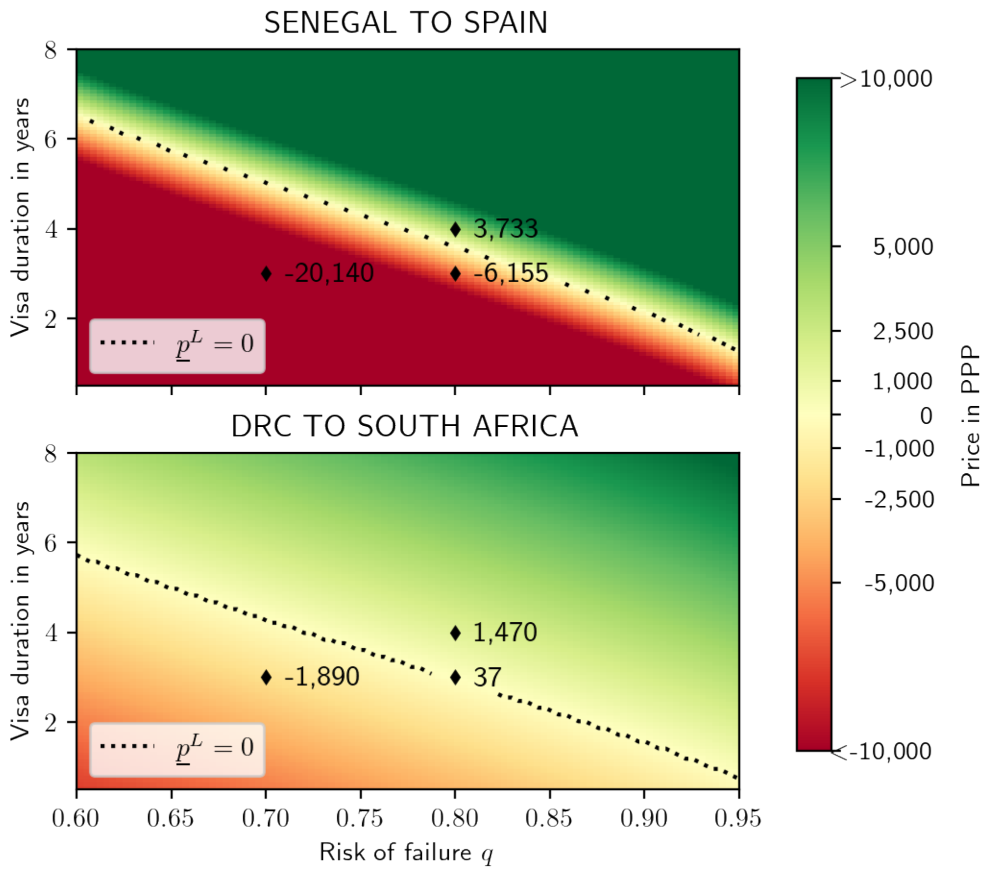
[1] Statement of 9 February 2021, `http://www.labour.gov.za/employment-and-labour-minister-tw-nxesi-announces-minimum-wage-increases?platform=hootsuite`

6.1. Visa prices

To predict migrants' decisions under high risk of failure, we use the CPT functional forms by Tversky and Kahneman (1992), which are consistent with agents' behavior while considering risky gambles (for a literature review see Rabin, 1998; Barberis and Thaler, 2003).[116]

116. Tversky and Kahneman (1992) generalize the seminal paper by Kahneman and Tversky (1972), which was one of the first to show that individuals have a poor ability to assess probabilities. In particular, this theory provides realistic predictions for individual behavior when confronted with risky choices, both inside (Glöckner and Betsch, 2008) and outside (Barberis et al., 2016) the lab.

FIGURE 3.1. Eviction prices on a South-North route and a South-South route



Using equation (3.11), the eviction price $\underline{p}^L(\tau)$ takes the following closed-form expression:

$$\underline{p}^L(\tau) = c + \tau(w_f - w_h) + \left(1 + \left(\lambda \frac{\omega^-(q)}{\omega^+(1-q)}\right)^{\frac{1}{\alpha}}\right)^{-1} (w_h - dw_f) \tag{3.18}$$

Eviction prices on the two routes are represented in figure 3.1 by different colors as functions of the visa duration in years (on vertical axis),[117] and risk of failure, q (on horizontal axis). The dashed lines represent isoquants of level 0, i.e. combinations of risk of failure q and visa duration such that eviction prices are zero. Points in green, North-East of the 0-isoquant, are positive eviction prices. The darker the color, the higher the price. In the opposite direction, points in red represent negative eviction prices (i.e., subsidies).

117. Using the model's notations, visa duration in years is equal to $40 \times \tau$.

Starting from a realistic risk of failure around 80% [118] and a short term visa of 4 years, the eviction price is around 3,733 PPP on this route, as compared to 1,470 PPP on the route from the DRC to South Africa. Reducing the visa duration decreases eviction prices substantially: for the same risk, a 3-year visa should be subsidized at -6,155 PPP on the Senegal-Spain route (priced at +37 PPP on the DRC-South Africa route). Similarly, a decrease in the risk of failure decreases sharply the eviction price. With a risk around 70%, a 3-year visa from Senegal to Spain should be subsidized as much as -20,140 PPP (-1,890 PPP for a 3-year visa from the DRC to South Africa).

Eviction prices on the Senegal-Spain route are much more dispersed than on the DRC-South Africa route. The area in dark red color for the Senegal to Spain route indicates that, for a large range of parameter values (q, τ), large subsidies above 10,000 PPP should be given to migrants in order to erode smugglers' profits on this route, an unrealistic scenario. This is because wages in low-wage jobs (in PPP) in Spain are still approximately 10 times the wages in Senegal. This ratio is twice as large on this route compared to the DRC to South Africa route. Due to this difference, individual prospects are more sensitive to the risk of failing irregular migration and to the visa duration on the South-North route.

Note that this does not imply that a host country should offer a menu of visas set at different prices for migrants from different origin countries. For example, setting visa prices below eviction prices on all routes to the same destination country will drive smugglers out of business, and has yet limited effects on increasing the share of workers choosing to migrate through TFWPs compared to the share of undocumented migrants under the status quo. Appendix G.2 illustrates this with an example of a visa scheme priced at the equivalent current embassy costs charged for visa applications from the DRC to South Africa and an example of TFWPS priced at the average smugglers' fees observed on this route.

However, since little information is available on irregular migration and since risks of crossing illegally vary a lot over time (see discussion in appendix G.1.1), the exacerbated sensitivity makes price-setting strategies particularly challenging on South-North routes.

6.2. Self-enforceability

A strong constraint on the success of temporary work permit schemes is the compliance of workers with their rules. Since the left hand side of the self-enforceability constraint (3.6) decreases with θ, low-skilled workers have more incentives to overstay

118. See discussion in appendix G.1.1 and Bah et al. (2019)

their visa duration than higher skilled workers. This implies that if (3.6) is satisfied for $\theta = 0$, then it is also satisfied for any worker of skill level $\theta > 0$. As the left hand side of (3.6) also decreases in s, we define the threshold share of income retention $\bar{s}$ above which workers of all skill levels will not have economic incentives to overstay, as the solution of the following equation:

$$\omega^{+}(1-\delta)u\left[(1-\tau)(dw_f - w_h) - s\tau w_f\right] + \omega^{-}(\delta)u\left[-s\tau w_f\right] = 0 \qquad (3.19)$$

For deportation rates ranging between 25% and 90%, we compute the minimum share of income retention required to incentivize workers' compliance. Results for each route are presented in figure 3.2. Dark colored areas represent combinations of visa duration, τ, and level of deportation, d, which require a high level of income retention to be enforceable. Lighter colored areas show that the minimum share of income retention is a decreasing function of the deportation rate and of the visa duration. This illustrates the complementarity of policy instruments (see proposition 3.3).

White areas are sets of visa duration and deportation rate such that visas are not enforceable ($s > 100\%$). The top panels show that such schemes may simply not work when the parameter d takes the benchmark value 0.8, especially where the wages differential is too large (top left figure) and deportations are not enforced. In most OECD destination countries deportation rates – although difficult to estimate– are relatively low. The European Commission estimates the fraction of "returnees" among the undocumented migrants ordered to leave Europe in 2019 to be around 29% on average.[119] This suggests that enforcing the policy to reach the required deportation rate will be difficult to implement in most EU countries and very costly.[120]

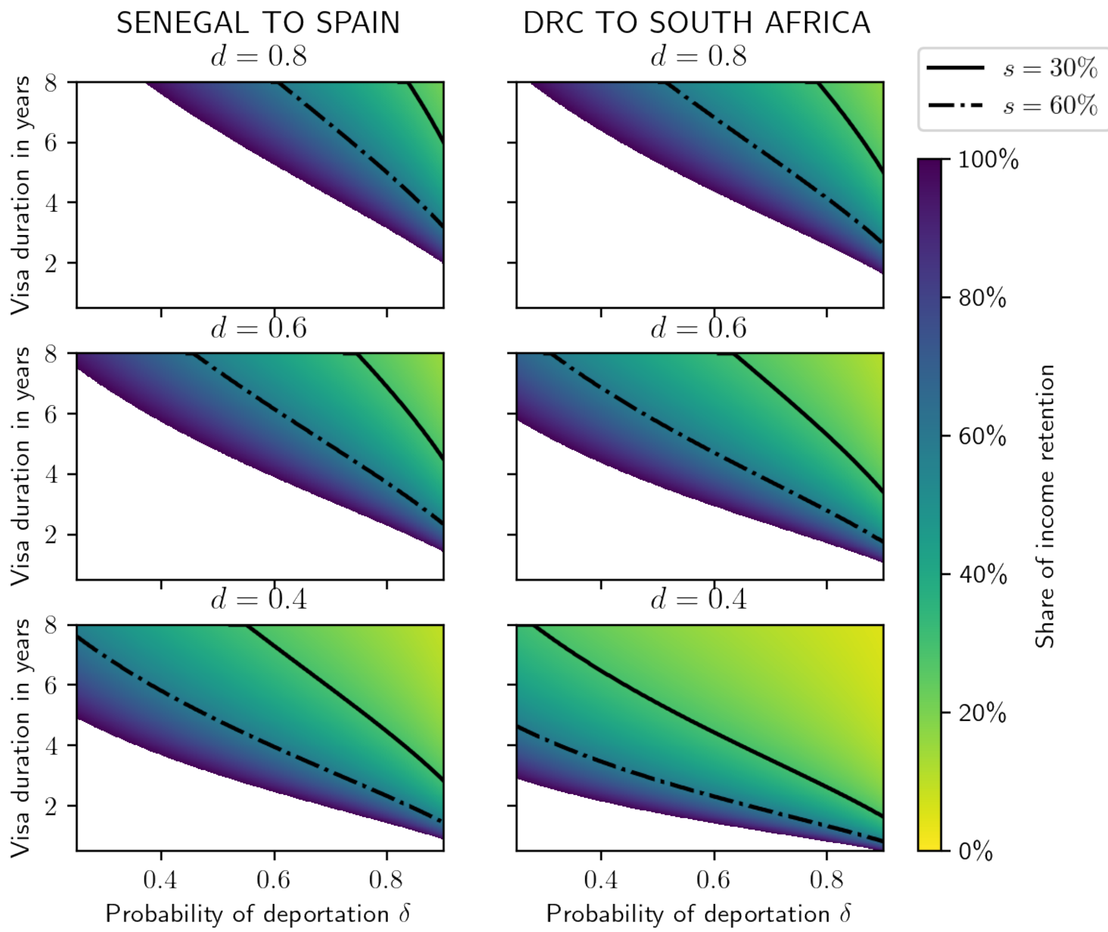
Even when theoretically feasible (colored areas), incentivizing short-term visa compliance would require retaining more than 50% of the income earned abroad (as highlighted in blue-green shaded areas) for a large range of deportation values. This may constrain migrants to over-accumulate savings abroad. Although the empirical evidence points to very uneven shares of annual income remitted to families of origin across routes, it rarely reaches 50% of the annual earnings.[121] Accordingly, retention

119. This statistic is an overestimate of the deportation rate for the overall population of undocumented migrants, since many of them are not caught and ordered to leave, and it varies a lot across countries. See Eurostat Statistics on migration to Europe, available online at `https://ec.europa.eu/info/strategy/priorities-2019-2024/promoting-our-european-way-life/statistics-migration-europe_en#illegalbordercrossings`.

120. Estimates of overall costs of deporting one person are around USD12,500 in the US in 2011, £11,000 in the UK (BBC 2009) and NOK 50,000 (USD 9000) in Norway in 2013 (Djajić and Vinogradova, 2015).

121. For example, workers from Senegal (respectively Morocco) remit from Spain 49.9% (resp.30.8%) of their earnings (Groenewold and Bilsborrow, 2004), while workers from Senegal (resp. Morocco) remit from France 11.2% (resp. 10.4%) of their earnings (Wor, 2009). See also Yang (2011).

Figure 3.2. Self-enforceability constraints on a South-North route and a South-South route



shares that are too high are likely to reduce the welfare of migrants and their families, in particular if these funds are otherwise used to consume while abroad or/and insure each other against negative income shocks.[122]

So is there another way forward? A tool often underused by policy makers is to strengthen the sanctions against employers of undocumented migrants by multiplying work-site controls and enforcing penalties. It is striking that, despite the evolution of biometric documentation and e-government, efforts to verify the legal status of workers in European or American companies are so sparse. In France, for example, the number of random checks is very low and they account for less than 10% of checks in

122. On the other hand, locking some earnings on a foreign bank account could be beneficial to migrants if the main motive for remittances is future consumption and investment after return. This would give migrants more control over their savings accumulated abroad, higher return to their savings and greater investment opportunities in the origin country once the funds, plus interest, are transferred back.

the fight against illegal employment. In 2017, when the accomodation and catering sectors were targeted, only 6,330 out of 700,000 employees were checked (i.e. 0.9% of the workforce).[123] Similarly, in the United States, there is very little enforcement against illegal employment in the workplace (Hanson, 2007). Few American employers who hire irregular immigrants are detected or prosecuted. Yet considerable investments have been increasingly allocated to reinforcing U.S. border controls. Since 1993, the annual budget of the U.S. Border Patrol has increased more than ten-fold, from $363 million to nearly $4.9 billion in 2021.[124] Consistently with proposition 3.6 and given these discrepancies between internal and border controls and the availability of new technologies that reduce the marginal cost of control, strengthening systematic workplace checks of undocumented workers may be a more effective way of stemming irregular migration than strengthening border controls.

Increasing the costs of employing undocumented migrants would lead to an equilibrium with lower relative earnings as undocumented worker, driving down the parameter d. As shown in the center and bottom heat maps in figure 3.2, for which d is set to 0.6 and 0.4 respectively, the self-enforceability constraint is largely relaxed: the minimum shares of income retention decline significantly at any given set of policy parameters (deportation-visa duration) such that the colored areas indicating feasible policies are extended.

7. Conclusion

We show how a system of temporary work visas enables a government to overcome the legalization-migration control trade-off. Politically appealing for governments in destination countries, these temporary visas are designed to meet labor market needs, to dry-up the smuggling markets, and to decrease the number of foreign workers staying irregularly in high wage countries, where they are negatively perceived by citizens, or used as a target by populists to build political support.

The main mechanism is to sell visas at an eviction price, which will drive smugglers out of business and can be adjusted to reach migration targets, if combined with appropriate enforcement of external and internal controls. Compared to more permanent visas, an advantage of selling TFWPs is that they are more affordable to poor workers from low income countries. Yet, their limited duration and their positive price limit their attractiveness, which regulates the flows of legal migrants. However a system of

123. See https://www.strategie.gouv.fr/publications/evaluation-travail-dissimule-de-impacts-finances-publiques-fin-juin-2019

124. See https://www.americanimmigrationcouncil.org/sites/default/files/research/the_cost_of_immigration_enforcement_and_border_security.pdf

visas against smuggling will need to address the two main weaknesses of past TFWPs: overstays and abuses of migrants' rights.

Regarding the first problem, our analysis shows that the larger the wage differential between the origin and the destination country, the harder it is to incentivize guest workers to return home when their visa expires. For this reason, regulating South-South migration flows with the help of TFWP may be feasible, as illustrated by our numerical applications to the DRC-South Africa route. In contrast, systems of self-enforceable TFWPs for migrants from low-wage countries to high-wage countries require very high levels of investment in policy enforcement and high retention shares on wages earned abroad. Our simulations for Senegalese workers migrating to Spain illustrate that the level of incentives needed to enforce the scheme may be too constraining. Where there are large economic disparities combined with lax enforcement of deportation and strong protection of migrants' rights, guest workers are likely to feed the undocumented labor market in host country.

These results illustrate the practical challenge of discouraging over-stayers. They also help to explain why very large TFWP programs flourish in the Gulf and Asian countries. First, the wage gap between origin and destination countries is smaller than in Europe or the US, which cushions the incentives to overstay. Second, enforcement of visa schemes through repressive measures is more effective in those parts of the world where states have strong authoritarian traditions and offer flimsy legal protection to foreign workers, who can be easily deported and sanctioned if caught working without a permit. This often leads to abuse of migrants' rights and the second criticism commonly addressed to TFWPs.

In response to these legitimate concerns we argue that socially just TFWPs built around migrant agency (Consterdine and Samuk, 2018) have the potential to promote rights-based policies, offering migrants safe passage and access to legal labor markets in high wage countries, with better legal protection than if they are left at the mercy of smugglers and illegal employers. To ensure timely return of the temporary guest workers, governments in advanced economies may adopt different combinations of enforcement measures, such as harsh punishment against employers of undocumented workers, the awarding of points toward more settled status in the future or preservation of future eligibility for visas, as seen in Canada.[125] Further, other important factors influence temporary workers' return to their home country: migrants may have preferences to consume in their home country, higher purchasing power, and better

125. Our framework provides an intuition for the effect of eligibility points awarded upon timely return. In our simple static model, this is captured by increasing the visa duration τ, which relaxes the enforceability constraint.

investment opportunities, which help insure the circularity of labor migration (Djajić, 2013; Djajić and Vinogradova, 2015; Mesnard, 2004). Embedding these additional factors in our framework of analysis would improve economic prospects in the origin country and relax the self-enforceability constraint.

Even though TFWPs have been implemented with varying levels of success in the past, they have not yet been designed to erode smugglers' profits, nor to promote migrants' rights. Given that migrant workers under this scheme would be employed legally as opposed to illegally under current policies, their living conditions and rights can be more easily protected. Carefully designed active labor recruitment policies from low income countries to high income countries have multiple economic and social benefits for migrants themselves, and for destination, transit and origin countries. This should be considered in the design of future migration policies.

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Appendix A

Cannabis laws in the U.S.

As of December 2020, fifteen states and the District of Columbia have legalized the use of recreational cannabis and four additional legalization ballots are expected to take place in November 2022. Cannabis possession remains a felony in other states such as Arizona, where sanctions and fines to enforce the law differ a lot. For example in Arizona, there is no guideline for punishment regarding small amounts of cannabis and possessing 2 pounds or less entails a risk of incarceration of up to 2 years and a fine of up to USD 150,000. In contrast, any amount on a first offense in Iowa is only a misdemeanor punishable by a maximum prison sentence of 6 months and a USD 1,000 fine.

The table below offers a synthetic overview of state cannabis laws across the United States. For each state, we reported the year during which cannabis was decriminalized in the second column. The third column records the year of the first ballot to legalize the use of medical cannabis, i.e. to instate a *Medical Marijuana Law* (MML), while the fourth column gives the year during which such a law was passed. The fifth column lists the year of the first ballot to legalize the recreational use of cannabis, and the sixth column the year of such a law being passed. The final column reports the year of the first legal retail sales of cannabis. Dashes represent the absence of the event described in the corresponding column.

State	Decrim.	1st MML ballot	MML	1st rec. ballot	Rec.	Retail
AL	-	- [a]	2021	-	-	-
AK	1975 [b]	1998	1998	2000	2014	2016

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

b. 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

State	Decrim.	1st MML ballot	MML	1st rec. ballot	Rec.	Retail
AZ	-	1996	2010	2016	2020	2021
AR	- [c]	2012	2016	- [d]	-	-
CA	1975	1996	1996	1972	2016	2018
CO	1975	2000	2000	2012	2012	2014
CT	2011	- [a]	2012	- [e]	2021	- [f]
DE	2015	- [a]	2011	-	-	-
D.C.	2014	1998	2010	2014	2014	- [g]
FL	- [h]	2014	2016	- [d]	-	-
GA	- [h]	-	- [i]	-	-	-
HI	2020	- [a]	2000	-	-	-
ID	-	-	-	-	-	-
IL	2016	- [a]	2013	- [e]	2019	2020
IN	- [j]	-	-	-	-	-
IA	-	-	-	-	-	-
KS	-	-	-	-	-	-
KY	- [h]	-	- [k]	-	-	-

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.

c. Although cannabis use remains a crime under state law, it is decriminalized locally.

d. A cannabis legalization initiative is expected to be on the ballot in November 2022 (“Marijuana on the ballot”, *Ballotpedia*. Retrieved online June 2022, `https://ballotpedia.org/Marijuana_on_the_ballot`)

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

f. Expected by the end of 2022.

g. Implementation still pending.

h. Although cannabis use remains a crime under state law, it is decriminalized locally.

i. A bill was passed in 2015, legalizing the use of *light cannabis*, i.e. cannabis products featuring low THC potency (see Georgia General Assembly, `https://www.legis.ga.gov/legislation/42674`).

j. Decriminalized in Marion County as of 2019 (see `https://web.archive.org/web/20190930193952/https://www.wthr.com/article/marion-county-will-no-longer-prosecute-simple-marijuana-cases`).

k. 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`).

State	Decrim.	1st MML ballot	MML	1st rec. ballot	Rec.	Retail
LA	2021	- [a]	2015 [l]	-	-	-
ME	1975	1999	1999	2016	2016	2020
MD	2014	- [a]	2013	-	-	-
MA	2008	2012	2012	2016	2016	2018
MI	2018	2008	2008	2018	2018	2019
MN	1976	- [a]	2014	-	-	-
MS	1978	2020	2020	- [d]	-	-
MO	2014	2018	2018	-	-	-
MT	- [h]	2004	2004	2020	2020	2022
NE	1979	- [m]	-	-	-	-
NV	2016	1998	1998	2006	2016	2017
NH	2017	- [a]	2013	-	-	-
NJ	-	- [a]	2010	2020	2020	2022
NM	2019	- [a]	2007	[e]	2021	2022
NY	1977	- [a]	2014	- [e]	2021	- [f]
NC	1977	-	-	-	-	-
ND	2019	2016	2016	2018	[d]	-
OH	1975	- [a]	2016	2015	-	-
OK	- [n]	2018	2018	- [d]	-	-
OR	1973	1998	1998	2012	2014	2015
PA	- [h]	- [a]	2016	-	-	-
RI	2012	- [a]	2005	- [e]	2022	-
SC	-	-	-	-	-	-
SD	-	2006	2020	2020	- [o] [d]	-
TN	-	-	-	-	-	-

l. Although *Medical Marijuana* was signed into law in 2015, it was unlawful to inhale cannabis until 2019 (see `https://www.mpp.org/states/louisiana/overview-of-louisianas-medical-cannabis-law/`).

m. A *Medical Marijuana* ballot is expected to be on the ballot in November 2022 ("Marijuana on the ballot", *Ballotpedia.* Retrieved online June 2022, `https://ballotpedia.org/Marijuana_on_the_ballot`).

n. 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)`).

o. The recreational use of cannabis was legalized by the 2020 ballot. However, in 2021, the South Dakota Supreme Court ruled the amendment responsible for the legalization of recreational as unconstitutional.

State	Decrim.	1st MML ballot	MML	1st rec. ballot	Rec.	Retail
TX	- [h]	-	-	-	-	-
UT	-	2018	2018	-	-	-
VT	2013	- [a]	2004	- [e]	2018	2020
VA	-	-	-	- [e]	2021	-
WA	2012	1998	1998	2012	2012	2014
WV	-	-	2017 [p]	-	-	-
WI	- [h]	-	-	-	-	-
WY	- [q]	-	-	-	-	-

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

q. Expected to be on the ballot in 2024 ("Marijuana on the ballot", *Ballotpedia*. Retrieved online June 2022, `https://ballotpedia.org/Marijuana_on_the_ballot`

Appendix B

Cumulative Prospect Theory: some takeaways

Tversky and Kahneman (1992) suggest a model featuring loss aversion, diminishing sensitivity for gains and losses and diminishing sensitivity regarding probabilities. Agents' appreciation for gains and losses is represented by a value function $u(x)$, which is S-shaped and has an inflection point in zero. This describes individuals being empirically risk-averse for gains and risk-seeking for losses; denoted by Kahneman and Tversky (1979) as the *reflection effect*.

FIGURE B.1. Value function as calibrated by Tversky and Kahneman (1992)

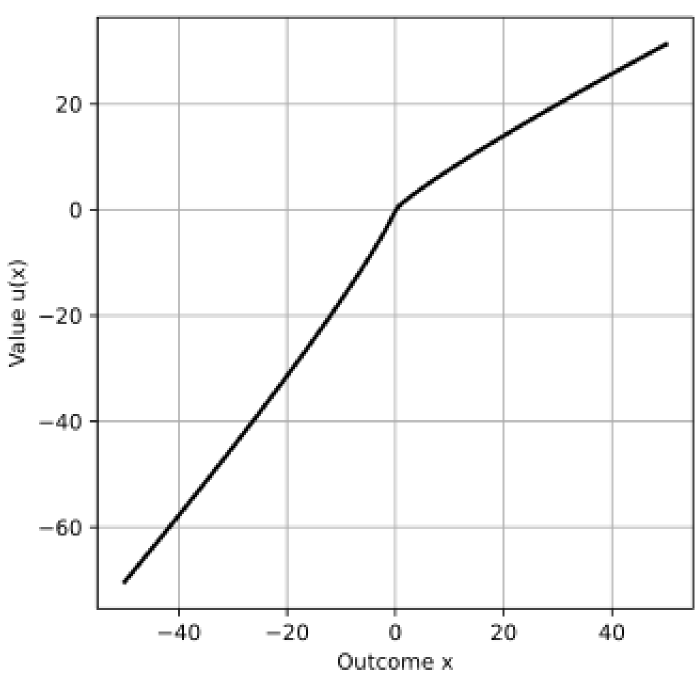
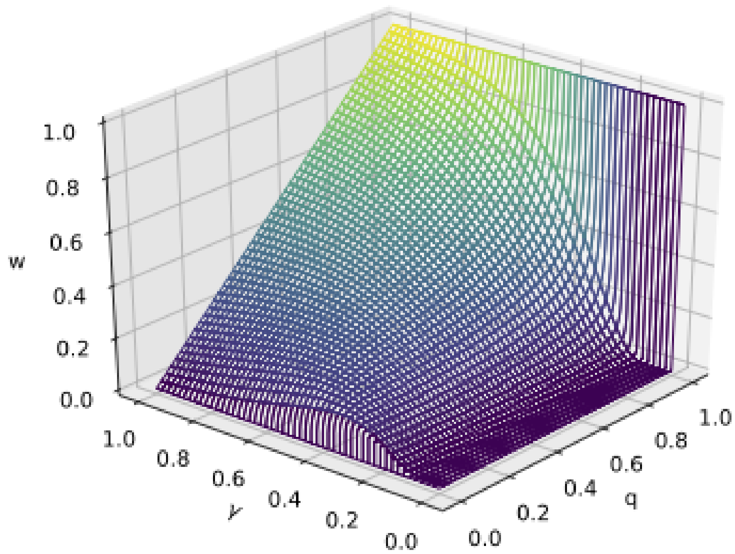


FIGURE B.2. Probability weighting functions for $\gamma \in (0, 1]$



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More specifically, the authors calibrate the following functional form for the value function:

$$u(x) = \begin{cases} x^{\alpha} \text{ , if } x > 0 \\ -\lambda(-x)^{\beta} \text{ , if } x \leq 0 \end{cases} \tag{B.1}$$

where $\alpha, \beta \in (0, 1)$ reflect the curvature and indicate the degree of risk preference; i.e. the degree of risk-aversion for gains and the degree of risk-seeking in the domain of losses. $\lambda \geq 1$ is the *coefficient of loss aversion*, which reflects that the decrease in utility from a loss is greater than the increase in utility from a gain of the same amount. In line with Tversky and Kahneman (1992) estimates, we assume $\alpha = \beta$.

The weighting functions w^{+}, for gains, w^{-}, for losses are concave near 0 and convex near 1 to capture diminishing sensitivity for probabilities. Tversky and Kahneman (1992) specify the weighting functions as follows :

$$w^{x}(q) = \frac{q^{\gamma^{x}}}{(q^{\gamma^{x}} + (1-q)^{\gamma^{x}})^{\frac{1}{\gamma^{x}}}} \qquad \text{with } x = +, -.$$

The form of such weighting functions is represented in Figure B.2. For $\gamma = 1$, $w^{x} : q \mapsto \frac{q^{\gamma}}{(q^{\gamma}+(1-q)^{\gamma})^{\frac{1}{\gamma}}}$ is the identity. The closer γ is to 0, the more distorted the probability weights are. When $\gamma \to 0$, the function w^{x} has an L-shape.

For $\gamma = 1$, $w^{x} : q \mapsto \frac{q^{\gamma}}{(q^{\gamma}+(1-q)^{\gamma})^{\frac{1}{\gamma}}}$ is the identity. The closer γ is to 0, the more distorted the probability weights. When $\gamma \to 0$, the function w^{x} has an L-shape.

Our models offer only two possible outcomes (success/failure) for an individual choosing between a legal and an illegal behavior (whether it is consuming cannabis illegally or migrating irregularly). Therefore, without any loss of generality, we directly apply the probability weights $\omega^+(1-q)$ and $\omega^-(q)$ to these two outcomes.

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Appendix C

First Article
Theoretical Proofs and Characterizations

C.1. Characterizing the marginal type of consumer θ^I, indifferent between no consumption and illegal consumption

An individual of type θ deciding between illegal consumption and no consumption considers the lottery $[-p-F, \theta v-p; q, 1-q]$. Not consuming entails a zero payoff. The utility associated with illegal consumption is given by: $w^+(1-q)u(\theta v-p)+w^-(q)u(-p-F)$, where u is a value function which is continuous, derivable and strictly increasing on $I\!R$, and such that $u(0)=0$.

The consumption condition is written as: $w^+(1-q)u(\theta v-p)+w^-(q)u(-p-F) > 0$.

Let us define $V_I(\theta) = w^+(1-q)u(\theta v - p) + w^-(q)u(-p-F)$

The marginal individual θ^I, indifferent between illegal consumption and no consumption, is characterized by:

$$V_I(\theta) = 0 \tag{C.1}$$

Since the value function u from not consuming is such that $u(0) = 0$, this condition is the same, whether θ^I is derived using Expected Utility Theory or Prospect Theory. The only difference is that under Expected Utility Theory, the weighting functions w^+ and w^- are equal to the identity. Since u is a function which is continuous, derivable, strictly increasing on $I\!R$, it admits a reciprocal function u^{-1} which is also strictly increasing and such that $u^{-1}(0) = 0$. Condition (C.1) is equivalent to:

$$\theta^I = \frac{u^{-1}\left(\frac{-w^-(q)u(-p-F)}{w^+(1-q)}\right) + p}{v} \tag{C.2}$$

We deduce that θ^I exists and is unique, with $\theta^I > \frac{p}{v}$ if $q > 0$ and $\theta^I = \frac{p}{v}$ if $q = 0$.

Expression (C.2) clearly shows that θ^I increases with q, p and F, since the value function u, its reciprocal and the weight functions are strictly increasing.

Finally, we focus on the absolute value of the price elasticity of demand, $\epsilon_{_{D,p}}$, as defined in (1.4). After differentiating $\epsilon_{_{D,p}}$ with respect to q, one can check that:

$$\frac{d\epsilon_{_{D^I,p}}}{dq} = \frac{d\{\frac{g(\theta^I)}{1-G(\theta^I)}\}}{d\theta^I}\frac{d\theta^I}{dq}\frac{d\theta^I}{dp}p + \frac{g(\theta^I)}{1-G(\theta^I)}\frac{d^2\theta^I}{dpdq}p. \tag{C.3}$$

As θ^I increases with p and q it follows that $\epsilon_{_{D^I,p}}$ increases with $q \in [0,1]$ if the cross-derivative of θ^I with p and q is positive and if the distribution $G(\theta)$ satisfies the monotone hazard rate (MHR) property. We next check under what condition this cross derivative is positive.

Differentiating equation (C.1) yields: $\sum_{i\in\{p,q,\theta,F\}} \alpha_i \mathrm{d}i = 0$, with

$$\begin{cases} \alpha_\theta = vw^+(1-q)u'(\theta v - p) \\ \alpha_q = -w^{+'}(1-q)u(\theta v - p) + w^{-'}(q)u(-p-F) \\ \alpha_p = -w^+(1-q)u'(\theta v - p) - w^-(q)u'(-p-F) \\ \alpha_F = -w^-(q)u'(-p-F) \end{cases}$$

In particular, it yields $\frac{\mathrm{d}\theta^I}{\mathrm{d}p} = -\frac{\alpha_p}{\alpha_\theta}$. From this follows that

$$\frac{\mathrm{d}^2\theta^I}{\mathrm{d}p\mathrm{d}q} = \frac{\alpha_p\alpha_{\theta q} - \alpha_{pq}\alpha_\theta}{\alpha_\theta^2}$$

where

$$\begin{cases} \alpha_{pq} = \dfrac{\partial\alpha_p}{\partial q} = w^{+'}(1-q)u'(\theta v - p) - w^{-'}(q)u'(-p-F) \\ \alpha_{\theta q} = \dfrac{\partial\alpha_\theta}{\partial q} = -vw^{+'}(1-q)u'(\theta v - p) \end{cases}$$

Since the function u is increasing and the weight functions are positive and increasing, we show that $\alpha_p\alpha_{\theta q} - \alpha_{pq}\alpha_\theta > 0$ as follows:

$$\begin{aligned} &\left[w^-(q)w^{+'}(1-q) + w^{-'}(q)w^+(1-q)\right] vu'(\theta v - p)\, u'(-p-F) > 0 \\ \Rightarrow & w^-(q)u'(-p-F)\, vw^{+'}(1-q)u'(\theta v - p) + w^{-'}(q)u'(-p-F)\, vw^+(1-q)u'(\theta v - p) > 0 \\ \Rightarrow & \alpha_p\alpha_{\theta q} - \alpha_{pq}\alpha_\theta > 0 \end{aligned}$$

We conclude that $\frac{\mathrm{d}^2\theta^I}{\mathrm{d}p\mathrm{d}q} > 0$ and that $\epsilon_{_{D^I,p}}$ increases with $q \in [0,1]$ if the distribution $G(\theta)$ satisfies the monotone hazard rate (MHR) property.

C.2. Characterizing the marginal consumer $\theta^L(p, p^L)$, indifferent between legal and illegal consumption

A consumer of type θ deciding between legal and illegal consumption faces a choice between a certain payoff of $\theta bv - p^L$ and the lottery $[-p-F, \theta v - p; q, 1-q]$. Note first that individuals with $\theta \leq 0$ will never purchase cannabis, whether it is legal or not. Second if $\theta v - p \leq \theta bv - p^L$ the only possibility is that the individual buys either the legal product or nothing. Symmetrically if $\theta v - p > 0 > \theta bv - p^L$ the only possibility is that he/she either purchases on the black market or not at all. It implies that a necessary condition for some consumers being willing to purchase cannabis illegally, while others prefer to purchase it legally, is that there exists some $\theta > 0$ such that $\theta v - p > \theta bv - p^L > 0$, or equivalently $\frac{p^L - p}{(b-1)v} > \theta > \frac{p^L}{bv}$. This requires that $\frac{p^L - p}{(b-1)v} > \frac{p^L}{bv}$ or equivalently $p^L > bp$.

C.2.1. Under Expected Utility Theory

If individuals are expected utility maximizers the marginal consumer, indifferent between legal and illegal consumption, solves the following equation: $(1-q)u(\theta v - p) + qu(-p-F) = u\left(\theta bv - p^L\right)$. Let

$$V_1(\theta) \equiv (1-q)u(\theta v - p) + qu(-p-F) - u\left(\theta bv - p^L\right) \tag{C.4}$$

If $\theta^L > 0$ exists, it is such that $V_1(\theta) = 0$.

We deduce that for $\frac{p^L - p}{(b-1)v} > \theta > \frac{p^L}{bv}$, $V_1'(\theta) = (1-q)vu'(\theta v - p) - bvu'\left(\theta bv - p^L\right) < 0$ since u' is decreasing (i.e., u is concave) and $1 - q \leq 1$, $\theta v - p > \theta bv - p^L$, $b > 1$. Hence, if $\theta^L > 0$ exists, it is unique. We have that: $V_1\left(\frac{p^L - p}{(b-1)v}\right) = -q\left[u\left(\frac{p^L - bp}{b-1}\right) - u(-p-F)\right] < 0$. Since $V_1(\theta)$ is decreasing for $\theta \in [\frac{p^L}{bv}, \frac{p^L - p}{(b-1)v}]$, to finish the proof we need to find the condition under which $V_1\left(\frac{p^L}{bv}\right) > 0$. Therefore, whenever

$$(1-q)u\left(\frac{p^L - bp}{b}\right) > -qu(-p-F) \tag{C.5}$$

the equation $V_1(\theta) = 0$ admits a unique solution.

Differentiating equation (C.4) yields $\alpha_q \mathrm{d}q + \alpha_{p^L}\mathrm{d}p^L + \alpha_p \mathrm{d}p + \alpha_F \mathrm{d}F + \alpha_{\theta^L}\mathrm{d}\theta^L + \alpha_b \mathrm{d}d = 0$ with

$$\begin{cases} \alpha_q = u\left(-p-F\right) - u\left(\theta^L v - p\right) & < 0 \\ \alpha_{p^L} = u'\left(\theta^L v - p^L\right) & > 0 \\ \alpha_p = -qu'\left(-p-F\right) - (1-q)u'\left(\theta^L v - p\right) & < 0 \\ \alpha_F = -qu'\left(-p-F\right) & < 0 \\ \alpha_{\theta^L} = v(1-q)u'\left(\theta^L v - p\right) - bvu'\left(\theta^L bv - p^L\right) & < 0 \\ \alpha_b = -\theta^L vu'\left(\theta^L bv - p^L\right) & < 0 \end{cases}$$

It is straightforward to show that θ^L decreases with q, p, F and b, while it increases with p^L.

C.2.2. Under Prospect Theory

Under PT the consumer's reference level of wealth is provided by the risk free option, $\theta bv - p^L$. A potential cannabis consumer deciding between buying from the black market or from the legal sector considers the lottery $[p^L - p - F - \theta bv, p^L - p + \theta(1-b)v; q, 1-q]$. Let

$$V_2(\theta) = w^+(1-q)u\left(p^L - p - (b-1)v\theta\right) + w^-(q)u\left(-p - F - \theta bv + p^L\right). \quad \text{(C.6)}$$

The marginal consumer, $\theta^L(p, p^L)$, indifferent between legal and illegal consumption solves $V_2(\theta) = 0$. We have $V_2'(\theta) = -(b-1)vw^+(1-q)u'\left(\theta(1-b)v - p + p^L\right) - bvw^-(q)u'\left(-p - F - \theta bv + p^L\right) < 0$ since $b \geq 1$ and u is strictly increasing.

We have: $V_2\left(\frac{p^L - p}{(b-1)v}\right) = w^-(q)u\left(p - p^L - (b-1)F\right) < 0$ since $p^L > bp \geq p$. The strict monotonicity of $V_2(\theta)$ implies that θ^L exists and is unique whenever $V_2\left(\frac{p^L}{bv}\right) > 0$. This is equivalent to:

$$w^+(1-q)u\left(\frac{p^L - bp}{b}\right) > -w^-(q)u(-p-F) \quad \text{(C.7)}$$

Condition (C.7) under PT is equivalent to (C.5) under EUT, where the probability weighting function is the identity. In both cases these conditions imply that $\theta^L > 0$ exists and is unique. It is easy to check that the conditions (C.5) and (C.7) are equivalent to $p^L > \tilde{p}^L(p)$ with $\tilde{p}^L(p)$ defined in (1.8), with the probability weighting functions equal to the identity in the case of EUT.

Differentiating equation (C.6) yields: $\alpha_{\theta^L}\mathrm{d}\theta^L + \alpha_q\mathrm{d}q + \alpha_{p^L}\mathrm{d}p^L + \alpha_p\mathrm{d}p + \alpha_F\mathrm{d}F + \alpha_d\mathrm{d}d = 0$ with

$$\begin{cases} \alpha_{\theta^L} = -w^-(q)vu'\left(p^L - p - F - \theta^L bv\right) - w^+(1-q)(d-1)vu'\left(p^L - p + \theta^L(1-b)v\right) & < 0 \\ \alpha_q = w^{-\prime}(q)u\left(p^L - p - F - \theta^L bv\right) - w^{+\prime}(1-q)u\left(p^L - p + \theta^L(1-b)v\right) & < 0 \\ \alpha_{p^L} = w^-(q)u'\left(p^L - p - F - \theta^L bv\right) + w^+(1-q)u'\left(p^L - p + \theta^L(1-b)v\right) & > 0 \\ \alpha_p = -w^-(q)u'\left(p^L - p - F - \theta^L bv\right) - w^+(1-q)u'\left(p^L - p + \theta^L(1-b)v\right) & < 0 \\ \alpha_F = -w^-(q)u'\left(p^L - p - F - \theta^L bv\right) & < 0 \\ \alpha_b = -\theta^L vw^+(1-q)u'\left(p^L - p + \theta^L(1-b)v\right) - \theta vqu'\left(-p - F - \theta bv + p^L\right) & < 0 \end{cases}$$

It is straightforward to show that θ^L decreases with q, p, F and b, while it increases with p^L.

C.3. Consumers facing legalization

C.3.1. Consumer choices

Appendix C.1 characterizes the consumer θ^I indifferent, under prohibition, between not consuming and consuming illegally : $V_I(\theta) = w^+(1-q)u(\theta^I v - p) + w^-(q)u(-p - F) = 0$. Any consumer with type higher than θ^I prefers to purchase cannabis on the black market than not to consume cannabis.

Under legalization, the consumer θ^0, indifferent between legal consumption and no consumption, is characterized by $u\left(\theta^0 bv - p^L\right) = 0$. Any consumer with type higher than $\theta^0 = \frac{p^L}{bv}$ prefers to purchase cannabis legally than not consume cannabis.

Appendix C.2 shows that consumer $\theta^L \in \left[\frac{p^L}{bv}, \frac{p^L - p}{(b-1)v}\right]$, indifferent between legal and illegal consumption, solves under

- Expected Utility Theory: $V_1(\theta) = (1-q)u(\theta v - p) + qu(-p - F) - u\left(\theta bv - p^L\right) = 0$
- Prospect Theory: $V_2(\theta) = w^+(1-q)u\left(p^L - p - \theta(b-1)v\right) + w^-(q)u\left(-p - F - \theta bv + p^L\right) = 0$ With $V_i(\theta)$ $(i = 1, 2)$ decreasing for $\theta \in \left[\frac{p^L}{bv}, \frac{p^L - p}{(b-1)v}\right]$. Any consumer with type higher than θ^L prefers to purchase cannabis legally than illegally.

We next compare the thresholds θ^0, θ^L, and θ^I. Depending on whether the legal price, p^L, is larger than $\tilde{p}^L(p)$ defined in (1.8) or not (i.e., depending whether condition (C.7) holds or not), two cases occur.

Condition (C.7) does not hold ($p^L \leq \tilde{p}^L(p)$): $\theta^L \leq \theta^0 \leq \theta^I$. We have, for $i = 1, 2$, $V_i(\theta^0) = w^+(1-q)u(p^L - bp) + w^-(q)u(-p-F)$, with the weighting functions being the identity function under EUT, while by definition of θ^L, $V_i(\theta^L) = 0$. We deduce that, when condition (C.7) does not hold, $V_i(\theta^0) < 0 = V_i(\theta^L)$, since the function $V_i(\theta)$ is decreasing in θ, $\theta^L \leq \theta^0$. When the legalization environment is such that an individual θ^L indifferent between legal and illegal purchases is of lower type than an individual θ^0 indifferent between legal purchase and no purchase at all, the individual θ^0 retrieves a negative payoff from illegal consumption.

Finally, since $V_i(\theta)$ is strictly increasing in θ, $\theta^0 < \theta^I \Leftrightarrow V_i(\theta^0) = w^+(1-q)u(\frac{p^L - bp}{b}) + w^-(q)u(-p-F) < 0$. We deduce that $\theta^L < \theta^0 \Rightarrow \theta^0 < \theta^I$. Therefore, the condition $w^+(1-q)u(\frac{p^L - bp}{b}) < -w^-(q)u(-p-F)$, which means that (C.7) does not hold, characterizes the legalization environment where $\theta^L < \theta^0 < \theta^I$. For instance, this condition is always true if $p^L = p$, as it leads to $u(\frac{p^L - bp}{b}) = u\left((1-b)p\right) < 0$ since $b > 1$. More generally condition (C.7) does not hold when the price on the legal market adjusted for the product quality, $\frac{p^L}{v}$, is low enough compared to the black market price and the level of repression. In this case the legal market replaces the black market and $\int_{\theta^0}^{\theta^I} g(\theta)\mathrm{d}\theta$ new consumers appear as illustrated in Figure 1.1.

When the probability of arrest and the fine are unchanged, legalization necessarily increases the overall demand for cannabis. Individuals with types lower than θ^0 never purchase cannabis, as they prefer not purchasing cannabis to purchasing both legal and black market cannabis. Individuals with types $\theta^0 < \theta < \theta^I$ prefer purchasing legal cannabis to black market cannabis or to not purchasing cannabis at all. They also prefer not purchasing cannabis to purchasing it illegally. These individuals constitute new customers for the newly legalized cannabis market. The better value for money on the legal market (i.e., the higher b), the lower θ^0 and the more new consumers emerge. Individuals with types $\theta^I < \theta$ always purchase cannabis, whether retail sales are legal or not; nevertheless, they purchase cannabis legally when they can.

Condition (C.7) holds ($p^L > \tilde{p}^L(p)$): $\theta^I < \theta^0 < \theta^L$. The reasoning is similar to the previous case but the inequalities are inverted. Condition (C.7) is equivalent to $V_i(\theta^0) > V_i(\theta^L) = 0$ such that $\theta^0 < \theta^L$ when $w^+(1-q)u(\frac{p^L - bp}{b}) > -w^-(q)u(-p-F)$. Similarly $\theta^I < \theta^0 \Leftrightarrow V_I(\theta^0) = w^+(1-q)u(\frac{p^L - bp}{b}) + w^-(q)u(-p-F) > 0$ such that $\theta^I < \theta^0$ under (C.7).

Here, the quality adjusted price differential between the legal market and the black market is too high for the legal market to entirely replace the black market, given the black market price and the repression parameters. Consumers with a low valuation for cannabis continue to purchase illegally. If the black market did not react to the legalization policy (i.e., assuming p is fixed), there would be no new consumers once the legal market is created and whatever the value of the quality parameter b, the overall demand for cannabis would remain at $1 - G\left(\theta^I\right)$. In practice and as is shown in Appendix C.3.2, the criminals react to the introduction of legal cannabis by lowering their prices p, such that θ^I decreases and new consumers, with a lower valuation for cannabis, appear.

C.3.2. The demand (proof of Proposition 3.4)

The above analysis reveals the following partial equilibrium result.

Lemma. *Everything else being held constant, including the price on the black market, after a legal cannabis market is established, the overall demand for cannabis either increases, if the price of legal cannabis is not too high ($p^L \leq \tilde{p}^L(p)$); otherwise it does not change.*

The black market responds strategically to the legal market by lowering its price to $p^N(p^L)$, the solution of (3.1) computed with $\varepsilon_{D^I,p} = -\frac{\partial D^I(p,p^L)}{\partial p}\frac{p}{D^I(p,p^L)}$, the direct price elasticity of the demand $D^I(p, p^L)$ defined in (1.9), which depends on p^L. The price reaction function of the black market sellers solves the following equation:

$$p(p^L) = \begin{cases} p^N(p^L) & \text{if } \; c \leq p^N(p^L) < \frac{p^L}{b} \\ \varnothing & \text{otherwise} \end{cases} \tag{C.8}$$

Since θ is distributed on $\mathbb{R}$, as long as $p^L < \infty$, there is a positive demand for legal cannabis ($1 - G\left(\theta^L(p, p^L)\right) > 0$).

If $p^L > \tilde{p}^L(p)$ ($\theta^I < \theta^0 < \theta^L$) and other policy parameters (c, b, q, F) are held constant, the demand for the black market product decreases following legalization and the absolute value of the price elasticity of the black market demand increases. Therefore, for any finite legal retail price p^L, the black market price p decreases after legalization. This implies that the demand for cannabis increases (θ^I decreases).

If $p^L \leq \tilde{p}^L(p)$ ($\theta^L \leq \theta^0 \leq \theta^I$), it is obvious that the overall demand for legal cannabis increases following legalization. We deduce that legalization always increases the overall demand for cannabis, when the operation costs of illegal providers, the quality differential and the repression of demand on the black market are held constant.

C.4. Proof of Proposition 1.2

Under Prospect Theory the threshold price, denoted $\underline{p}^L$, below which the criminals exit the market is such that $\theta^L(c, \underline{p}^L) = \theta^I(c)$, where $\theta^I(c)$ and $\theta^L\left(c, \underline{p}^L\right)$ are defined in equations (1.2) and (1.7) with $p = c$. Therefore, $\theta^I(c)$ (or equivalently $\theta^L\left(c, \underline{p}^L\right)$) is determined by the following system of equations:

$$\begin{cases} w^+(1-q)u\left(\theta v - c\right) + w^-(q)u\left(-c-F\right) = 0 \\ w^+(1-q)u\left(\theta v - \theta bv + \underline{p}^L - c\right) + w^-(q)u\left(-\theta bv + \underline{p}^L - c - F\right) = 0 \end{cases}$$

Under Expected Utility Theory, the same reasoning yields the following system of equations

$$\begin{cases} (1-q)u\left(\theta v - c\right) + qu\left(-c-F\right) = 0 \\ (1-q)u\left(\theta v - c\right) + qu\left(-c-F\right) = u\left(\theta bv - p^L\right) \end{cases}$$

In both cases, this yields $\underline{p}^L = dv\theta^I(c)$.

The legal demand is at the same level as if illegal suppliers were pricing at marginal cost:

$$D^L(\underline{p}^L) = \int_{\theta^L(\underline{p}^L,c)}^{+\infty} g(\theta)d\theta = 1 - G\left(\theta^L(\underline{p}^L,c)\right) = 1 - G(\theta^I(c)) = D^I(c). \tag{C.9}$$

C.5. Proof of the corollary of Proposition 3.4

The price $\underline{p}^L = bv\theta^I(c)$ being linear in the quality differential b and the parameters θ^I and v being positive, it is straightforward that $\underline{p}^L$ increases with b. Regarding the other parameters, comparative statics are derived in Appendix C.1 with $p = c$.

Appendix D

First Article
Detail on the Numerical Applications

D.1. Application to Tversky and Kahneman (1992)

Eviction price under Tversky and Kahneman (1992)

In line with Tversky and Kahneman (1992), we assume that $\gamma^+ < \gamma^-$. Substituting the function (B.1) in (C.2), the type θ^I indifferent between consuming illegally and not consuming is given by:

$$\theta^I = \frac{1}{v}\left[\left(\lambda\frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}}(F+p)+p\right] \tag{D.1}$$

This implies that:

$$\frac{\partial\theta^I}{\partial p} = \frac{1}{v}\left[\left(\lambda\frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}}+1\right] > 0$$

Let us note $\omega(q) \equiv \frac{w^-(q)}{w^+(1-q)}$, which is strictly increasing since w^x is increasing for $x = +, -$. It yields:

$$\frac{\partial\theta^I}{\partial q} = \frac{\lambda^{\frac{1}{\alpha}}(F+p)}{\alpha v}\omega'(q)\left[\omega(q)\right]^{\frac{1-\alpha}{\alpha}} > 0.$$

We deduce that the eviction price $\underline{p}^L = bv\theta^I(c)$ under Tversky and Kahneman (1992)'s specification is:

$$\underline{p}^L = b\left[\left(\lambda\frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}}(F+c)+c\right]. \tag{D.2}$$

Static comparative of the eviction price

We now study how the eviction price varies when the policy parameters change.

- $$\frac{\partial \underline{p}^L}{\partial F} = b\left(\lambda \frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}} > 0$$

- $$\frac{\partial \underline{p}^L}{\partial c} = b\left[\left(\lambda \frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}} + 1\right] > 0$$

- $$\frac{\partial \underline{p}^L}{\partial b} = \left[\left(\lambda \frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}} (F+c) + c\right] > 0$$

- $$\frac{\partial \underline{p}^L}{\partial q} = -b\frac{(F+c)\lambda^{\frac{1}{\alpha}}}{\alpha}\frac{\omega'(q)}{\omega^2(q)} > 0$$

Marginal consumer indifferent between legal and illegal consumption

Under the Tversky and Kahneman (1992) specification, one can solve for the type θ^L indifferent between consuming legal and black market cannabis, substituting the function (B.1) in equation (1.7). This parameter is given as follows.

$$\theta^L = \left[\left(\lambda \frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}} b + b - 1\right]^{-1} \left[\left(p^L - p\right)\left(1 + \left(\lambda \frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}}\right) - \left(\lambda \frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}} F\right] \tag{D.3}$$

D.2. The policy mix: a numerical application

This Appendix completes the policy implications discussed in Section 5 with further explanations of the calibrations, as well as with further sensitivity analyses of the *post-legalization* equilibrium to the behavioral and policy parameters.

D.2.1. Calibration of the distribution of "taste" for cannabis

We calibrate the distribution of the "taste" for cannabis using our model and the literature on demand for cannabis, which estimates the range of price elasticities of demand, $\epsilon_{D^I p}$, between -0.5 and -0.8. Let us assume the "taste" for cannabis, $\theta \in \mathbb{R}$, is drawn from a normal distribution $\mathcal{N}(\mu, \sigma^2)$. The expression of the price elasticity of demand in equation (1.4) becomes

$$\epsilon_{D^I p} = \frac{p}{v}\left[\left(\lambda \frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}} + 1\right] \frac{1}{\sigma\sqrt{2\pi}} \frac{e^{\frac{-(\theta^I-\mu)^2}{2\sigma^2}}}{1-\phi(\frac{\theta^I-\mu}{\sigma})} \tag{D.4}$$

In 2017, 15% of Americans are estimated to have used cannabis in the past year (CBHSQ, 2018). This margin is simply given by:

$$\varsigma = 1 - \phi\left(\frac{\theta^I - \mu}{\sigma}\right) \tag{D.5}$$

Using the estimates of ϵ and ς discussed in the literature, we calibrate the parameters μ and σ solving the system defined by equations (D.4) and (D.5), normalizing $v \equiv 1$ and using the benchmark values for the model parameters described in Section 5.1. Using an iterative solver, we obtain the set of solutions described in Table D.1 for μ and σ, as well as the benchmark values for the *post-legalization* increase in consumption implementing the eviction price $\underline{p}^L = 97.79$ [1], $\Delta\%D\left(\underline{p}^L\right)$. As the demand becomes more inelastic, the distribution tail becomes fatter and the mean taste lower. The more inelastic the demand, the lower the *post-legalization* increase in demand.

TABLE D.1. Distribution parameters and *post-legalization* increases in consumption

$\epsilon_{D^I p}$	$\hat{\mu}$	$\hat{\sigma}$	$\Delta\%D\left(\underline{p}^L\right)$
0.5	-690.4	1065.8	53%
0.6	-506.3	888.1	65%
0.7	-374.8	761.3	78%
0.8	-276.2	666.1	91%

Notes: Behavioral parameters are set based on Tversky and Kahneman (1992): $\lambda = 2.25$, $\alpha = 0.88$, $\gamma^+ = 0.61$, $\gamma^- = 0.69$. Variation in demand relies on the baseline estimate of $\underline{p}^L = 97.79$.

The sensitivity of the distribution parameters and of the predictions of the models to the behavioral parameters γ^+, γ^-, α and λ is discussed in Appendix D.2.2. This Appendix also shows that small variations around the values calibrated by Tversky and Kahneman (1992) induce relatively little change in the predicted policy price $\underline{p}^L$ and subsequent increases in consumption.

D.2.2. Sensitivity analysis of $\underline{p}^L$ to the behavioral parameters

Policy parameters are set at benchmark values $q_L = 0.1\%$, $F = 1,000$, $b = 1.58$, and $c = 50$. Prices and costs are for one ounce of cannabis. $\Delta\%D\left(\underline{p}^L\right)$ is the percentage

1. This eviction price assumes that, under legalization, the probability of arrest is ten times smaller ($q_L = 0.1\%$) than under prohibition ($q = 1\%$); and that the marginal cost on the black market is USD 50 *post-legalization*.

Table D.2. Sensitivity of eviction price and demand to behavioral parameters for $\epsilon = -0.5$

parameter	variation	$\hat{\mu}$	$\hat{\sigma}$	$\underline{p}^L$	$\Delta\%D\left(\underline{p}^L\right)$
$\gamma^+ = 0.61$	+10%	0.1%	-0.22%	-0.21%	-0.3%
	+5%	0.06%	-0.12%	-0.12%	-0.16%
	-5%	-0.06%	0.15%	0.16%	0.2%
	-10%	-0.14%	0.33%	0.36%	0.46%
$\gamma^- = 0.69$	+10%	0.86%	-1.91%	-7.97%	-2.63%
	+5%	0.47%	-1.03%	-4.51%	-1.41%
	-5%	-0.53%	1.19%	5.86%	1.61%
	-10%	-1.15%	2.57%	13.45%	3.44%
$\alpha = 0.88$	+10%	-0.8%	1.8%	9.66%	2.43%
	+5%	-0.39%	0.89%	4.57%	1.21%
	-5%	0.39%	-0.87%	-4.04%	-1.18%
	-10%	0.77%	-1.7%	-7.54%	-2.33%
$\lambda = 2.25$	+10%	-0.33%	0.76%	2.2%	1.03%
	+5%	-0.16%	0.38%	1.1%	0.52%
	-5%	0.18%	-0.38%	-1.09%	-0.51%
	-10%	0.34%	-0.75%	-2.17%	-1.03%

Benchmark values in column 1 are $\hat{\mu} = -690.4$, $\hat{\sigma} = 1065.8$, $\underline{p}^L = 97.79$ and $\Delta\%D\left(\underline{p}^L\right) = 53.18\%$.

predicted increase in consumption following a legalization process that drives dealers out of business.

We study the sensitivity of the eviction price, $\underline{p}^L$, to the exogenous behavioral parameters γ^+, γ^-, α and λ. The benchmark values are: $\alpha = 0.88$, $\lambda = 2.25$, $\gamma^+ = 0.61$ and $\gamma^- = 0.69$.

Tables D.2 to D.5 present in columns 3 and 4 the sensitivity of the distribution parameters, and in columns 5 and 6 the sensitivity of both the eviction price and the subsequent increase in consumption *post-legalization*. The magnitude of variations of the behavioral parameters around the benchmark values are presented in column 2.

Overall, the distribution parameters are not very sensitive to the variations in the behavioral parameters: variations in the behavioral parameters by 10% entail variations in the distribution parameters of less than 8% for most cases. The policy price seems fairly sensitive to the parameter γ^-: a 10% variation in this parameter causes a change in price of up to 13.5%. This is also true for the parameter α. Finally, *post-legalization* cannabis consumption is not very responsive to small variations in the behavioral parameters (by less than 10%) as it changes by less than 2% in most cases.

TABLE D.3. Sensitivity of eviction price and demand to behavioral parameters for $\epsilon = -0.6$

parameter	variation	$\hat{\mu}$	$\hat{\sigma}$	$\underline{p}^L$	$\Delta\%D\left(\underline{p}^L\right)$
$\gamma^+ = 0.61$	+10%	0.22%	-0.21%	-0.21%	-0.34%
	+5%	0.13%	-0.12%	-0.12%	-0.19%
	-5%	-0.14%	0.15%	0.16%	0.24%
	-10%	-0.32%	0.34%	0.36%	0.53%
$\gamma^- = 0.69$	+10%	1.87%	-1.91%	-7.97%	-3.05%
	+5%	1.01%	-1.03%	-4.51%	-1.63%
	-5%	-1.16%	1.2%	5.86%	1.87%
	-10%	-2.5%	2.57%	13.45%	3.99%
$\alpha = 0.88$	+10%	-1.75%	1.81%	9.66%	2.82%
	+5%	-0.86%	0.9%	4.57%	1.4%
	-5%	0.85%	-0.86%	-4.04%	-1.37%
	-10%	1.66%	-1.69%	-7.54%	-2.7%
$\lambda = 2.25$	+10%	-0.73%	0.77%	2.2%	1.2%
	+5%	-0.36%	0.38%	1.1%	0.6%
	-5%	0.38%	-0.37%	-1.09%	-0.6%
	-10%	0.74%	-0.75%	-2.17%	-1.19%

Benchmark values in column 1 $\hat{\mu} = -506.3$, $\hat{\sigma} = 888.1$, $\underline{p}^L = 97.79$ and $\Delta\%D\left(\underline{p}^L\right) = 65.45\%$.

D.2.3. Sensitivity analysis to policy parameters

To illustrate how governments may use a combination of policy instruments to regulate the market for cannabis *post-legalization*, Table D.6 exploits combined variations in several policy parameters.

The first row presents the current benchmark values for the different policy parameters, the recommended legal price $\underline{p}^L$ and the *post-legalization* increase in the extensive margin of consumption.

Rows 2 to 5 present scenarios in which the government certifies the quality of legal cannabis, such that b goes up to 2, and does not invest a lot in detecting illegal purchases, such that the probability of arrest q is half the benchmark value, but doubles the fines for illegal purchase (F=2000). At the same time it may choose or not to enforce repression against illegal providers, the marginal cost c varying from 15 – i.e. less than a third of the benchmark value – to 200 – i.e. four times the benchmark value. Simulations show that the government is able to contain consumption at the *pre-legalization* level when the marginal cost is four times the benchmark value ($c = 200$).

Rows 6 to 11 show that investing in quality differentiation (increasing b) is effective at reducing cannabis consumption. Even with lax enforcement of arrest of illegal users

Table D.4. Sensitivity of eviction price and demand to behavioral parameters for $\epsilon = -0.7$

parameter	variation	$\hat{\mu}$	$\hat{\sigma}$	$\underline{p}^L$	$\Delta\%D\left(\underline{p}^L\right)$
$\gamma^+ = 0.61$	+10%	0.37%	-0.22%	-0.21%	-0.39%
	+5%	0.21%	-0.12%	-0.12%	-0.21%
	-5%	-0.24%	0.14%	0.16%	0.27%
	-10%	-0.55%	0.33%	0.36%	0.6%
$\gamma^- = 0.69$	+10%	3.2%	-1.92%	-7.97%	-3.43%
	+5%	1.73%	-1.03%	-4.51%	-1.84%
	-5%	-1.98%	1.19%	5.86%	2.11%
	-10%	-4.27%	2.56%	13.45%	4.49%
$\alpha = 0.88$	+10%	-3.0%	1.8%	9.66%	3.17%
	+5%	-1.48%	0.89%	4.57%	1.58%
	-5%	1.45%	-0.87%	-4.04%	-1.54%
	-10%	2.84%	-1.7%	-7.54%	-3.03%
$\lambda = 2.25$	+10%	-1.26%	0.76%	2.2%	1.35%
	+5%	-0.62%	0.37%	1.1%	0.67%
	-5%	0.64%	-0.38%	-1.09%	-0.67%
	-10%	1.27%	-0.76%	-2.17%	-1.34%

Benchmark values in column 1 $\hat{\mu} = -374.8$, $\hat{\sigma} = 761.3$, $\underline{p}^L = 97.79$ and $\Delta\%D(\underline{p}^L) = 78.23\%$.

($q = 0.05\%$), row 11 shows that limiting the consumption increase *post-legalization* can be achieved by investing in quality differentiation and certification of legal cannabis, such that $b = 4$.

Rows 12 to 16 show simulations of policies which increase repression on the demand side through various intensities of arrests q and fine amounts F, while the other parameters are kept at benchmark values. While increasing the level of fines seems to be an effective way to limit *post-legalization* consumption, high fines may be neither cost-effective nor fair, especially to low income users. Similarly, increased enforcement of arrests combined with statistical discrimination may also result in an uneven burden on some populations.

The fourth part of the table (rows 17 to 25) presents results where the *post-legalization* consumption is contained around the *pre-legalization* level. They highlight that a government aiming at controlling cannabis consumption through legalization would have to invest in strict repression of either the supply or the demand side, as well as in product differentiation, certification and information campaigns. For instance, a legalization policy combined with significant investments in quality differentiation of legal cannabis ($b = 2$) and increased fines for illegal consumption up to USD 4000 would

TABLE D.5. Sensitivity of eviction price and demand to the behavioral parameters for $\epsilon = -0.8$

parameter	variation	$\hat{\mu}$	$\hat{\sigma}$	$\underline{p}^L$	$\Delta\%D\left(\underline{p}^L\right)$
$\gamma^+ = 0.61$	+10%	0.58%	-0.22%	-0.21%	-0.42%
	+5%	0.32%	-0.12%	-0.12%	-0.23%
	-5%	-0.38%	0.15%	0.16%	0.29%
	-10%	-0.88%	0.34%	0.36%	0.66%
$\gamma^- = 0.69$	+10%	5.02%	-1.91%	-7.97%	-3.78%
	+5%	2.71%	-1.03%	-4.51%	-2.02%
	-5%	-3.12%	1.2%	5.86%	2.32%
	-10%	-6.72%	2.57%	13.45%	4.95%
$\alpha = 0.88$	+10%	-4.73%	1.81%	9.66%	3.5%
	+5%	-2.33%	0.89%	4.57%	1.74%
	-5%	2.27%	-0.86%	-4.04%	-1.7%
	-10%	4.44%	-1.69%	-7.54%	-3.34%
$\lambda = 2.25$	+10%	-1.99%	0.76%	2.2%	1.48%
	+5%	-0.99%	0.38%	1.1%	0.74%
	-5%	1.0%	-0.38%	-1.09%	-0.74%
	-10%	1.98%	-0.75%	-2.17%	-1.47%

Benchmark values in column 1 $\hat{\mu} = -276.2$, $\hat{\sigma} = 666.1$, $\underline{p}^L = 97.79$, $\Delta\%D(\underline{p}^L) = 91.49\%$.

lead to the eviction price of USD 430 per ounce, decreasing cannabis consumption by 2.35% to 3.75%.

The last exercise illustrates an extreme case of no differentiation between legal and illegal products in a liberal state without repression on the demand and supply sides of the market, thus pricing legal cannabis at the marginal cost of production, which is the same on the illegal market. The absence of regulation results in large increases in *post-legalization* consumption, larger than 50% in most scenarios and more than 100% with large price elasticities of demand or low production costs.

D.2.4. On the existence of θ^L when $b < 1$

In the theory, for the sake of simplicity, we prove the existence and uniqueness of θ^L under the sufficient condition $b \geq 1$. However, this condition is not necessary.

Take the weighting and value functions calibrated in Tversky and Kahneman (1992), as well as $v = 1$. In this case,

$$\underline{p}^L = b\left[\left(\lambda\frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}}(F+c)+c\right],$$

Table D.6. Sensitivity analysis of eviction price and post-legalization demand

Policy parameters				Eviction Price	Increase in Demand			
c	b	q	F	$\underline{p}^L$	$\epsilon = -0.5$	$\epsilon = -0.6$	$\epsilon = -0.7$	$\epsilon = -0.8$
50	1.58	0.1%	1000.0	97.79	53%	65%	78%	91%
15	2.00	0.05%	2000.0	56.39	61%	75%	90%	106%
25	2.00	0.05%	2000.0	76.52	57%	71%	84%	99%
100	2.00	0.05%	2000.0	227.5	30%	36%	43%	50%
200	2.00	0.05%	2000.0	428.81	-2%	-3%	-3%	-3%
50	1.00	0.05%	1000.0	56.88	61%	75%	90%	106%
50	1.25	0.05%	1000.0	71.09	58%	72%	86%	101%
50	1.58	0.05%	1000.0	89.86	55%	67%	81%	94%
50	2.00	0.05%	1000.0	113.75	50%	62%	74%	86%
50	3.00	0.05%	1000.0	170.63	40%	49%	58%	67%
50	4.00	0.05%	1000.0	227.5	30%	36%	43%	50%
50	1.58	0.05%	1000.0	89.86	55%	67%	81%	94%
50	1.58	0.1%	2000.0	115.68	50%	61%	73%	85%
50	1.58	0.05%	3000.0	110.55	51%	62%	75%	87%
50	1.58	0.2%	500.0	96.06	54%	66%	79%	92%
50	1.58	0.5%	5000.0	404.51	1%	2%	2%	2%
50	2.00	1.0%	2000.0	392.45	3%	4%	5%	5%
100	1.58	1.5%	1500.0	408.79	1%	1%	1%	1%
50	2.00	0.5%	4000.0	430.44	-2%	-3%	-3%	-4%
100	2.25	1.0%	1000.0	401.54	2%	2%	3%	3%
15	2.50	1.0%	2000.0	396.82	3%	3%	4%	4%
15	1.58	0.5%	6000.0	411.41	0%	0%	1%	1%
25	1.25	2.0%	2500.0	427.67	-2%	-2%	-3%	-3%
50	1.58	2.0%	1500.0	386.59	4%	5%	6%	7%
50	3.00	1.0%	1000.0	374.68	6%	7%	8%	9%
15	1.00	0%	-	15.0	69%	86%	103%	121%
25	1.00	0%	-	25.0	67%	83%	100%	117%
50	1.00	0%	-	50.0	62%	77%	92%	108%
75	1.00	0%	-	75.0	58%	71%	85%	99%
100	1.00	0%	-	100.0	53%	65%	78%	91%
125	1.00	0%	-	125.0	48%	59%	70%	82%

Notes: Behavioral parameters are set at values calibrated by Tversky and Kahneman (1992): $\lambda = 2.25$, $\alpha = 0.88$, $\gamma^+ = 0.61$, and $\gamma^- = 0.69$. Variation in demand relies on the baseline estimates for the parameters of the distribution of θ corresponding to different price elasticities of demand, as described in Table D.1.

while

$$\theta^L = \left[\left(\lambda \frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}} b + b - 1\right]^{-1} \left[\left(\lambda \frac{w^-(q)}{w^+(1-q)}\right)^{\frac{1}{\alpha}} \left(p^L - p - F\right) + p^L - p\right];$$

which does not require that $b \geq 1$. For instance, when $c = 50$, $b = 0.5$, $q = 0.1\%$ and $F = 1000$, the legal price threshold $\underline{p}^L$ is around 31\$ and $\theta^L\left(c, \underline{p}^L\right)$ exists and is unique – it is approximately equal to 61.89.

D.3. Exploring other tools and policy objectives

D.3.1. Survival of the black market

After the government chooses the price of the legal cannabis, $p^L = (1+\tau)c^L$, the repression (i.e. the probability of arrest q, the fine F and the increase in marginal cost to produce illegally $\delta \geq 0$), as well as the quality differential between legal and illegal products, $b \geq 1$, the consumers decide whether to consume or not, and on which market. From here, two cases may occur.

(1) Taxes are set low enough such that, given the level of repression on both the demand and supply sides and the quality differential, the black market does not survive. In this case τ satisfies $1+\tau \leq bv\frac{\theta^I\left((1+\delta)c^L\right)}{c^L}$ where $\theta^I\left((1+\delta)c^L\right)$ is defined in (1.2). Let $\theta^0 = \frac{(1+\tau)c^L}{vb}$ be the agent indifferent between consuming legal cannabis at price $p^L = (1+\tau)c^L$ and not consuming. The demand for (legal) cannabis is given by: $D^L\left((1+\tau)c^L\right) = 1 - G\left(\frac{(1+\tau)c^L}{vb}\right)$.

(2) If the government sets taxes too high, such that $(1+\tau)c^L > bv\theta^I\left((1+\delta)c^L\right)$, then the demand is split between the legal and illegal markets, as follows:

$$D^L\left(p, (1+\tau)c^L|b\right) = 1 - G\left(\theta^L\left(p, (1+\tau)c^L|b\right)\right)$$

$$D^I\left(p, (1+\tau)c^L|b\right) = G\left(\theta^L\left(p, (1+\tau)c^L|b\right)\right) - G\left(\theta^I\left(p\right)\right)$$

where $\theta^I(p)$ is defined in (1.2) and $\theta^L\left(p, (1+\tau)c^L|b\right)$ in (1.7). Illegal providers set the black market price p as defined in (3.1). The price reaction function of the illegal sector is analogous to the best response described in (1.10) with $p^L = (1+\tau)c^L$.

D.3.2. Maximizing tax revenue when θ follows an exponential distribution

Let us assume that on the positive real line, θ follows an exponential distribution $G(\theta) \equiv 1 - e^{-\eta\theta}$, with $0 < \eta < 1$, (1.17) becomes

$$1 = \eta c^L \tau \frac{\partial \theta^l}{\partial p^L}. \tag{D.6}$$

If the black market has been initially shut down, then (D.6) yields $\tau_0^{\alpha_T} = \frac{bv}{\eta c^L}$. If the black market is not shut down, with risk-neutral consumers we have $\theta^L = \frac{p^L - p - qF}{(b+q-1)v}$, so that (D.6) yields: $\tau^{\alpha_T} = \frac{b+q-1}{\eta c^L} v \geq 0$. This is the optimal solution if the demand for cannabis is strictly positive for this level of taxes which requires that $\theta^L(\tau^{\alpha_T}) = \frac{(1+\tau^{\alpha_T})c^L - p - qF}{(b+q-1)v} > 0$. This is equivalent to $\eta < \frac{v(b+q-1)}{qF+p-c^L} \leq \frac{v(b+q-1)}{qF+\delta c^L} = \eta^{\alpha_T}$. We deduce that the unconstrained solution (i.e., in the absence of competition by the black market) leads to a larger excise tax than the constrained solution: $\tau_0^{\alpha_T} \geq \tau^{\alpha_T}$,[2] which is intuitive.

When the government does not have to deal with competition it can impose higher taxes, as the consumers are captive. In both cases, the tax rate increases with vb, the quality of the legal product, and decreases with c^L, the marginal cost of production of legal cannabis, and with η, the distribution of consumers' type parameter. Indeed, a higher η implies that the distribution of taste is skewed towards the low values of θ: few people are willing to pay a high price for cannabis, which implies that the tax rate should be relatively low.

Next, we check under which conditions the optimal tax level τ^{α_T} is such that the final price $p^L(\tau^{\alpha_T}) = (1 + \tau^{\alpha_T})\, c^L$ is lower than the eviction price $\underline{p}^L = bv\theta^I((1+\delta)c^L) = b\frac{(1+\delta)c^L + qF}{1-q}$. Let $\eta^{evic} = \frac{(1-q)(b+q-1)v}{b(\delta c^L + qF) + (b+q-1)c^L} > 0$. It is easy to check that if $\eta \geq \eta^{evic}$, then $p^L(\tau^{\alpha_T}) \leq \underline{p}^L$. Under our assumptions, $0 < \eta^{evic} < \eta^{\alpha_T}$. Only when $\eta^{evic} \leq \eta < \eta^{\alpha_T}$ is it possible to maximize tax revenues while simultaneously eradicating the black market through an eviction price.

Based on the number of users of cannabis worldwide, it is unrealistic to assume that the distribution of tastes for cannabis in the general population is skewed towards the low values of θ (i.e., it is unrealistic to consider large values for η). Yet, if $\eta < \eta^{evic} < \eta^{\alpha_T}$, then the price that maximizes tax revenue is higher than the eviction price. In other words, when there is a large demand for cannabis, maximizing tax revenue implies setting the price of the legal products relatively high, such that the black market can survive by selling illegal cannabis at a discount.

D.3.3. Maximizing tax revenues: a numerical application

This section provides detail on the tax policy application discussed in Section 6. It also presents the results for the other values of the price demand elasticity, as well as other examples, where there is very lax enforcement on the demand side of the market, leading to a probability of arrest close to zero, $q = 0$.

2. They are equal only when $q = 1$.

Table D.7. Legalization price and resulting demand when the government maximizes tax revenue ($\epsilon = -0.5$)

	Policy parameters				Equilibrium prices		Equilibrium demand and revenue			Eviction scenario		
$\frac{1}{N}$	c	b	q	F	p	p^L	$\Delta\%D\left(p,p^L\right)$	$s^I\left(p,p^L\right)$	R	$\underline{p}^L$	$\Delta\%D\left(\underline{p}^L\right)$	$\underline{R}$
0.55	50	1.58	0.1%	1000	122.89	417.78	-1%	38%	363	97.79	60%	119
0.55	25	1.58	0.1%	1000	106.32	413.84	-3%	41%	348	57.84	65%	55
0.55	125	1.58	0.1%	1000	172.96	430.04	5%	27%	412	217.63	46%	286
0.55	200	1.58	0.1%	1000	223.61	442.94	12%	15%	466	337.47	32%	421
0.10	50	1.58	0.1%	1000	68.37	404.99	-7%	48%	315	97.79	60%	119
0.25	50	1.58	0.1%	1000	90.64	410.15	-5%	44%	334	97.79	60%	119
0.75	50	1.58	0.1%	1000	138.60	421.58	1%	35%	378	97.79	60%	119
1.00	50	1.58	0.1%	1000	154.09	425.36	3%	31%	393	97.79	60%	119
0.55	50	1.00	0.1%	1000	53.11	65.03	59%	0%	65	61.89	60%	60
0.55	50	1.10	0.1%	1000	62.68	106.11	25%	24%	99	68.08	60%	70
0.55	50	1.30	0.1%	1000	94.38	237.41	7%	35%	213	80.46	60%	90
0.55	50	1.80	0.1%	1000	137.95	557.87	-4%	39%	475	111.41	60%	141
0.55	50	1.58	0.2%	1000	120.48	424.13	-1%	37%	372	111.56	58%	140
0.55	50	1.58	0.5%	1000	114.49	439.87	0%	34%	394	146.68	54%	191
0.55	50	1.58	1.0%	1000	106.15	461.47	2%	30%	424	197.33	48%	260
0.55	50	1.58	0.0%	1000	126.22	408.95	-2%	39%	351	79.00	62%	89
0.55	50	1.58	0.1%	100	126.28	416.18	-2%	39%	357	81.68	62%	94
0.55	50	1.58	0.1%	500	124.77	416.89	-1%	39%	360	88.84	61%	105
0.55	50	1.58	0.1%	1500	121.01	418.68	-1%	37%	367	106.74	59%	132
0.55	50	1.58	0.1%	2000	119.13	419.57	0%	36%	370	115.68	58%	146

Notes: The above results are based on a price demand elasticity of 0.5 and the corresponding distribution parameters (see Table D.1). The marginal cost on the legal market, c^L, is USD 25 per ounce. The tax revenue in USD *per capita* and *per annum* is given as the product of the difference $p^L - c^L$ with the extensive and intensive margins of consumption. The intensive margin is approximated using Orens et al. (2018) estimates for consumption in Colorado in 2017.

The methodology of this numerical exercise relies on the same principle as in Section 5 and Appendix D.2, as well as the calibration results of Appendix D.1. We use an iterative solver on the system of equations (1.17) and (1.10) with $p^L = (1+\tau)c^L$.

Results with elasticities varying from -0.7 to -0.5. We present, in Tables D.7 to D.9, the results of the numerical exercise from Section 6 for higher values of the demand price elasticity (-0.5, -0.6 and -0.7). As expected, the more inelastic the demand, the higher the equilibrium prices and the government revenue. Again we find that the price maximizing tax revenue is generally well above the eviction price (except when the quality is the same on both markets) and the corresponding extensive margins of consumption are of the same magnitude.

Results with $q = 0$. We detail in Tables D.10 to D.13 scenarios where consumers going to the illegal market are not arrested. Since the case where $b = 1$ and $q = 0$ yields perfect competition between the legal and the illegal markets, we prefer to present a case where there is very little quality differentiation ($b = 1.01$), rather than no differentiation. When there are no arrests on the demand side, individuals are all the more sensitive to quality. For a government maximizing tax revenue, quality has a large influence on the optimal price: when the quality differential is 1.01, the equilibrium

Table D.8. Legalization price and resulting demand when the government maximizes tax revenue ($\epsilon = -0.6$)

$\frac{1}{N}$	Policy parameters				Equilibrium prices		Equilibrium demand and revenue			Eviction scenario		
	c	b	q	F	p	p^L	$\Delta\%D\left(p,p^L\right)$	$s^I\left(p,p^L\right)$	R	$\underline{p}^L$	$\Delta\%D\left(\underline{p}^L\right)$	$\underline{\text{R}}$
0.55	50	1.58	0.1%	1000	110.50	363.72	10%	37%	348	97.79	74%	129
0.55	25	1.58	0.1%	1000	93.89	359.59	7%	41%	331	57.84	80%	60
0.55	125	1.58	0.1%	1000	160.82	376.65	18%	24%	403	217.63	56%	306
0.55	200	1.58	0.1%	1000	211.81	390.40	26%	9%	464	337.47	39%	443
0.10	50	1.58	0.1%	1000	65.21	352.61	3%	47%	304	97.79	74%	129
0.25	50	1.58	0.1%	1000	83.68	357.08	6%	43%	321	97.79	74%	129
0.75	50	1.58	0.1%	1000	123.60	367.03	12%	34%	362	97.79	74%	129
1.00	50	1.58	0.1%	1000	136.54	370.34	14%	30%	376	97.79	74%	129
0.55	50	1.00	0.1%	1000	51.86	63.69	74%	0%	68	61.89	74%	65
0.55	50	1.10	0.1%	1000	59.24	96.04	41%	21%	98	68.08	74%	76
0.55	50	1.30	0.1%	1000	86.15	208.78	18%	33%	206	80.46	74%	98
0.55	50	1.80	0.1%	1000	123.41	484.03	6%	38%	454	111.41	74%	153
0.55	50	1.58	0.2%	1000	108.07	369.42	10%	36%	357	111.56	72%	152
0.55	50	1.58	0.5%	1000	102.03	383.54	12%	32%	380	146.68	67%	207
0.55	50	1.58	1.0%	1000	93.64	402.94	13%	28%	412	197.33	59%	279
0.55	50	1.58	0.0%	1000	113.88	355.81	9%	38%	335	79.00	77%	97
0.55	50	1.58	0.1%	100	113.87	362.05	9%	38%	341	81.68	77%	102
0.55	50	1.58	0.1%	500	112.38	362.79	9%	38%	344	88.84	75%	114
0.55	50	1.58	0.1%	1500	108.64	364.66	10%	36%	352	106.74	73%	144
0.55	50	1.58	0.1%	2000	106.77	365.60	11%	35%	356	115.68	71%	158

Notes: The above results are based on a price demand elasticity of 0.6 and the corresponding distribution parameters (see Table D.1). The marginal cost on the legal market, c^L, is USD 25 per ounce. The tax revenue in USD *per capita* and *per annum* is given as the product of the difference $p^L - c^L$ with the extensive and intensive margins of consumption. The intensive margin is approximated using Orens et al. (2018) estimates for consumption in Colorado in 2017.

price on the legal market, p^L, is between USD 54 and 57 per ounce, depending on the elasticity; when $b = 1.80$, this price rises up to USD 387 to 549 per ounce.

Table D.13. Legalization price and resulting demand when the government maximizes tax revenue and $q = 0$, for $\epsilon = -0.8$

$\frac{1}{N}$	Policy parameters		Equilibrium prices		Equilibrium demand and revenue			Eviction scenario		
	c	b	p	p^L	$\Delta\%D\left(p,p^L\right)$	$s^I\left(p,p^L\right)$	R	$\underline{p}^L$	$\Delta\%D\left(\underline{p}^L\right)$	$\underline{\text{R}}$
0.55	50	1.58	98.73	290.60	91%	37%	327	79.0	108%	115
0.55	25	1.58	82.06	286.12	97%	41%	307	39.5	117%	32
0.55	125	1.58	149.39	304.83	74%	21%	393	197.5	82%	320
0.55	200	1.58	200.96	320.27	58%	1%	471	316.0	58%	469
0.10	50	1.58	62.22	280.90	104%	47%	284	79.0	108%	115
0.25	50	1.58	77.08	284.80	99%	43%	301	79.0	108%	115
0.75	50	1.58	109.34	293.51	88%	34%	340	79.0	108%	115
1.00	50	1.58	119.85	296.42	84%	31%	353	79.0	108%	115
0.55	50	1.01	56.78	57.33	106%	0%	68	50.5	108%	54
0.55	50	1.10	57.17	76.48	106%	22%	84	55.0	108%	64
0.55	50	1.30	78.97	166.77	98%	34%	189	65.0	108%	85
0.55	50	1.80	109.22	386.64	88%	38%	429	90.0	108%	138

Notes: The above results are based on a price demand elasticity of 0.8 and the corresponding distribution parameters (see Table D.1). The marginal cost on the legal market, c^L, is USD 25 per ounce. The tax revenue in USD *per capita* and *per annum* is given as the product of the difference $p^L - c^L$ with the extensive and intensive margins of consumption. The intensive margin is approximated using Orens et al. (2018) estimates for consumption in Colorado in 2017.

Table D.9. Legalization price and resulting demand when the government maximizes tax revenue ($\epsilon = -0.7$)

$\frac{1}{N}$	Policy parameters c	b	q	F	Equilibrium prices p	p^L	Equilibrium demand and revenue $\Delta\%D\left(p,p^L\right)$	$s^I\left(p,p^L\right)$	R	Eviction scenario $\underline{p}^L$	$\Delta\%D\left(\underline{p}^L\right)$	$\underline{\mathrm{R}}$
0.55	50	1.58	0.1%	1000	101.78	325.65	21%	36%	342	97.79	89%	140
0.55	25	1.58	0.1%	1000	85.11	321.32	18%	40%	323	57.84	96%	66
0.55	125	1.58	0.1%	1000	152.34	339.28	31%	21%	403	217.63	67%	328
0.55	200	1.58	0.1%	1000	203.66	353.91	42%	3%	473	337.47	47%	467
0.10	50	1.58	0.1%	1000	62.98	315.69	14%	45%	300	97.79	89%	140
0.25	50	1.58	0.1%	1000	78.78	319.69	17%	42%	316	97.79	89%	140
0.75	50	1.58	0.1%	1000	113.04	328.62	23%	33%	355	97.79	89%	140
1.00	50	1.58	0.1%	1000	124.19	331.60	25%	30%	368	97.79	89%	140
0.55	50	1.00	0.1%	1000	57.06	69.03	87%	0%	84	61.89	89%	71
0.55	50	1.10	0.1%	1000	56.88	89.07	58%	18%	100	68.08	89%	83
0.55	50	1.30	0.1%	1000	80.38	188.68	31%	32%	204	80.46	89%	107
0.55	50	1.80	0.1%	1000	113.15	431.97	17%	37%	445	111.41	89%	166
0.55	50	1.58	0.2%	1000	99.34	330.90	22%	34%	351	111.56	86%	164
0.55	50	1.58	0.5%	1000	93.27	343.94	23%	31%	376	146.68	80%	223
0.55	50	1.58	1.0%	1000	84.87	361.86	25%	26%	409	197.33	71%	299
0.55	50	1.58	0.0%	1000	105.18	318.35	20%	38%	328	79.00	92%	106
0.55	50	1.58	0.1%	100	105.13	323.89	20%	37%	334	81.68	92%	111
0.55	50	1.58	0.1%	500	103.64	324.67	20%	37%	337	88.84	90%	124
0.55	50	1.58	0.1%	1500	99.93	326.63	22%	35%	346	106.74	87%	156
0.55	50	1.58	0.1%	2000	98.08	327.62	22%	34%	350	115.68	85%	171

Notes: The above results are based on a price demand elasticity of 0.7 and the corresponding distribution parameters (see Table D.1). The marginal cost on the legal market, c^L, is USD 25 per ounce. The tax revenue in USD *per capita* and *per annum* is given as the product of the difference $p^L - c^L$ with the extensive and intensive margins of consumption. The intensive margin is approximated using Orens et al. (2018) estimates for consumption in Colorado in 2017.

Table D.10. Legalization price and resulting demand when the government maximizes tax revenue and $q = 0$, for $\epsilon = -0.5$

$\frac{1}{N}$	Policy parameters c	b	Equilibrium prices p	p^L	Equilibrium demand and revenue $\Delta\%D\left(p,p^L\right)$	$s^I\left(p,p^L\right)$	R	Eviction scenario $\underline{p}^L$	$\Delta\%D\left(\underline{p}^L\right)$	$\underline{\mathrm{R}}$
0.55	50	1.58	126.22	408.95	48%	39%	351	79.0	62%	89
0.55	25	1.58	109.70	405.04	51%	43%	336	39.5	67%	25
0.55	125	1.58	176.18	421.13	39%	29%	399	197.5	48%	260
0.55	200	1.58	226.76	433.97	30%	16%	452	316.0	34%	399
0.10	50	1.58	69.26	395.67	59%	50%	302	79.0	62%	89
0.25	50	1.58	92.55	401.03	54%	46%	321	79.0	62%	89
0.75	50	1.58	142.60	412.89	45%	36%	366	79.0	62%	89
1.00	50	1.58	158.75	416.82	42%	33%	382	79.0	62%	89
0.55	50	1.01	53.84	54.37	62%	0%	48	50.5	62%	42
0.55	50	1.10	64.21	96.67	60%	29%	83	55.0	62%	50
0.55	50	1.30	96.96	228.35	53%	37%	200	65.0	62%	66
0.55	50	1.80	141.64	549.15	45%	40%	463	90.0	62%	108

Notes: The above results are based on a price demand elasticity of 0.5 and the corresponding distribution parameters (see Table D.1). The marginal cost on the legal market, c^L, is USD 25 per ounce. The tax revenue in USD *per capita* and *per annum* is given as the product of the difference $p^L - c^L$ with the extensive and intensive margins of consumption. The intensive margin is approximated using Orens et al. (2018) estimates for consumption in Colorado in 2017.

Table D.11. Legalization price and resulting demand when the government maximizes tax revenue and $q = 0$, for $\epsilon = -0.6$

$\frac{1}{N}$	Policy parameters		Equilibrium prices		Equilibrium demand and revenue			Eviction scenario		
	c	b	p	p^L	$\Delta\%D\left(p,p^L\right)$	$s^I\left(p,p^L\right)$	R	$\underline{p}^L$	$\Delta\%D\left(\underline{p}^L\right)$	$\underline{R}$
0.55	50	1.58	113.88	355.81	62%	38%	335	79.0	77%	97
0.55	25	1.58	97.31	351.71	66%	42%	319	39.5	83%	27
0.55	125	1.58	164.07	368.64	50%	26%	389	197.5	59%	280
0.55	200	1.58	214.98	382.30	39%	11%	450	316.0	42%	421
0.10	50	1.58	66.10	344.17	73%	49%	289	79.0	77%	97
0.25	50	1.58	85.61	348.86	68%	45%	308	79.0	77%	97
0.75	50	1.58	127.66	359.27	58%	35%	350	79.0	77%	97
1.00	50	1.58	141.27	362.73	55%	32%	364	79.0	77%	97
0.55	50	1.01	53.56	54.08	76%	0%	52	50.5	77%	46
0.55	50	1.10	61.00	87.50	74%	26%	82	55.0	77%	54
0.55	50	1.30	88.87	200.65	68%	36%	192	65.0	77%	72
0.55	50	1.80	127.09	476.21	59%	39%	442	90.0	77%	117

Notes: The above results are based on a price demand elasticity of 0.6 and the corresponding distribution parameters (see Table D.1). The marginal cost on the legal market, c^L, is USD 25 per ounce. The tax revenue in USD *per capita* and *per annum* is given as the product of the difference $p^L - c^L$ with the extensive and intensive margins of consumption. The intensive margin is approximated using Orens et al. (2018) estimates for consumption in Colorado in 2017.

Table D.12. Legalization price and resulting demand when the government maximizes tax revenue and $q = 0$, for $\epsilon = -0.7$

$\frac{1}{N}$	Policy parameters		Equilibrium prices		Equilibrium demand and revenue			Eviction scenario		
	c	b	p	p^L	$\Delta\%D\left(p,p^L\right)$	$s^I\left(p,p^L\right)$	R	$\underline{p}^L$	$\Delta\%D\left(\underline{p}^L\right)$	$\underline{R}$
0.55	50	1.58	105.18	318.35	76%	38%	328	79.0	92%	106
0.55	25	1.58	88.56	314.06	81%	42%	310	39.5	100%	30
0.55	125	1.58	155.60	331.86	62%	23%	388	197.5	70%	300
0.55	200	1.58	206.85	346.39	48%	6%	457	316.0	50%	445
0.10	50	1.58	63.87	307.84	88%	48%	284	79.0	92%	106
0.25	50	1.58	80.71	312.06	83%	44%	302	79.0	92%	106
0.75	50	1.58	117.13	321.48	73%	34%	342	79.0	92%	106
1.00	50	1.58	128.96	324.63	69%	31%	356	79.0	92%	106
0.55	50	1.01	55.18	55.71	91%	0%	60	50.5	92%	50
0.55	50	1.10	58.78	81.12	90%	24%	82	55.0	92%	59
0.55	50	1.30	83.18	181.16	82%	35%	189	65.0	92%	78
0.55	50	1.80	116.83	424.77	73%	39%	432	90.0	92%	127

Notes: The above results are based on a price demand elasticity of 0.7 and the corresponding distribution parameters (see Table D.1). The marginal cost on the legal market, c^L, is USD 25 per ounce. The tax revenue in USD *per capita* and *per annum* is given as the product of the difference $p^L - c^L$ with the extensive and intensive margins of consumption. The intensive margin is approximated using Orens et al. (2018) estimates for consumption in Colorado in 2017.

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Appendix E

Second Article
Further Detail and Robustness Checks

E.1. Data cleaning and processing

E.1.1. 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 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.

E.1.2. 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%.

E.2. Robustness to staggered policy adoption

This appendix provides the results of the diagnostic test `twowayfeweights` described in de Chaisemartin and d'Haultfœuille (2020), which I apply to check the robustness of the TWFE estimator to treatment heterogeneity in my data.

Table E.1 reports the percentage of negative weights associated to ATT estimates, as well as in brackets the sum of these negative weights and in braces (for the single treatment cases) the minimal value of the standard deviation of the treatment effect across the treated groups and time periods under which $\hat{\beta}^{fe}$ is compatible with a data generating process (DGP) where the average of those ATT estimates is 0, which I further denote $\underline{\sigma}_{fe}$. These are computed for three specifications, assuming:

(i) the effect of the legalization of recreational use was computed without controlling for the implementation of retail sales;

(ii) the effect of the implementation of retail sales was computed without controlling for the legalization of recreational cannabis use;

(iii) the effect of the implementation of retail sales was computed controlling for the legalization of recreational cannabis use.

Columns (1)-(3) describe the results for the outcome variable being the logarithm of price per once, columns (4)-(6) for the logarithm of the THC potency and columns (7)-(9) for the logarithm of quality adjusted price, which is the difference between the two previous outcomes.

There are no negative weights under specifications (i) and (ii). Therefore, for these single treatment cases, should all the ATT effects be of the same sign, the TWFE estimator has the same sign as the causal effect. Moreover, the value $\underline{\sigma}_{fe}$ is relatively large for these specifications. It is reasonable to state the average of the ATT effects is unlikely zero. [1]

1. As shown later in table 2.1, the effect of policies on THC potency is relatively small. Hence, the seemingly small values for $\underline{\sigma}_{fe}$ obtained in the case of THC potency remain large enough such that the average ATT is unlikely zero.

Table E.1. Diagnostic tests for specifications (i)-(iii)

	Price			THC			Quality adjusted price		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
legal	0 %		46.20%	0%		46.84%	0%		46.84%
	[0.00]		[-1.00]	[0.00]		[-1.00]	[0.00]		[-1.00]
	{0.95}		-	{0.01}		-	{0.68}		-
retail		0%	0%		0%	0%		0%	0%
		[0.00]	[0.00]		[0.00]	[0.00]		[0.00]	[0.00]
		{1.63}	-		{0.12}	-		{1.33}	-

This table reports the percentage of all ATT estimates that display a negative weight, as well as in brackets the sum of negative weights attached to the TWFE estimators and in braces (for the single treatment cases) the minimal value of the standard deviation of the treatment effect across the treated groups and time periods under which $\hat{\beta}^{TWFE}$ is compatible with a data generating process where the average of those ATT estimates is 0. These figures are obtained running the `twowayfeweights` Stata command described in de Chaisemartin and d'Haultfœuille (2020). The outcome variable in columns (1)-(3) is the logarithm of the price per ounce. In columns (4)-(6), it is the logarithm of the THC potency and in columns (7)-(9) the logarithm of the quality adjusted price, i.e. the difference between the logarithms of the price per ounce and the THC potency. Columns (1), (4) and (7) relate to the specification (i) where the effect of the legalization of cannabis use for recreational purposes was estimated without controlling for the implementation of retail sales. Columns (2), (5) and (8) relate to the specification (ii) where the effect of implementing retail sales was estimated without controlling for the legalization of recreational cannabis use. Columns (3), (6) and (9) relate to the specification (iii) where the effect of the legalization of cannabis use for recreational purposes was estimated while controlling for the implementation of retail sales.

Under specification (iii), more than 40% of the weights related to the estimate of the parameter for *legal* are negative, which raises the issue of contamination between the two treatments.

Table E.2 reports the results of the same diagnostic tests as above, for the following specifications:

(i′) the effect of the legalization of recreational use prior to the implementation of retail sales, i.e. on the subset of observations for which *retail* is zero;

(ii′) the effect of the implementation of retail sales was once recreational cannabis use is legal, i.e. on the subset of observations for which *legal* is one.

While all weights related to the treatment *legal* are positive, nearly a third of weights for the treatment *retail* are negative, although their sum is around -0.4. This raises the concern of a possible average zero treatment effect or of a treatment effect of opposite sign for the treatment *legal* – relative to the results from estimating the TWFE model.

Table E.2. Diagnostic tests for specifications (i′) and (ii′)

	Price		THC		Quality adjusted price	
	(1)	(2)	(3)	(4)	(5)	(6)
legal	0 %		0%		0%	
	[0.00]		[0.00]		[0.00]	
	{2.13}		{0.06}		{1.42}	
retail		28.25%		32.74%		28.89%
		[-0.38]		[-0.38]		[-0.38]
		{0.02, 0.05}		{0.005, 0.01}		{0.01, 0.03}

This table reports the percentage of all ATT estimates that display a negative weight, as well as in brackets the sum of negative weights attached to the TWFE estimators and in braces the minimal value of the standard deviation of the treatment effect across the treated groups and time periods under which $\hat{\beta}^{TWFE}$ is compatible with a data generating process where the average of those ATT estimates is 0 (first element) or of opposite sign (second element, if any). These figures are obtained running the `twowayfeweights` Stata command described in de Chaisemartin and d'Haultfœuille (2020). The outcome variable in columns (1)-(2) is the logarithm of the price per ounce. In columns (3)-(4), it is the logarithm of the THC potency and in columns (5)-(6) the logarithm of the quality adjusted price, i.e. the difference between the logarithms of the price per ounce and the THC potency. Columns (1), (3) and (5) relate to the specification (i′) where the effect of the legalization of cannabis use for recreational purposes was estimated on the subset for which $retail = 0$. Columns (2), (4) and (6) relate to the specification (ii′) where the effect of implementing retail sales was estimated on the subset for which $legal = 1$.

E.3. Avorted cannabis reforms

The TWFE results in Section 3 suggest 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 TWFE results on avorted legalization attempts.

These attempts are modeled using 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.

Columns (2) and (3) of Table E.3 provide results regarding prices, columns (4) and (5) 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 binary

Table E.3. OLS estimates of the TWFE model of the effects of unsuccessful legalization attempts

	Price		THC		Quality adjusted price	
No successful ballot	0.0319		0.000496		0.0627***	
	(0.0220)		(0.00366)		(0.0164)	
Failed ballot		-0.118		-0.0113		-0.0651
		(0.108)		(0.0118)		(0.0888)
N	8,373	8,373	7,272	7,272	7,272	7,272

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

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 and 5 specify the fixed effects used.

I find in general no significant effect of failed cannabis ballots on the black-market price and quality of cannabis. The exception is the effect of having no successful ballot on the quality adjusted price, the understanding of which would require further investigation.

E.4. Heterogenous responses to legalization reforms

This section aims at providing comparison between several states on how the equilibrum price and quality on the black market for cannabis evolve after legalization. I generalize the TWFE model described previously and use an event-study type of analysis, in which I compare states affected by legalization to states that were never treated in my data.[2]

This exercise also allows to distinguish short-term effects from long-term effects of cannabis policies on the illegal markets. Shedding light on the permanence 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.

2. Restricting the analysis to the five groups described in section 3.2 drastically reduces the number of observations, which is why I conduct separate regressions, each time comparing one treated state to all never treated states.

Consider the following econometric model:[3][4]

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

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:

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

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

The coefficients $(\beta_\tau)_{\tau\in\{-q,\ldots,m\}}$ estimate the time path of the average price per once of cannabis before ($\tau = -q, ..., -1$) and after ($\tau = 1, ..., m$) 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:

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

I estimate the model described by equation (E.1) using ordinary least squares, including a set of event-time binary variables along with binary variables for the 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 12 months before and up to 24 months after the date of policy implementation;[5] formally $\tau \in \{-4, ..., -1, 1, ..., 8\}$. Further, I impose $\beta_{-1} = 0$, so that all post-treatment coefficients should be thought as treatment effects.

My data is an unbalanced panel, in which some states are more represented than others, and covers dates until February 2019. Estimating model (E.1), I compare the effects of legalization on price and potency in states for which I have a sufficient number of observations before and after the policy change: Colorado, California, Maine,

3. The variables y_{ist}, θ_s, ψ_t and ϵ_{ist} follow the same notation as in equation (2.1).

4. 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.

5. Because the treatments *legal* and *retail* are likely contaminated, as previously, I restrict the analysis of the effect of legalization on subsamples for which retail sales have not yet been implemented. Conversely, I restrict the analysis of the implementation of retail sales on the subsample for which legalization has already taken place.

Massachusetts, Nevada, Oregon and Washington. Figures E.1 and E.2 describe the results of these estimations.

The results clearly show that responses to legalization differ from one state to the next. While there is a clear immediate and substantial decrease in prices in Oregon, Washington and Massachusetts, the effect is more mitigated in Maine and seems smaller and somehow delayed in Colorado. Further, the dynamics of the price effects seem different from one state to the next: some states seem to endure lasting drops in prices while other feature a more temporary shock. On THC potency, tendencies are more mitigated and difficult to interpret.

E.5. Instrumental variables

Estimating equation (2.12) requires instruments on prices, which are likely correlated to the unobservable heterogeneity $\Delta\xi_{jmt}$ and thereby endogenous.

Instruments on black-market prices. 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, 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 3.1 and Table 2.9, 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}.

In the state of Washington, commercial prices are set freely by retailers, who decide of the profit margin they obtain from re-selling the upstream product. Therefore, the upstream price of a given product influences its retail price. Note that the legal cannabis industry is regulated by the WSLCB. Independent cannabis growers, processors and retailers can apply for state business licenses. Retailers are not allowed to hold a processor or grower license simultaneously. The number of licenses awarded is controlled by the state: licenses are attributed to qualified applications based on a lottery. T he density of retail stores is not constant across locations. Further, retail sales of cannabis are subject to relatively high (37%) state taxes, as well as further local taxes. These, combined with the oligopoly structure of the market enable the government to manipulate the retail prices. Besides, the extent to which prices are inflated by policy varies from one location to the next. These features of the WSLCB regulation enable one to discard the concern of upstream prices being perfectly collinear with retail prices.

E.6. First-stage estimation: predicted market shares

TABLE E.4. 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%

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FIGURE E.1. Dynamic effect of the legalization of recreational cannabis on its black-market price: comparing Colorado, Maine, Massachusetts, Oregon and Washington

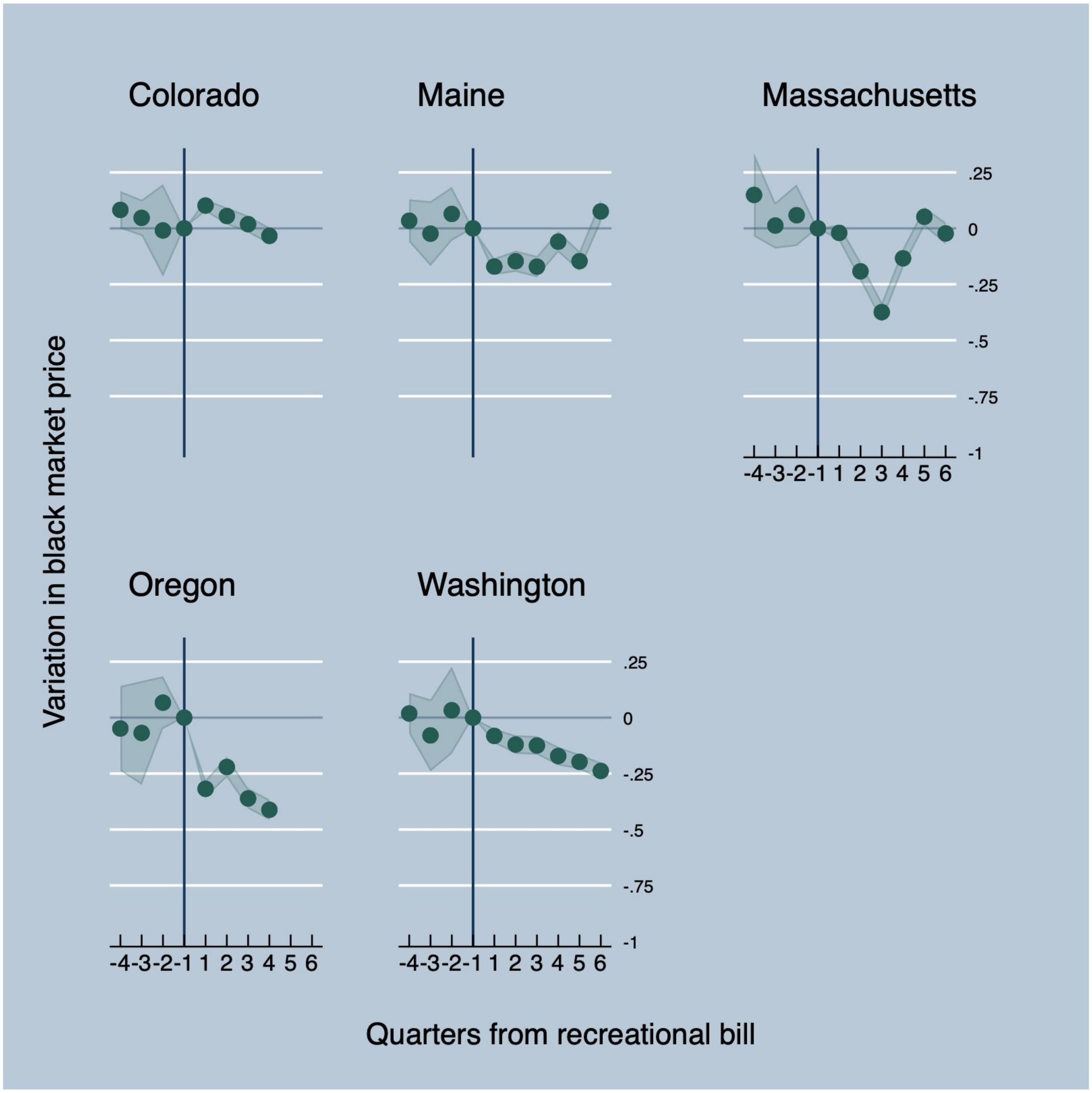
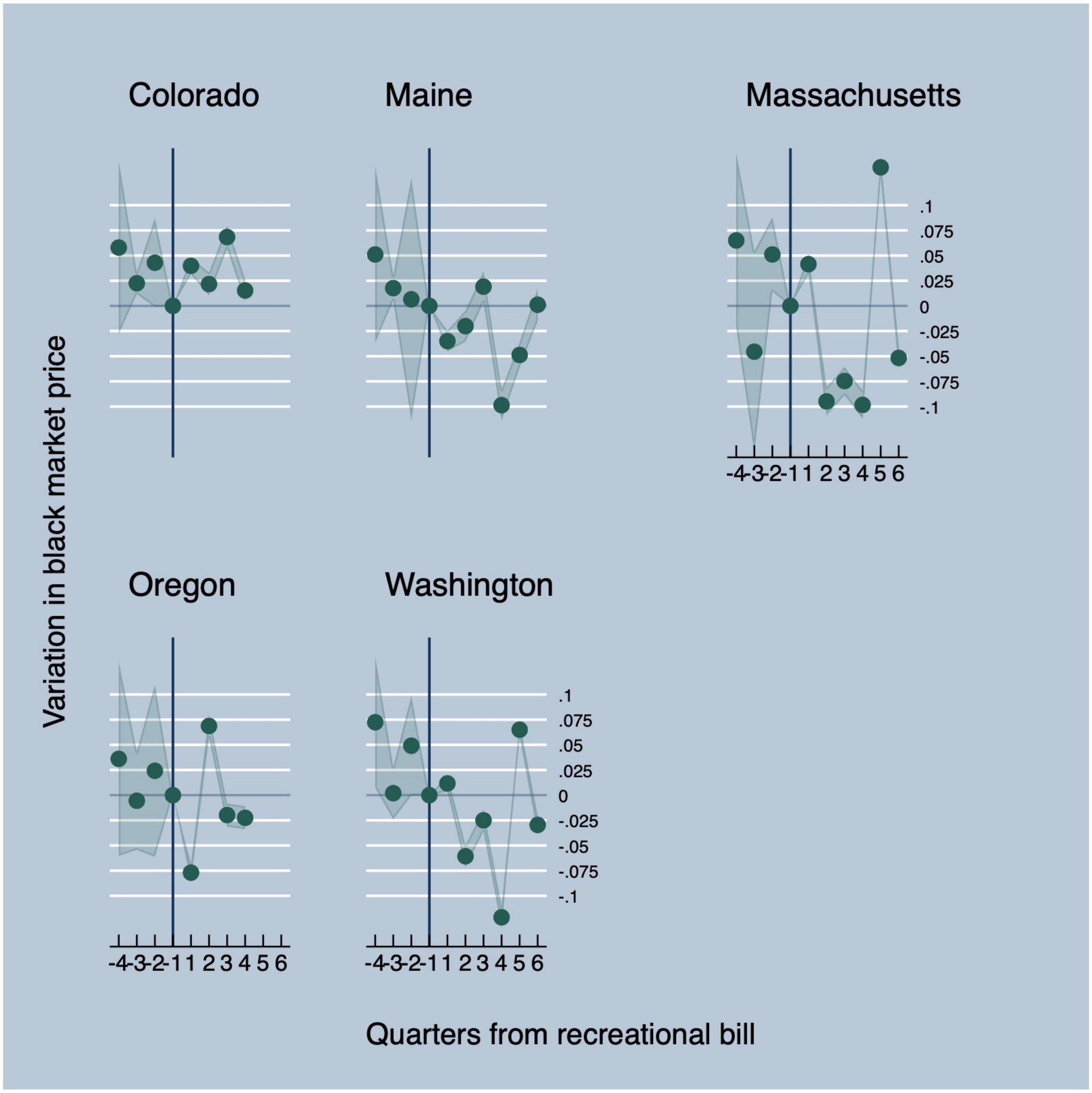


Figure E.2. Dynamic effect of the legalization of recreational cannabis on its black-market THC potency: comparing Colorado, Maine, Massachusetts, Oregon and Washington



Appendix F

Third Article
Theoretical Proofs and Characterizations

F.1. Characterizing the marginal type of migrant indifferent between migrating illegally and not migrating

Under EUT

An individual deciding between irregular migration or staying in origin country compares the expected utility from the lottery $\mathcal{L}_{illegal}$, $(1-q)u\left(dw_f - p^I\right) + qu\left(\Delta_h(\theta)w_h - p^I\right)$, to the utility derived from staying in origin country, $u\left(\Delta_h(\theta)w_h\right)$, where the utility function u is increasing and concave. Therefore, the type θ^I of the individual indifferent between these two options is solution of the following equation.

$$(1-q)u\left(dw_f - p^I\right) + qu\left(\Delta_h(\theta)w_h - p^I\right) = u\left(\Delta_h(\theta)w_h\right) \tag{F.1}$$

Let us define $V_0(\theta) := (1-q)u\left(dw_f - p^I\right) + qu\left(\Delta_h(\theta)w_h - p^I\right) - u\left(\Delta_h(\theta)w_h\right)$. Since $V_0'(\theta) = w_h\Delta_h'(\theta)\left(qu'\left(\Delta_h(\theta)w_h - p^I\right) - u'\left(\Delta_h(\theta)w_h\right)\right)$, for $q < \frac{u'(\Delta_h(\theta)w_h)}{u'(\Delta_h(\theta)w_h - p^I)} \equiv \tilde{q}$, V is decreasing. This condition is satisfied if the probability of failure is not too high relatively to the price of irregular migration. The necessary condition for some migration to occur is $\theta^I > 0$, which implies $V_0(0) > 0$. As we have $\lim_{\theta\to\infty} V(\theta) = -\infty$, equation (F.1) admits a unique solution.

Taking the total differential of equation (F.1) yields

$$\alpha_\theta \mathrm{d}\theta + \alpha_q \mathrm{d}q + \alpha_d \mathrm{d}d + \alpha_{w_f}\mathrm{d}w_f + \alpha_{p^I}\mathrm{d}p^I + \alpha_{w_h}\mathrm{d}w_h = 0$$

where, for $q < \tilde{q}$,

$$\begin{aligned}
\alpha_\theta &= \Delta_h'(\theta)w_h \left[qu'\left(\Delta_h(\theta)w_h - p^I\right) - u'\left(\Delta_h(\theta)w_h\right)\right] && < 0\\
\alpha_q &= -u\left(dw_f - p^I\right) + u\left(\Delta_h(\theta)w_h - p^I\right) && < 0\\
\alpha_d &= (1-q)w_f u'\left(dw_f - p^I\right) && > 0\\
\alpha_{w_f} &= (1-q)du'\left(dw_f - p^I\right) && > 0\\
\alpha_{p^I} &= -(1-q)u'\left(dw_f - p^I\right) - qu'\left(\Delta_h(\theta)w_h - p^I\right) && < 0\\
\alpha_{w_h} &= \Delta_h(\theta)\left[qu'\left(\Delta_h(\theta)w_h - p^I\right) - u'\left(\Delta_h(\theta)w_h\right)\right] && < 0
\end{aligned}$$

This implies that the threshold θ^I increases in d and w_f and decreases in q, p^I and w_h.

Under CPT

The marginal type θ^I is the solution of the following equation:

$$V_1(\theta) := \omega^+(1-q)u\left(dw_f - p^I - \Delta_h(\theta)w_h\right) + \omega^-(q)u\left(-p^I\right) = 0$$

The function V_1 is clearly decreasing. Besides, for any irregular migration to occur, the condition $V_1(0) > 0$ must be satisfied and $\lim_{\theta\to\infty} V_1(\theta) = -\infty$; which guarantees the existence and uniqueness of the threshold θ^I. Since V_1 increases with d and w_f and decreases in p^I and w_h, so does θ^I. Besides, the marginal value with respect to q is given by $V_{1q}(\theta) = -\omega'^+(1-q)u\left(dw_f - p^I - \Delta_h(\theta)w_h\right) + \omega'^-(q)u\left(-p^I\right) < 0$: θ^I decreases with q.

F.2. Characterizing the marginal type of migrant indifferent between migrating legally and not migrating

Legal migration and staying in origin country are not subject to risk. An individual choosing between these options compares their payoffs and migrates legally if and only if

$$\tau\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h - p^L > \Delta_h(\theta)w_h \Leftrightarrow \Delta_f(\theta)w_f - \Delta_h(\theta)w_h > \frac{p^L}{\tau}$$

We assume

$$\forall\theta \in \mathbb{R}_+^*,\ \Delta_f'(\theta)w_f < \Delta_h'(\theta)w_h \tag{F.2}$$

In other words, the quantity $\Delta_f(\theta)w_f - \Delta_h(\theta)w_h$ decreases with θ. This monotony assumption guarantees the threshold θ_L is unique, if it exists, and is implicitly determined by the following equation:

$$\Delta_f(\theta)w_f - \Delta_h(\theta)w_h = \frac{p^L}{\tau} \tag{3.4}$$

Condition (F.2) implies that legal migration selects individuals negatively – i.e. by individuals of type $\theta < \theta^L$ – if θ^L exists.

Legal migration occurs if and only if the threshold θ^L is higher than 0, that is $\Delta_f(0)w_f - \Delta_h(0)w_h > w_f\Delta_f(\theta^L)w_f - \Delta_h(\theta^L)w_h$; equivalently,

$$w_f - w_h > \frac{p^L}{\tau} \tag{F.3}$$

This condition insures that, for the legal visa scheme (τ, p^L), θ^L exists.

We show that the threshold θ^L increases with w_f and τ and decreases with w_h and p^L by differentiating equation (3.4):

$$\left(\Delta'_f(\theta)w_f - \Delta'_h(\theta)w_h\right)\mathrm{d}\theta + \Delta_f(\theta)\mathrm{d}w_f - \Delta_h(\theta)\mathrm{d}w_h - \frac{1}{\tau}\mathrm{d}p^L + \frac{p^L}{\tau^2}\mathrm{d}\tau = 0.$$

F.3. Characterizing the marginal type of migrant indifferent between migrating legally and illegally

When visas can be bought legally, the individual of type θ compares the lottery $\mathcal{L}_{illegal}$ with the payoff she retrieves from migrating legally, $\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h$.

Under EUT

In the EUT framework, the marginal type of migrant θ^{LI} indifferent between migrating through legal channels and irregularly is characterized by the following equation.

$$(1-q)u\left(dw_f - p^I\right) + qu\left(\Delta_h(\theta)w_h - p^I\right) = u\left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right) \tag{F.4}$$

Let us define $W_0(\theta) = (1-q)u\left(dw_f - p^I\right) + qu\left(\Delta_h(\theta)w_h - p^I\right) - u\left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right)$.

Since u is S-shaped, for $\tau < \frac{\Delta'_h(\theta)w_h}{\Delta'_f(\theta)w_f - \Delta'_h(\theta)w_h} \frac{qu'\left(\Delta_h(\theta)w_h - p^I\right) - u'\left(\Delta_f(\theta)w_f - p^L\right)}{u'\left(\Delta_f(\theta)w_f - p^L\right)}$, we have

$$\begin{aligned}
W'_0(\theta) =& \Delta'_h(\theta)w_h qu'\left(\Delta_h(\theta)w_h - p^I\right) \\
& - \left[\tau\Delta'_f(\theta)w_f + (1-\tau)\Delta'_h(\theta)w_h\right] u'\left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right) \\
& < 0
\end{aligned}$$

For some irregular migration to occur, we necessarily have $W_0(0) > 0$. Besides, since $\Delta_f(\theta)w_f > \Delta_h(\theta)w_h$ and $\lim_{\theta\to\infty}\Delta_f(\theta) = \lim_{\theta\to\infty}\Delta_h(\theta) = +\infty$, $\lim_{\theta\to\infty} W_1(\theta) = -\infty$

Therefore, when the probability of deportation is low enough – leaving room for irregular migration – equation (F.4) determines implicitly the threshold type, θ^{LI}, such that any individual above this threshold prefers to migrate legally than undocumented.

Taking the total differential of equation (F.4) yields

$$\alpha_\theta \mathrm{d}\theta + \alpha_q \mathrm{d}q + \alpha_d \mathrm{d}d + \alpha_{w_f}\mathrm{d}w_f + \alpha_{p^I}\mathrm{d}p^I + \alpha_{w_h}\mathrm{d}w_h + \alpha_\tau \mathrm{d}\tau + \alpha_{p^L}\mathrm{d}p^L = 0$$

where, in the neighborhood of θ^{LI}, for $q < \hat{q}$,

$$\begin{aligned}
\alpha_\theta =& \Delta'_h(\theta)w_h qu'\left(\Delta_h(\theta)w_h - p^I\right) \\
& - \left[\tau\Delta'_f(\theta)w_f + (1-\tau)\Delta'_h(\theta)w_h\right] u'\left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right) && < 0 \\
\alpha_q =& -u\left(dw_f - p^I\right) + u\left(\Delta_h(\theta)w_h - p^I\right) && < 0 \\
\alpha_d =& w_f(1-q)u'\left(dw_f - p^I\right) && > 0 \\
\alpha_{w_f} =& d(1-q)u'\left(dw_f - p^I\right) && > 0 \\
\alpha_{p^I} =& -(1-q)u'\left(dw_f - p^I\right) - qu'\left(\Delta_h(\theta)w_h - p^I\right) && < 0 \\
\alpha_\tau =& -\left(\tau\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h\right) u'\left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right) && < 0 \\
\alpha_{p^L} =& u'\left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right) && > 0 \\
\alpha_{w_h} =& \Delta_h(\theta)\left[u'\left(\Delta_h(\theta)w_h - p^I\right) - (1-\tau)u'\left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right)\right]
\end{aligned}$$

This shows that $\partial\theta^{LI}/\partial q < 0$, $\partial\theta^{LI}/\partial d > 0$, $\partial\theta^{LI}/\partial p^I < 0$, $\partial\theta^{LI}/\partial\tau < 0$ and $\partial\theta^{LI}/\partial p^L > 0$.

Under CPT

In the CPT framework, the the marginal type of migrant θ^{LI} indifferent between migrating legally and irregularly is characterized by the following equation.

$$\begin{aligned}
&\omega^+(1-q)u\left[dw_f - p^I - \left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right)\right] \\
&+\omega^-(q)u\left[\Delta_h(\theta)w_h - p^I - \left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right)\right] = 0
\end{aligned} \tag{3.5}$$

Let us define $W_1(\theta) = \omega^+(1-q)u\left[dw_f - p^I - \left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right)\right]$ $+ \omega^-(q)u\left[\Delta_h(\theta)w_h - p^I - \left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right)\right]$.

The value of irregular migration with respect to legal migration, $W_1(\theta)$, is decreasing as long as

$$\begin{aligned}
&\left(\tau\Delta_f'(\theta)w_f + (1-\tau)\Delta_h'(\theta)w_h\right) \\
&\omega^+(1-q)u'\left[dw_f - p^I - \left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right)\right] \\
>&\tau\left(\Delta_h'(\theta)w_h - \Delta_f'(\theta)w_f\right) \\
&\omega^-(q)u'\left[\Delta_h(\theta)w_h - p^I - \left(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\right)\right]
\end{aligned}$$

This inequality is verified under the following sufficient condition

$$\tau < \frac{\omega^+(1-q)u'\left[dw_f - \Delta_h(\theta)w_h - p^I\right]}{\omega^+(1-q)u'\left[dw_f - \Delta_h(\theta)w_h - p^I\right] + \omega^-(q)u'\left[-p^I\right]} < 1 \tag{F.5}$$

This involves that, if irregular migration does not always select individuals negatively, at least there exists a threshold value for τ under which it does.

Assume the function W_1 is decreasing.

A necessary condition for some irregular migration to occur is that $W_1(0) > 0$. Besides, since $\theta^L > \theta^I$, $W_1(\theta^L) = \omega^+(1-q)u\left[dw_f - p^I - \Delta_h(\theta^L)w_h\right] + \omega^-(q)u\left[-p^I\right] < 0$. This implies that, when an illegal market exists, equation (3.5) determines implicitly the threshold type, θ^{LI}, such that any individual above this threshold prefers to migrate legally rather than irregularly.

Taking the total differential of equation (3.5) yields

$$\alpha_\theta \mathrm{d}\theta + \alpha_q \mathrm{d}q + \alpha_d \mathrm{d}d + \alpha_{w_f}\mathrm{d}w_f + \alpha_{p^I}\mathrm{d}p^I + \alpha_{w_h}\mathrm{d}w_h + \alpha_\tau \mathrm{d}\tau + \alpha_{p^L}\mathrm{d}p^L = 0$$

where we already saw that $\alpha_\theta = W_1'(\theta) < 0$ and it is quite straightforward that,

$$\begin{aligned}
\alpha_q =& -\omega'^{+}(1-q)u\left[dw_f - p^I - \Big(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\Big)\right] \\
&+ \omega'^{-}(q)u\left[\Delta_h(\theta)w_h - p^I - \Big(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\Big)\right] && < 0 \\
\alpha_d =& w_f\omega^{+}(1-q)u'\left[dw_f - p^I - \Big(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\Big)\right] && > 0 \\
\alpha_{w_f} =& d\omega^{+}(1-q)u'\left[dw_f - p^I - \Big(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\Big)\right] && > 0 \\
\alpha_{p^I} =& -\omega^{+}(1-q)u'\left[dw_f - p^I - \Big(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\Big)\right] \\
&- \omega^{-}(q)u'\left[\Delta_h(\theta)w_h - p^I - \Big(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\Big)\right] && < 0 \\
\alpha_\tau =& (\Delta_h(\theta)w_h - \Delta_f(\theta)w_f) \\
&\times \{\omega^{+}(1-q)u'\left[dw_f - p^I - \Big(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\Big)\right] \\
&\quad + \omega^{-}(q)u'\left[\Delta_h(\theta)w_h - p^I - \Big(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\Big)\right]\} && < 0 \\
\alpha_{p^L} =& -\alpha_{p^I} && > 0
\end{aligned}$$

Besides, under the sufficient condition (F.5),

$$\begin{aligned}
\alpha_{w_h} =& -(1-\tau)\Delta_h(\theta)\omega^{+}(1-q)u'\left[dw_f - p^I - \Big(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\Big)\right] \\
&+ \tau\Delta_h(\theta)\omega^{-}(q)u'\left[\Delta_h(\theta)w_h - p^I - \Big(\tau\Delta_f(\theta)w_f - p^L + (1-\tau)\Delta_h(\theta)w_h\Big)\right] \\
<& -(1-\tau)\Delta_h(\theta)\omega^{+}(1-q)u'\left[dw_f - \Delta_h(\theta)w_h - p^I\right] + \tau\Delta_h(\theta)\omega^{-}(q)u'\left[-p^I\right] \\
<& 0
\end{aligned}$$

This yields $\partial\theta^{LI}/\partial q < 0$, $\partial\theta^{LI}/\partial d > 0$, $\partial\theta^{LI}/\partial w_f > 0$, $\partial\theta^{LI}/\partial p^I < 0$, $\partial\theta^{LI}/\partial\tau < 0$, $\partial\theta^{LI}/\partial p^L > 0$ and $\partial\theta^{LI}/\partial w_h < 0$.

F.4. Self-enforceability of return migration

Migrants facing the decision to overstay to work undocumented compare the payoff they derive from the lottery $\mathcal{L}_{overstay} = [\tau(1-s)\Delta_f(\theta)w_f + (1-\tau)dw_f - p^L, \tau(1-s)\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h - p^L; 1-\delta, \delta]$, with their payoff if they comply with the rules of the guest worker program, $\tau\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h - p^L$.

We show, in both EUT and CPT frameworks, that for any migration contract of duration τ and positive share of wages retention, s, there exists a minimum probability of deportation such that temporary migration visas are self enforceable.

Under EUT

Let us define the function $\phi(\delta)$ as:

$$\begin{aligned}\phi(\delta) = (1-\delta)u\left[\tau(1-s)\Delta_f(\theta)w_f + (1-\tau)dw_f\right] \\ +\delta u\left[\tau(1-s)\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h\right] \\ -u\left(\tau\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h\right)\end{aligned}$$

The derivative of ϕ is simply given as

$$\begin{aligned}\phi'(\delta) =& u\left[\tau(1-s)\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h\right] \\ &- u\left[\tau(1-s)\Delta_f(\theta)w_f + (1-\tau)dw_f\right]\end{aligned}$$

Since $dw_f > \Delta_h(\theta)w_h$, it is quite straightforward that $\phi'(\delta) < 0$.

Besides, if $s > 0$, $\phi(1) < 0$.

Two cases arise:

- if $\phi(0) < 0$ then, by continuity, the enforceability constraint is always satisfied;
- if $\phi(0) > 0$, there exists a unique threshold deportation probability $0 < \underline{\delta} < 1$, above which the temporary visas are self-enforceable.

This threshold is the implicit solution of $\phi(\underline{\delta}) = 0$.

Under CPT

The level of deportation $\underline{\delta}$ such that the individual of type θ is indifferent between overstaying or complying with the visa rules is the solution of the following equation

$$\begin{aligned}\omega^+(1-\delta)u\left[\tau(1-s)\Delta_f(\theta)w_f + (1-\tau)dw_f - (\tau\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h)\right] \\ +\omega^-(\delta)u\left[\tau(1-s)\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h - (\tau\Delta_f(\theta)w_f + (1-\tau)\Delta_h(\theta)w_h)\right] = 0\end{aligned} \tag{F.6}$$

which can be rewritten as follows

$$\omega^+(1-\delta)u\left[-\tau s\Delta_f(\theta)w_f + (1-\tau)\left(dw_f - \Delta_h(\theta)w_h\right)\right] + \omega^-(\delta)u\left[-\tau s\Delta_f(\theta)w_f\right] = 0$$

The function $\phi(\delta) := \omega^+(1-\delta)u\left[-\tau s\Delta_f(\theta)w_f + (1-\tau)\left(dw_f - \Delta_h(\theta)w_h\right)\right] + \omega^-(\delta)$ $u\left[-\tau s\Delta_f(\theta)w_f\right]$ is decreasing in δ.[1]

Since $\phi(0) > 0$ and $\phi(1) < 0$, the equation (F.6) admits a unique solution, which is the threshold deportation probability $\underline{\delta}$, above which the temporary visas are self-enforceable.

1. As $\phi'(\delta) = -\omega'^+(1-\delta)u\left[-\tau s\Delta_f(\theta)w_f + (1-\tau)\left(dw_f - \Delta_h(\theta)w_h\right)\right] + \omega'^-(\delta)u\left[-\tau s\Delta_f(\theta)w_f\right] < 0$.

With a similar reasoning we can show that it is not always possible to enforce a temporary stay of workers by retaining a share of earnings abroad. Let us define the function $\psi(s) := \omega^{+}(1-\delta)u\left[-\tau s\Delta_f(\theta)w_f + (1-\tau)\left(dw_f - \Delta_h(\theta)w_h\right)\right] + \omega^{-}(\delta)u\left[-\tau s\Delta_f(\theta)w_f\right]$.

It is straightforward to show that this continuous function is decreasing in s and that $\psi(0) > 0$.Two cases arise:

- if the income in the home country is too low, relative to the income obtained as undocumented worker in the foreign country, and $\psi(1) > 0$, then for the level of deportation δ enforced, temporary visas are not self-enforceable;
- otherwise, if $\psi(1) < 0$, there exists a threshold share of earnings retained $\underline{s}$ under which temporary visas are not self-enforceable.

F.5. Characterizing the eviction price

The threshold price, denoted $\underline{p}^L$, below which smugglers are driven out of business is such that $\theta^{IL} = 0$ for $p^I = c$.

Under EUT

Using (F.4), the threshold price is defined implicitly as follows:

$$(1-q)u\left(dw_f - c\right) + qu\left(w_h - c\right) = u\left(\tau w_f - \underline{p}^L + (1-\tau)w_h\right)$$

which is equivalent to

$$\underline{p}^L = \tau w_f + (1-\tau)w_h - u^{-1}\left[(1-q)u\left(dw_f - c\right) + qu\left(w_h - c\right)\right]$$

Since u is increasing and $dw_f > w_h$, the eviction price is increasing in the probability of arrest q, the duration of the migration visa τ, and the marginal cost for smugglers to operate c. It is decreasing in the discount factor d.

Moreover, $\underline{p}^L > 0$ if and only if $\tau > \underline{\tau} \equiv \frac{u^{-1}\left[(1-q)u\left(dw_f - c\right) + qu(w_h - c)\right] - w_h}{w_f - w_h}$. Note that, since $dw_f - c > w_h - c$ and u^{-1} is increasing, the threshold $\underline{\tau}$ decreases in q. It is also straightforward to establish that it decreases in c and increases in d.

Under CPT

The eviction price is defined implicitly as follows

$$\begin{aligned} &\omega^{+}(1-q)u\left[dw_f - c - \left(\tau w_f - \underline{p}^L + (1-\tau)w_h\right)\right] \\ &\quad + \omega^{-}(q)u\left[w_h - c - \left(\tau w_f - \underline{p}^L + (1-\tau)w_h\right)\right] = 0, \end{aligned} \tag{3.11}$$

which simplifies to:

$$\begin{aligned}\omega^{+}(1-q)u\left[(d-\tau)w_f-(1-\tau)w_h-c+\underline{p}^L\right]&\\ +\omega^{-}(q)u\left[\underline{p}^L-c-\tau\left(w_f-w_h\right)\right]&=0\end{aligned} \tag{F.7}$$

Taking the total differential of the above equation yields

$$\alpha_{\underline{p}^L}\mathrm{d}\underline{p}^L+\alpha_q\mathrm{d}q+\alpha_d\mathrm{d}d+\alpha_{w_f}\mathrm{d}w_f+\alpha_{p^I}\mathrm{d}p^I+\alpha_{w_h}\mathrm{d}w_h+\alpha_\tau\mathrm{d}\tau=0$$

We can sign straightforwardly:

$$\begin{aligned}\alpha_{\underline{p}^L}=&\omega^{+}(1-q)u'\left[(d-\tau)w_f-(1-\tau)w_h+\underline{p}^L-c\right]\\&+\omega^{-}(q)u'\left[\tau(w_h-w_f)+\underline{p}^L-c\right] && >0\\ \alpha_d=&w_f\omega^{+}(1-q)u'\left[(d-\tau)w_f-(1-\tau)w_h+\underline{p}^L-c\right] && >0\\ \alpha_{w_f}=&d\omega^{+}(1-q)u'\left[(d-\tau)w_f-(1-\tau)w_h+\underline{p}^L-c\right] && >0\\ \alpha_c=&-\omega^{+}(1-q)u'\left[(d-\tau)w_f-(1-\tau)w_h+\underline{p}^L-c\right]\\&-\omega^{-}(q)u'\left[\tau(w_h-w_f)+\underline{p}^L-c\right] && <0\\ \alpha_{w_h}=&-(1-\tau)\omega^{+}(1-q)u'\left[dw_f-c-\left(\tau w_f-\underline{p}^L+(1-\tau)w_h\right)\right]\\&+\tau\omega^{-}(q)u'\left[w_h-c-\left(\tau w_f-\underline{p}^L+(1-\tau)w_h\right)\right] && <0\end{aligned}$$

$$\begin{aligned}\alpha_\tau=&(w_h-w_f)\{\omega^{+}(1-q)u'\left[(d-\tau)w_f-(1-\tau)w_h+\underline{p}^L-c\right]\\&+\omega^{-}(q)u'\left[\tau(w_h-w_f)+\underline{p}^L-c\right]\} && <0\end{aligned}$$

If legal migration occurs, the rationality constraint is satisfied such that: $\underline{p}^L<\tau(w_f-w_h)$. Besides, if irregular migration persists for a legal price higher than the eviction price, necessarily the payoffs in case of success of irregular migration must be positive for the lowest skilled worker such that: $(d-\tau)w_f-(1-\tau)w_h+\underline{p}^L-c>0$. This implies that:

$$\begin{aligned}\alpha_q=&-\omega'^{+}(1-q)u\left[(d-\tau)w_f-(1-\tau)w_h+\underline{p}^L-c\right]\\&+\omega'^{-}(q)u\left[\tau w_h-\tau w_f+\underline{p}^L-c\right] && <0\end{aligned}$$

This shows that the eviction price is increasing in the probability of failing irregular migration q, the duration of the migration visa τ, and the marginal cost for smugglers to operate c. It is decreasing in the discount factor d.

In particular,

$$\frac{\partial\underline{p}^L}{\partial\tau}=-\frac{\alpha_\tau}{\alpha_{\underline{p}^L}}=w_f-w_h \tag{F.8}$$

which we use later in appendix F.6.

Note that $\tau > \frac{dw_f - w_h}{w_f - w_h} - \frac{c}{w_f - w_h}$ is a sufficient condition for the eviction price to be positive.

Indeed, by definition of $\underline{p}^L$,

$$\begin{aligned} &\omega^+(1-q)u\left[dw_f - c - \left(\tau w_f - \underline{p}^L + (1-\tau)w_h\right)\right] \\ &\quad +\omega^-(q)u\left[w_h - c - \left(\tau w_f - \underline{p}^L + (1-\tau)w_h\right)\right] = 0 \end{aligned} \tag{3.11}$$

Moreover we can show easily that: $\tau > \frac{dw_f - w_h}{w_f - w_h} - \frac{c}{w_f - w_h}$ assures that

$$\omega^+(1-q)u\left[dw_f - w_h - c - \tau(w_f - w_h)\right] + \omega^-(q)u\left[-c - \tau\left(w_f - w_h\right)\right] < 0$$

This yields

$$\begin{aligned} &\omega^+(1-q)u\left[dw_f - c - \left(\tau w_f - \underline{p}^L + (1-\tau)w_h\right)\right] \\ &\quad + \omega^-(q)u\left[w_h - c - \left(\tau w_f - \underline{p}^L + (1-\tau)\ w_h\right)\right] \\ &> \omega^+(1-q)u\left[dw_f - c - (\tau w_f + (1-\tau)w_h)\right] \\ &\quad + \omega^-(q)u\left[w_h - c - (\tau w_f + (1-\tau)w_h)\right] \end{aligned}$$

Yet, since $\omega^+(1-q)u\left[dw_f - c - \left(\tau w_f - \underline{p}^L + (1-\tau)w_h\right)\right] + \omega^-(q)u\left[w_h - c - \left(\tau w_f - \underline{p}^L + (1-\tau)w_h\right)\right]$ increases with $\underline{p}^L$, the above inequality is equivalent to $\underline{p}^L > 0$.

Hence, there exists a threshold $\underline{\tau} \leq \frac{dw_f - w_h}{w_f - w_h} - \frac{c}{w_f - w_h}$, such that for any $\tau > \underline{\tau}$, $\underline{p}^L > 0$.

This threshold is implicitly defined by equation (3.11) for $\underline{p}^L = 0$ as:

$$\omega^+(1-q)u\left[dw_f - w_h - c - \underline{\tau}(w_f - w_h)\right] + \omega^-(q)u\left[-c - \underline{\tau}\left(w_f - w_h\right)\right] = 0 \tag{F.9}$$

Yet the expression $\omega^+(1-q)u\left[dw_f - w_h - c - \underline{\tau}(w_f - w_h)\right] + \omega^-(q)u\left[-c - \underline{\tau}\left(w_f - w_h\right)\right]$ decreases with q, c, and $\underline{\tau}$ and increases with d. Therefore, differentiating equation (F.9) yields that the threshold $\underline{\tau}$ decreases with q and c and increases with d.

F.6. Proof of Proposition 3.5

Let us show that the function $z(\tau) = \frac{\underline{p}^L(\tau)}{\Delta_f\left(\theta^I_{p^I}\right)w_f - \Delta_h\left(\theta^I_{p^I}\right)w_h}$ has a unique fixed point on the interval $(0,1)$, which decreases with q. Since $\Delta_f\left(\theta^I_{p^I}\right)w_f - \Delta_h\left(\theta^I_{p^I}\right)w_h$ does not depend on τ, this is equivalent to showing that $\underline{p}^L(\tau)$ has a unique fixed point (decreasing in q) on the interval $\left(0, \Delta_f\left(\theta^I_{p^I}\right)w_f - \Delta_h\left(\theta^I_{p^I}\right)w_h\right)$.

Under EUT

One can show directly $\underline{p}^L$ admits a unique fixed point decreasing in q, since u is increasing and $dw_f > w_h$.

$$\tilde{\tau} w_f + (1-\tilde{\tau}) w_h - u^{-1}\left[(1-q)u\left(dw_f - c\right) + qu\left(w_h - c\right)\right] - \tau = 0$$
$$\Leftrightarrow \tilde{\tau} = \frac{u^{-1}\left[(1-q)u\left(dw_f - c\right) + qu\left(w_h - c\right)\right] - w_h}{w_f - w_h - 1}$$

This shows that $\tilde{\tau}$ is decreasing in q and in c and increasing in d.

Since $z(\tau) > 0$, $\tilde{\tau} > 0$; which also involves $\Delta_f\left(\theta^I_{p^I}\right) w_f - \Delta_h\left(\theta^I_{p^I}\right) w_h > w_f - w_h > 1$.

Besides,

$$\begin{aligned} &\tilde{\tau} w_f + (1-\tilde{\tau}) w_h - u^{-1}\left[(1-q)u\left(dw_f - c\right) + qu\left(w_h - c\right)\right] \\ =& \left[u^{-1}\left[(1-q)u\left(dw_f - c\right) + qu\left(w_h - c\right)\right] - w_h\right] \frac{1}{w_f - w_h - 1} \\ <& \frac{dw_f - w_h - c}{w_f - w_h - 1} \end{aligned}$$

Yet, as long as $1 - c < (1-d) w_f$, $\frac{dw_f - w_h - c}{w_f - w_h - 1} < 1$.

Under CPT

Recall that $\underline{p}^L$ is implicitly defined by equation (3.11):

$$\begin{aligned} &\omega^+(1-q)u\left[dw_f - c - \left(\tau w_f - \underline{p}^L + (1-\tau) w_h\right)\right] \\ &\quad + \omega^-(q) u\left[w_h - c - \left(\tau w_f - \underline{p}^L + (1-\tau) w_h\right)\right] = 0 \end{aligned}$$

We showed in appendix F.5 that $\underline{p}^L$ is increasing in τ ($\frac{\partial \underline{p}^L}{\partial \tau} = w_f - w_h > 0$) and positive for $\tau > \frac{dw_f - w_h}{w_f - w_h} - \frac{c}{w_f - w_h}$.

Besides, for $\tau = 1$, equation (3.11) becomes

$$\omega^+(1-q)u\left[dw_f - c - \left(w_f - \underline{p}^L\right)\right] + \omega^-(q)u\left[w_h - c - \left(w_f - \underline{p}^L\right)\right] = 0$$

and in this case $\underline{p}^L_{\tau=1} < w_f - w_h < \Delta_f\left(\theta^I_{p^I}\right) w_f - \Delta_h\left(\theta^I_{p^I}\right) w_h$. [2]

The function $\underline{p}^L(\tau)$ admits a unique fixed point $\tilde{\tau}$ on $\left(0, \Delta_f\left(\theta^I_{p^I}\right) w_f - \Delta_h\left(\theta^I_{p^I}\right) w_h\right)$.

Since $\underline{p}^L$ increases with q and c and decreases with d (see appendix F.5), $\tilde{\tau}$ decreases with q and c and increases with d.

2. Indeed $\omega^+(1-q)u\left[dw_f - c - \left(w_f - \underline{p}^L\right)\right] + \omega^-(q)u\left[w_h - c - \left(w_f - \underline{p}^L\right)\right]$ is decreasing in $\underline{p}^L$ and $\omega^+(1-q)u\left[dw_f - w_h - c\right] + \omega^-(q)u\left[-c\right] < \omega^+(1-q)u\left(dw_f - c - e^{\Delta_h \theta^I_c} w_h\right) + \omega^-(q)u\left(-c\right) = 0$.

Appendix G

Third Article
Detail on the Numerical Applications

G.1. Detail on numerical applications

G.1.1. Benchmark values

Smuggling fees. According to the survey that Mbaye (2014) did among migrants in Dakar before they undertook their dangerous trip to Europe or the United States, the price charged to reach Spain by sea was around 391,981 Fcfa on average in 2007, which corresponds to 1,690 PPP. Congolese (undocumented) migrants living in South Africa, surveyed by Tshimpaka and Inaka (2020), mention smuggling prices of 600 USD, i.e. approximately 1,220 PPP in 2020 DRC, for a an overland journey.

Marginal costs to operate. Human smuggling is a highly differentiated illegal activity, which makes its profitability challenging to assess (Sanchez, 2017). In particular, data on operating costs is scarce. As a benchmark for the marginal costs of smugglers' operations, c, we rely on the costs for a captain to reach Spain from Senegal with a typical dingy carrying 30 people, which were estimated in 2007 to be around 8,000,000 Fcfa, i.e. around 267,000 Fcfa per person (Mbow and Tamba, 2007), or 1,150 PPP in international dollars. This corresponds to a profit margin of 32%. Assuming smugglers on the Congo-South Africa route have a similar profit margin, the marginal cost on this route would be around 830 PPP.

Failure rate of illegal migration. The failure rate of illegal migration is difficult to estimate and highly volatile: according to the Washington Post, while the success rate of the central Mediterranean route was around 95% between 2015 and 2017, it fell to

45% in 2018.[1] This increase in the risk of failure is also documented by Bah et al. (2019) who report the high risks of failure, including death, expected by undocumented migrants from Gambia travelling to Europe. The risk of failure has increased further due to Covid-19 border closures and severe mobility restrictions in most countries. Accordingly, our numerical applications allow for a large range of parameters q.

Relative earnings of informal labor. Monràs et al. (2020) estimate the wage ratio between undocumented and legal workers in similar types of jobs in Spain, d, to be around 0.8, which we use in our simulations.[2] This is also in line with evidence from the US labor market (Rivera-Batiz, 1999; Kossoudji and Cobb-Clark, 2002).

Minimum wages. Finally, in line with the large body of empirical research on returns to skills (see Lemieux, 2006, for a detailed literature review), we specify the income X_{ij} of an individual i working legally in country $j = h, f$ using a Mincer (1970) equation:

$$\ln X_{ij} = \ln w_j + \tilde{\Delta}_j \theta_i \tag{G.1}$$

where $\tilde{\Delta}_j \geq 0$ denotes the returns to skills θ in country j.

To calibrate the income distributions in origin and destination countries we assume that X_{ij} follows a log-normal distribution $\ln X_{ij} \sim \mathcal{N}\left(\mu_j, \sigma_j^2\right)$. We use GDP data and Gini coefficients from the World Development Indicators (WDI) database to estimate the parameters μ_j and σ_j^2.[3]

Many countries either do not enforce minimum wage regulations or they have a large informal sector. In Senegal for example, 9 workers out of 10 and 97% of companies belong to the informal sector (International Labour Organization, 2020). Since the minimum wage set by law is not likely to reflect the wage of low-skilled workers, we follow Grogger and Hanson (2011) to calibrate the low-skill wage, which is set to the 20th percentile of the income distribution. We follow the same approach regarding the DRC, where the informal sector accounts for 80% of the economy and where the minimum wage, the *salaire minimum interprofessionnel garanti*, was drastically re-evaluated in 2018.[4]

1. Chico Harlan, 2018. "Fewer migrants are making it to Europe. Here's why." The Washington Post, July 23.

2. Using wages data from the *Encuesta Nacional de Immigrantes*, they find a remarkably robust ratio, irrespective of the subgroups of workers considered.

3. The standard deviation can be written as $\sigma_j = \sqrt{2}\Phi^{-1}\left(\frac{\Gamma_j+1}{2}\right)$ where Φ^{-1} is the reciprocal of the standard normal cumulative density function and Γ_j is the Gini coefficient of income inequality in country j. The expected value of income, $E(X_j)$, is given by $E(X_j) = \exp\left(\mu_j + \frac{\sigma_j^2}{2}\right)$.

4. Article 91 of the DRC Labor Code, decree # 18/017 of 22 May 2018 stipulates that the *salaire minimum interprofessionnel garanti* should adjust to 7,075 FC daily from 1 July 2019 – instead of 1,680 FC prior 2018. On a basis of 25 workdays, this yields a 176,875 FC monthly wage.

G.1.2. Functional forms

In line with Tversky and Kahneman (1992) the weighting function $w^+(1-q)$ (respectively $w^-(q)$) applied to probabilities associated with positive (respectively negative) outcomes is:

$$w^t(q) = \frac{q^{\gamma^t}}{\left(q^{\gamma^t} + (1-q)^{\gamma^t}\right)^{\frac{1}{\gamma^t}}} \qquad \text{with } t = +, -. \tag{G.2}$$

and the value function is:

$$u(x) = \begin{cases} x^\alpha \text{ , if } x > 0 \\ -\lambda(-x)^\alpha \text{ , if } x \leq 0 \end{cases} \qquad \text{with } \alpha \in (0,1) \text{ and } \lambda \geq 1. \tag{G.3}$$

As benchmark values, we choose the parameters calibrated by Tversky and Kahneman (1992): $\lambda = 2.25$, $\alpha = 0.88$, $\gamma^+ = 0.61$ and $\gamma^- = 0.69$.

Using these functional forms and equation (3.11), the eviction price $\underline{p}^L(\tau)$ takes the closed-form expression (3.18).

Assuming the log-linearity of income $\ln X_{ih}$ in skill level θ_i (Mincer, 1970), the variation in the share of population who migrates is the variation in the log-income of this population if they work in the origin country.

Formally,

$$\frac{F\left(\theta^L\right) - F\left(\theta^I\right)}{F\left(\theta^I\right)} = \frac{G\left(\ln X_h^L\right) - G\left(\ln X_h^I\right)}{G\left(\ln X_h^I\right)} \tag{G.4}$$

where G denotes the cumulative density function of the distribution $\mathcal{N}(\mu_h, \sigma_h)$, while $X_h^L = \Delta_h(\theta^L)w_h$ and $X_h^I = \Delta_h(\theta^I)w_h$ are the incomes of individuals θ^L and θ^I in the home country.

Using the Tversky and Kahneman (1992) functional forms, equation (3.2) yields

$$X_h^I = dw_f - p^I - \left(\lambda \frac{\omega^-(q)}{\omega^+(1-q)}\right)^{\frac{1}{\alpha}} p^I \tag{G.5}$$

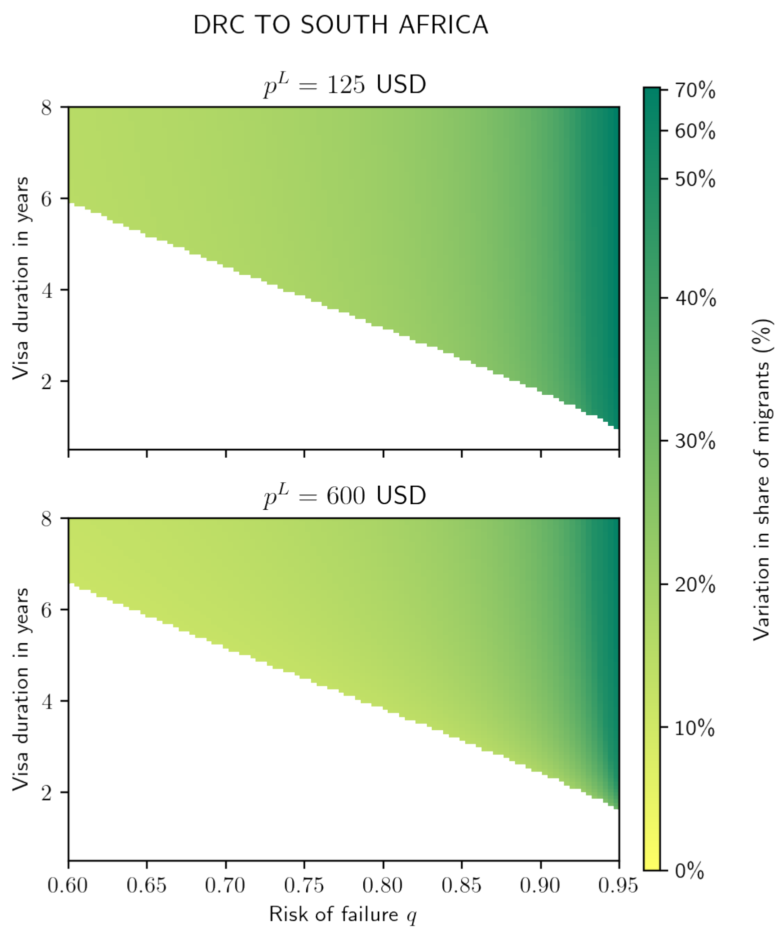
Focusing on foreign work permits paid at minimum wages, for which there are no returns to skills, we set $\tilde{\Delta}_f = 0$. In this case, the rationality constraint (3.4) becomes $w_f - e^{\tilde{\Delta}_h \theta} w_h = \frac{p^L}{\tau}$ and under the scheme $\left(\tau, \underline{p}^L(\tau)\right)$, the marginal migrant with skill θ^L earns in home country:

$$X_h^L = w_f - \frac{\underline{p}^L(\tau)}{\tau} \tag{G.6}$$

Using equations (G.4) (G.5) (G.6) and (3.18) we compute the variation in the share of population who migrates following the sale of temporary visas for low-wage jobs ($\underline{p}^L(\tau)$,τ).

G.2. Setting temporary visas at embassy or smuggling prices: the case of the DRC to South Africa

FIGURE G.1. Variation in the share of migrants for temporary visas priced at 125 USD and 600 USD, on the route from the DRC to South Africa



In section 6 we characterized the maximum eviction price set to drive smugglers out of business on each route. This would result in a destination country pricing visas differently, depending on migrants' origin countries. A more feasible policy we consider here is to sell visas at a low price, which could be benchmarked to current embassy prices or to smugglers' prices on some important route to the destination country. As an example for South-Africa, which is an important destination for economic migrants in Africa, it could be set around USD 125, the embassy price, [5] or around USD 600, the smugglers' price to reach South Africa from the DRC (see the survey led by Tshimpaka and Inaka, 2020). Figure G.1 presents in different colors the variations in the share of workers from DRC who would be willing to migrate to South-Africa under these schemes relatively to the status quo.

In the colored areas, the visa price under such schemes (USD 125 at the top and, resp. USD 600 at the bottom) is below the maximum eviction price, such that smugglers would be driven out of business. As shown by light shaded areas, the predicted increases in migration flows would still be limited for a large set of policy parameters (q, τ).

The white areas correspond to combinations of policy parameters (q, τ) such that the smuggling market would persist as human smugglers could still make profits after responding to these schemes by lowering their prices.

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