What Fueled the Illicit Opioid Epidemic? New Evidence from a Takeover of White Powder Heroin Markets*

PRELIMINARY DRAFT: DO NOT CIRCULATE

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Abstract

In recent years, the majority of drug overdose deaths in the U.S. have involved illicitly-produced opioids (primarily heroin and fentanyl), overtaking prescription opioids as the main driver of the opioid epidemic. In this paper, we provide novel evidence about a change in the heroin market that played a critical role in driving this transition: the takeover of white powder heroin production by Mexican Drug Trafficking Organizations (DTOs) from Colombian DTOs beginning in 2012. This resulted in heroin that was more potent, more variable, and more likely to be adulterated with fentanyl. Using a difference-in-differences approach that exploits the fact that white powder heroin markets were exposed to these changes while black tar heroin markets were not, we find that the Mexican DTO takeover increased heroin and fentanyl death rates by over 110% and 235%, respectively, from 2012 to 2019. We show that previously studied legal market interventions (e.g., the OxyContin reformulation and Prescription Drug Monitoring Programs) cannot explain our results and conclude that illicit market changes are a key determinant of the ongoing overdose epidemic.

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Over one million Americans have died of a drug overdose since 1999, making the ongoing overdose epidemic one of the worst public health crises in modern U.S. history (CDC 2021). There have been three waves of the epidemic, each involving a different form of opioids: prescription opioids in the 1990s and early 2000s, heroin from 2010 to 2013, and synthetic opioids, primarily illegally-produced fentanyl, ever since (see Figure 1). A natural question is why has the epidemic continued to persist with increasingly devastating effects but also change in terms of substances, geography (Zoorob 2019), and user demographics (Ruhm 2019). One explanation is demand-focused, namely that working class Americans abuse substances as their economic and social prospects continue to decline (Case and Deaton 2017; Deaton and Case 2021). However, changes in these factors alone only explain small share of the rise in deaths (Ruhm 2019; Currie and Schwandt 2021; Cutler and Glaeser 2021; Cutler and Donahoe 2024).

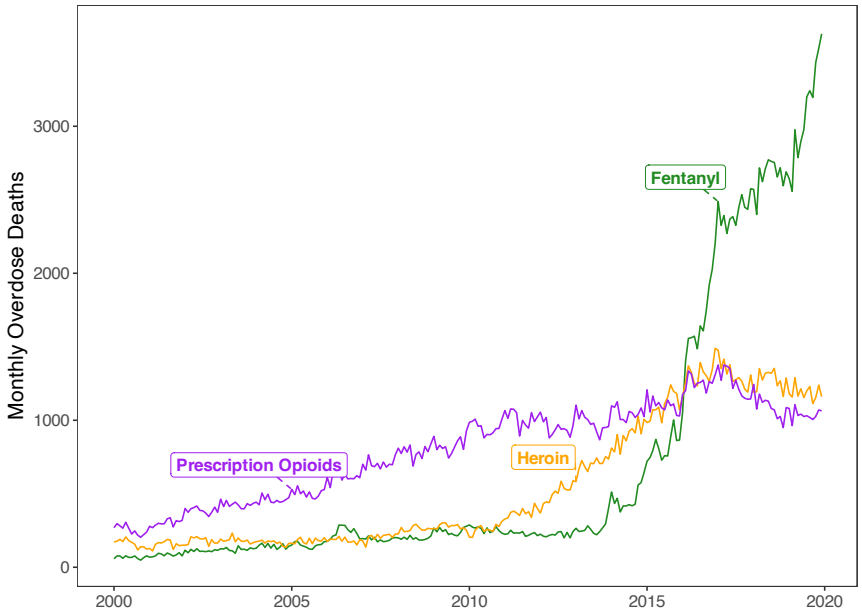


Figure 1: U.S. opioid overdose deaths by month and type of opioid from 2000 to 2019

Notes: Monthly mortality data are from the National Vital Statistics System (NVSS). We use the following ICD-9 codes for overdose death types: T40.2 for prescription opioids, T40.1 for heroin, and T40.4 for fentanyl.

An alternative explanation is that the transition from prescription to illicit opioid deaths is supply-driven. One hypothesis points to unintended consequences of interventions disrupting legal supply as driving the transition to heroin, such as the OxyContin reformulation and the introduction of Prescription Drug Monitoring Programs (Alpert et al. 2018; Evans et al. 2019; Kim 2021; Powell and Pacula 2021; Mallatt 2022). The implied mechanism is that curtailing prescription opioid supply causes increased demand for heroin due to user substitution. However, recent evidence suggests that this narrative is incomplete, and it also has limited ability to explain the current (synthetic opioid) wave of the epidemic. Zhang and Guth (2021) use new and more detailed data on OxyContin supply than prior literature and argue the OxyContin reformulation had no impact heroin mortality, and Donahoe (2024) and Soliman (2022) find that enforcement in the legal market caused declines in overdose deaths. Additionally, Zoorob (2019) and Moore et al. (2023) show that geography and smuggling are important factors in

explaining the ongoing fentanyl epidemic, but it is unknown how they came to matter.

In this paper, we provide the first causal evidence as to whether changes in the illicit market have led to increases in opioid overdose mortality. More specifically, our research question of interest is whether changes in the way heroin is produced and supplied caused use to be more lethal and fueled the second and third waves of the opioid epidemic. Qualitative research with longstanding heroin users suggests there were changes to heroin quality (e.g., adulteration with fentanyl) that began in 2012, particularly in eastern areas of the U.S. (Ciccarone et al. 2017). However, the origin of these changes has received limited attention in the literature and there is almost no causal evidence about how much they contributed to rising illicit opioid death rates.

Drawing from annual Drug Enforcement Administration (DEA) reporting on the types of heroin that are available, its purity, and where it is sourced from in 31 U.S. cities from 2004 to 2016, we begin our analysis by describing geographic variation in the heroin available in different areas and how it has changed over time. During the early 2000s, geography was highly predictive of the type and source of heroin available in different cities (Ciccarone 2009). In eastern cities, heroin was a predominantly white powder produced in Colombia to mimic the Southeast Asian heroin that became popular during the 1970s in the eastern U.S. Meanwhile, in western cities, heroin was predominantly a black tar that was produced in Mexico. This changed in 2012, when Mexican Drug Trafficking Organizations (DTOs) began to take over the production of white powder heroin from Colombian DTOs.[1]

We show that the takeover of white powder heroin production by Mexican DTOs led to several changes to heroin quality in cities where white powder heroin was more prevalent. First, it caused average heroin potency to increase by 33% from 2011 to 2016, reversing a 7-year decline, as well as caused potency to be more variable. Second, as Mexican DTOs took over the market, illegally-produced fentanyl, a more potent synthetic opioid, was increasingly used to cut or replace white powder heroin. Ethnographic research suggests that it was easier for suppliers to sell fentanyl to white powder heroin users (relative to black tar heroin users), even against users' desires, because white powder heroin and fentanyl look similar and it is difficult for users to know what they are purchasing before using (Mars et al. 2018, 2019). Further, Mexican DTOs had already experimented with introducing fentanyl in cities with white powder heroin markets before they were the main white powder heroin suppliers, causing a mini-epidemic that ended after the DEA raided a single fentanyl-producing lab in Mexico (CDC 2008).

We next turn to examining what effects these changes in heroin markets and quality had on mortality. To do so, we use restricted death records for all U.S. counties from 2000 to 2019 from the National Vital Statistics System (NVSS) and aggregate up to commuting zones. Our primary empirical analysis exploits the natural experiment resulting from the Mexican DTO takeover exclusively affecting cities with white powder heroin markets. We use a difference-in-differences design that compares changes in overdose mortality post-takeover for commuting zones that historically had white powder heroin markets compared to those that had black tar heroin markets. Commuting zones that were supplied black tar heroin serve as a good control group because Mexican DTOs remained their supplier and we do not observe a change in heroin

[1]Section 2 details historical divisions in the U.S heroin market and why they changed over time, providing data and citations from governmental intelligence reports that support our claims.

production over this period. However, they were subject to OxyContin being reformulated and other potential causes of increased illicit opioid death rates.

Consistent with the takeover being exogenous, we do not observe differential pre-trends in mortality for commuting zones with white powder versus black tar heroin markets for the eleven years prior to the Mexican DTO takeover. Then, following the takeover beginning in 2012, we find significant and dynamically growing increases in heroin and fentanyl overdose death rates in white powder heroin markets. On average, we estimate that the takeover caused heroin and fentanyl death rates to increase by roughly 110% and 235%, respectively, from 2012 to 2019. We perform several robustness checks that show these increases are not explained by other causes of rising illicit opioid death rates that have been examined in the literature (such as higher pre-reformulation OxyContin use in white powder heroin markets, state-level policies intended to curb prescription opioid diversion, changes in enforcement, and trade). Thus, we argue that the takeover of heroin supply by Mexican DTOs in 2012 is a key determinant of the heroin and fentanyl waves of the U.S. opioid epidemic.

Our main contribution to the literature is establishing a new driver of the sharp rise in illicit opioid death rates over the last decade, namely changes in heroin markets following the takeover of white powder heroin production by Mexican DTOs. Prior literature has largely argued that these increases are due to users substituting to heroin after policies were implemented to curtail prescription opioid misuse, most notably the reformulation of OxyContin to be abuse-deterrent (Alpert et al. 2018; Evans et al. 2019; Powell and Pacula 2021). We replicate and extend these studies and find that the takeover effect was just as important as the user substitution effect in driving the heroin wave of the opioid epidemic. However, we find that the takeover was twice as important as substitution in driving the later fentanyl wave through 2019. We also show that our findings explain key features of the changing epidemic, such as the shifting of overdose death rates to the eastern U.S. (Zoorob 2019), heroin death rates rising faster than use, and the opioid epidemic's increasing impact on non-Hispanic Black individuals despite limited exposure to prescription opioids (Hansen et al. 2023).

These findings have important policy implications because addressing changes in heroin markets requires a different approach than if substitution due to the curtailment of prescription opioids was the main cause of rising illicit opioid death rates. As one example, we are not aware of any current nationwide efforts to collect surveillance on drug supply and make that data available to public health departments and organizations that provide services to prevent overdoses. While it is unknown whether such programs would be effective, the immense harm to heroin users due to poorly understood changes in supply in recent years suggests a role for experimenting with such interventions.

More generally for the economics literature, our work highlights supply-side moral hazard as an important determinant of death rates in markets for illegal drugs. Because drugs are experience goods and quality is not regulated or standardized, suppliers may take actions that degrade consumer health to enhance profits against consumers' demands (Galenianos et al. 2012; Galenianos and Gavazza 2017). Users may thus be vulnerable to market changes, like who supplies illicit drugs, that lead to new or altered forms of existing products. More research in this area would be helpful to inform strategies to mitigate supply-side moral hazard in illegal

drug markets (e.g., through providing drug checking kits) and test whether they are effective.

The remainder of this paper is organized as follows. Section 1 describes the data sources. Section 2 presents empirical facts that motivate our focus on illicit opioid supply changes as well as provides information about U.S. heroin markets and how they have changed over time. Section 3 discusses our methodology and presents our main results that use data on heroin supply and overdose mortality for 31 cities were both sources of data are available. Section 4 shows how our findings can be extended to explain key facts about the illicit opioid epidemic nationally. Section 5 concludes.

1 Data

Our paper combines several sources of data. First, to measure overdose mortality, we obtain micro-data from the CDC's Restricted-Use Vital Statistics Data, which are also known as the Multiple Cause of Death (MCOD) research files. NCHS (2021) provide a comprehensive collection of information on all deaths in the United States. They include details on the decedent, the county and year of occurrence, the county of residence, the underlying cause of death, and multiple conditions (if applicable) since 1999. To code causes of death (e.g., prescription opioids, heroin, and fentanyl overdoses), we follow coding conventions used by the CDC (CDC 2021). We focus on the pre-COVID pandemic period from 1999 to 2019.

To better understand heroin trafficking (e.g., what organizations were involved in the production, distribution, and retail of heroin) and how it changed over time, we use federal intelligence information from the DEA's annual Heroin Domestic Monitoring Program (HDMP) and Heroin Signature Program (HSP) reports. The HDMP provides yearly information on the geographic source of heroin along with the type and purity sold at the street level in roughly 31 U.S. cities during the years reports were released: 1992, 1993, 2006, 2011, 2013-2016.[2] Data for additional years are obtained in some of these reports (e.g., the 2006 report also reports prices and where heroin originated from in 2004-2005), which gives us a more consistent panel covering 2004 to 2006 and 2009 to 2016. To our knowledge, the HDMP has not been updated since 2016. The HSP provides information on the purity and geographic source of all types of heroin nationally in the U.S. from 1999 to 2018.

While these are the best possible data that we are aware of in terms of tracking changes to heroin supply over time, there are several limitations to using them. First, they are based on undercover purchases made by DEA agents in retail heroin markets. Thus, samples are likely not an independent and identically distributed sample of retail heroin supply—they reflect the intelligence and priorities of the DEA. Because of this, we expect that changes to the drug environment (e.g., new entrants) to be measured with some lag. An example of this is that the DEA did not develop the capacity to chemically identify Mexican-originating white powder heroin until several years after they had already suspected that it was widely available (see Section 2). Second, we only observe aggregate city-level seizures and are not able to observe key features of the market that could impact mortality—such as the variation in potency across

[2]Some cities are only available in particular years or available separately as part of a much smaller "Geoprobes" program. Our main analysis focuses on the 31 cities with data consistently available from 2004-2011.

buys within markets. This will lead us to understate true underlying variability of potency (since each observation already represents an average over several samples).

To examine prescription opioid distribution across space and time, we use the Automation of Reports and Consolidated Orders System (ARCOS) database. These data contain the record of every controlled substance shipped in the United States from 2006 to 2019. Each record contains the DEA number, address, name, and business type for both the reporter and the buyer, as well as information on each transaction, such as the transaction date, opioid drug name, quantity, strength, and Morphine Milligram Equivalent (MME) conversion factor. This allows us to examine shipments of, for example, generic oxycodone or OxyContin, at any level of temporal or geographical aggregation. We also obtain other data sources that are cited where they appear from the literature, to incorporate controls for other variables shown to relate to illicit opioid deaths in prior work (e.g., state OxyContin misuse rates and trade flows).

2 Motivation and Background on U.S. Heroin Supply

This section helps contextualize our empirical setting and results. We start by presenting three motivating facts that are not fully explained by the existing literature on the transition from the prescription opioid wave to the heroin wave. We then present background information on U.S. heroin supply and how it has evolved over time. As we show, supply-side divisions that were already present in the 1990s would go on to shape the opioid epidemic in decades to come.

2.1 Facts Not Fully Explained by the User Substitution Narrative

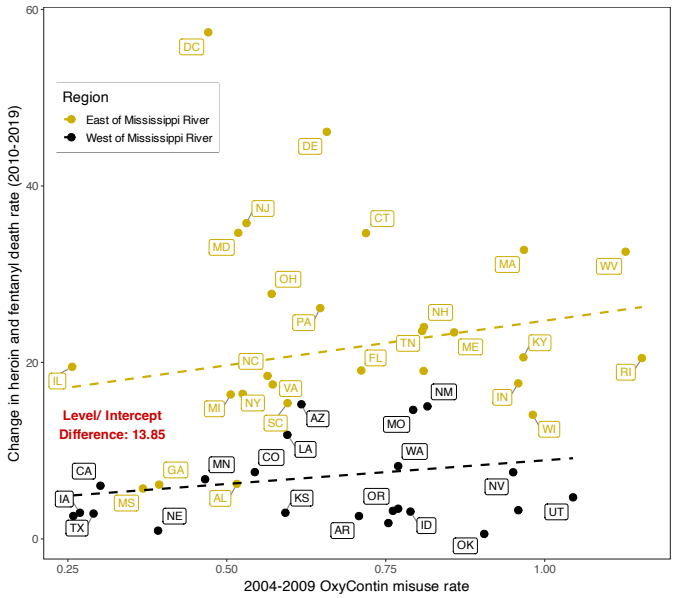
There are three empirical facts not fully explained by the mechanism suggested by the existing literature on the transition from the prescription opioid wave to the heroin wave of the opioid epidemic, namely that legal market interventions intended to curtail prescription opioid supply induced users to substitute to the illicit market. One of the most commonly exploited natural experiments in this literature is the OxyContin reformulation. For context, OxyContin, the blockbuster painkiller introduced by Purdue Pharma in 1996, became popular for non-medical use because pills could be easily manipulated to access the entire amount of the active ingredient. In August 2010, Purdue Pharma replaced this existing version with an abuse-deterrent formulation that made it difficult to abuse the drug in this fashion (Evans et al. 2019).

Figure 2 presents these three facts. The first is in Panel A, where we observe the relationship between a state's pre-reformulation OxyContin misuse rate and their change in illicit opioid death rate after the reformulation. This figure highlights that the geographic variation in heroin and fentanyl deaths is only partly explained by geographic variation in the extent of prescription opioid epidemic. Put differently, if substitution were the primary channel, one would predict that this correlation would be considerably stronger. Additionally, there is a suprising and significant geographic split relative to the Mississippi River, where states east of it experience considerably larger changes in illicit opioid mortality despite facing a similar distribution of OxyContin misuse rates in the pre-reformulation period relative to western states.

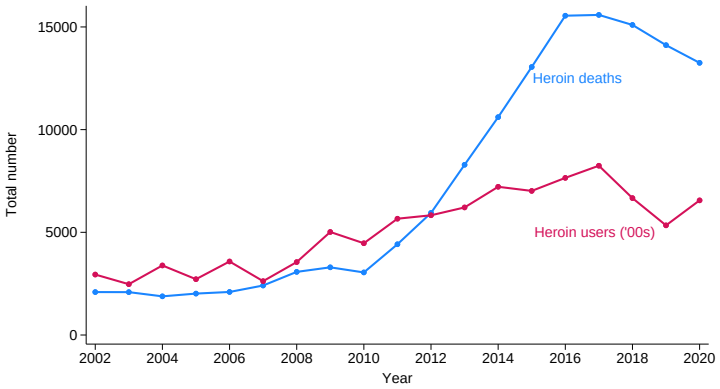
The next fact is in Panel B of Figure 2, which examines the yearly trends in heroin mortality and past-year heroin use. Heroin use data comes from the National Survey on Drug Use and

Figure 2: Empirical Facts Not Well-Explained by the User Substitution Hypothesis

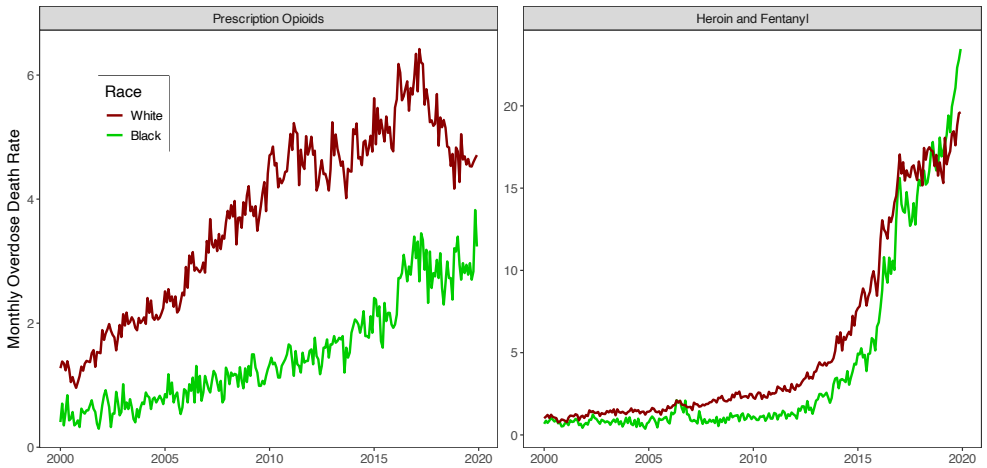
Panel A: Relationship between OxyContin Misuse and Changes in Illicit Opioid Overdose Deaths



Panel B: Trends in Yearly Heroin Overdose Deaths and Number of Heroin Users



Panel C: Monthly Trends in Opioid Overdose Deaths by Race and Opioid Class



Notes: Panel A presents a state-level scatter plot between the change in illicit opioid overdose deaths after the OxyContin reformulation on the y-axis and the pre-reformulation OxyContin misuse rate from Alpert et al. (2018) on the x-axis. Correlations are split by whether the state was east or west of the Mississippi River. Panel B shows the yearly number of heroin deaths (from the NVSS) and the estimated yearly number of heroin users (from the NSDUH). Panel C uses monthly NVSS mortality data and splits them by race and opioid type.

Health. If user substitution was the primary mechanism, one would predict that the number of heroin users would increase at the time of the OxyContin reformulation. However, the increase in use is stable over time and only heroin deaths begin to climb at a faster rate.[3] Lastly, the left figure of Panel C highlights that White individuals died at a considerably higher rate from prescription opioids than Black individuals. Therefore, if user substitution was the primary channel, we would predict that White individuals would die at a much higher rate (and be on a different trajectory) for heroin and fentanyl death rates than Black individuals. However, the right figure of Panel C shows that heroin and fentanyl death rates increased similarly for Black and White individuals despite very different levels of exposure to the prescription opioid wave of the epidemic. Because of these challenges, we turn to other potential explanations relating to the supply of illegal drugs. We also return to explaining these facts in Section 4.

2.2 The Transformation of the U.S. Heroin Market

In the early 1970s, heroin was supplied to the largest and most lucrative heroin markets in the eastern U.S. as a white powder that was sourced from the Golden Triangle of Southeast Asia (DEA 1994). In the 1990s, Colombian Drug Trafficking Organizations (DTOs) developed a "mimic" white powder heroin to compete for market share (DEA 1994). Owing in part to the infrastructure they developed to distribute cocaine in the 1980s, Colombian DTOs were able to sell their mimic heroin at a lower cost than traffickers coming from Southeast Asia and took over as the dominant suppliers in the east (Rosenblum et al. 2014). Meanwhile, Mexican DTOs established dominance in the heroin markets of the west. There, they produced different types of heroin that resembled black tar and, to a lesser extent, brown powder (DEA 1994).

The result of this is that by the early 2000s, the U.S. heroin market was geographically segmented (DEA 2013a, p. 3). Figure 3 highlights this phenomenon by showing that areas further east, namely longitudes greater than -91 degrees, were primarily supplied white powder heroin, while those further west were primarily supplied black tar heroin. One crude marker that is cited in DEA reports for this division of supply is the Mississippi River (hence the division in Figure 2); though, there is no evidence this was an explicit boundary and we observe some cities that straddle the river (e.g., St. Louis) receiving a mix of both types of heroin. In terms of country of geographic origin, chemical analyses of HDMP data indicate that most (74 percent) of the heroin sold in eastern cities was white powder heroin that was produced in Colombia (see Panel A of Appendix Figure A.1). Meanwhile, in western cities, most (89 percent) of the heroin sold was black tar heroin that was produced in Mexico (see Panel B of Appendix Figure A.1). These differences endured over time, in part, because heroin users in these different markets developed sticky tastes for the types of heroin they were sold (Ciccarone 2009).

The means of trafficking heroin into the U.S. by the Colombian and Mexican groups also differed in fundamental ways. Colombian DTOs used couriers who concealed or swallowed packages of heroin and smuggled them on flights destined for the U.S., principally the Miami

[3]Prior literature shows that the NSDUH under-counts heroin use in the U.S. by a factor of about 3 (Reuter et al. 2021). Thus, this figure is not definitive proof that heroin use did not rise after OxyContin reformulation as it is possible NSDUH failed to capture a differentially greater rate of increasing heroin use in 2010. Still, the very fast rate of increase in deaths relative to use is suggestive of part of the increase being due to rising death rates rather than rising use and motivates us to explore this possibility further in the remainder of the paper.

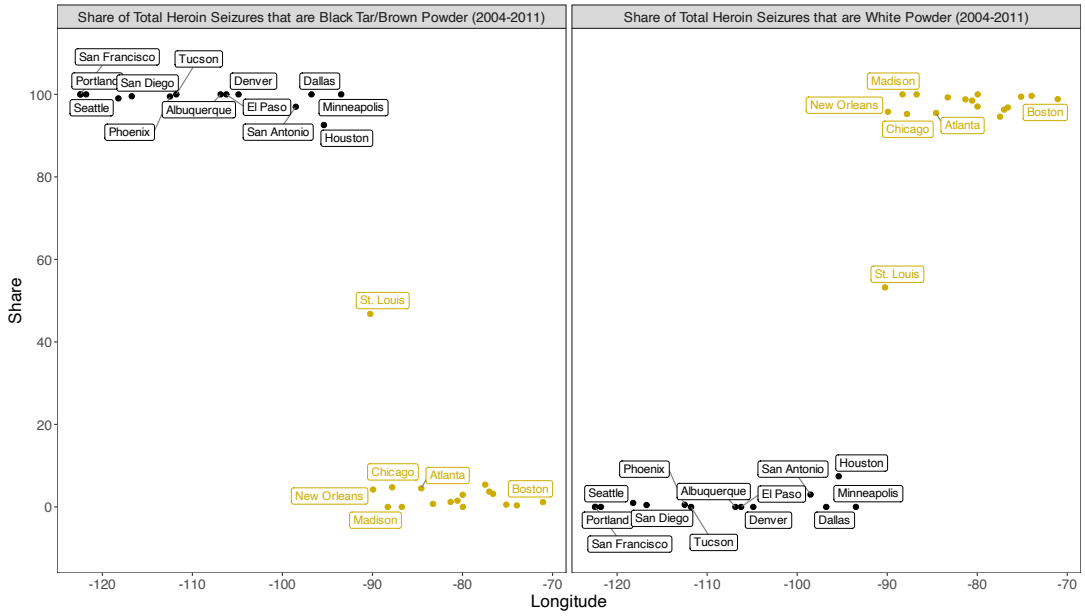


Figure 3: Geographic segmentation of the U.S. Heroin Market (2004 to 2011)

Notes: The data used to generate these come from the Heroin Domestic Monitoring Program (HDMP) and each dot represents a city that is repeatedly sampled as part of this program. The share of each type of heroin in a given city is calculated by using the total number of exhibits collected by heroin type from 2004 to 2011. The centroid of the city is used to plot the longitude.

(FL) and John F. Kennedy (NY) airports (DEA 2001). In contrast, Mexican DTOs smuggled heroin across the U.S.-Mexico border, primarily in San Diego, CA and El Paso, TX (DEA 2001).

In the early 2000s, several factors pushed Colombian DTOs to abandon heroin trafficking. First, in 1997, the U.S. and Colombia re-instated a treaty that permitted narcotics traffickers to be extradited to the U.S. Several high-profile narcotics traffickers were extradited, put on trial, and imprisoned, such as Fabio Ochoa Vásquez; he was a leader of the Medellin cartel and was extradited to the U.S. in 2001 and sentenced to 30 years in prison.[4] Second, Al-Qaeda's September 11, 2001, attacks on the U.S. caused airport security to tighten significantly. This raised the risks of smuggling drugs through airports and shifted trafficking to the U.S.-Mexico border, where Mexican DTOs had a geographic comparative advantage (DEA 2003).

Ultimately, Colombian DTOs scaled back trafficking and limited their focus to wholesale production. They sold heroin to Mexican DTOs to traffic across the border and distribute to retail suppliers throughout the U.S. Quotes that describe this transition in various DEA reports are provided in Appendix Table B.1. One representative quote is as follows:

> "The amount of South American heroin seized in the U.S. Arrival Zone along the Southwest Border—particularly Texas—increased significantly in 2003... Law enforcement reporting indicates that Colombian DTOs are increasingly relying on Mexican DTOs and criminal groups to transport South American heroin to the United States..." (DEA 2005, p. 68)

[4]Colombian DTOs clearly perceived the costs of this extradition treaty to be high. In the mid-1980s, Pablo Escobar founded a domestic terrorist organization called "Los Extraditables" to intimidate lawmakers to oppose the treaty. Their motto was "we prefer a grave in Colombia to a prison in the United States" (Butt 2022).

This chain of events ultimately resulted in Mexican DTOs taking over production themselves, but this started gradually (DEA 2001). Throughout the 2000s, Mexican DTOs sold black tar and brown powder heroin in eastern markets (DEA 2011, p. 3), but demand for these products was low and never "took off" due to users' and retailer sellers' preferences for white powder heroin.[5] Mexican DTOs even made a first attempt at introducing fentanyl in white powder heroin markets when they were a small player in these markets, leading to the spike in fentanyl deaths in eastern cities from 2005 to 2007 in Appendix Figure 1. This ended after the lab that manufactured the fentanyl in Toluca, Mexico was raided by the DEA in May 2006 (CDC 2008).

The tipping point was 2012-2013. The DEA's 2011 HDMP report does not suggest that anything had changed by that point, even stating "HDMP data for 2011 confirm that South America continues to be the primary source of heroin found east of the Mississippi River" (DEA 2013b, p. iii). Then, the first page of the 2013 HDMP report[6] notes:

> "Since the inception of the HDMP, the formal signature for Mexico has encompassed both brown and black tar Mexican produced heroin. Over the last several years however, DEA's Special Testing and Research Laboratory (SFL1) has tracked the phenomenon of alleged Mexican white powder heroin (AMW) produced from opium harvested in Mexico... Of particular interest is the fact that 57 of the 64 (89.1 percent) heroin exhibits classified as UNK which displayed the characteristics of alleged Mexican white heroin were purchased east of the Mississippi River, in cities identified as traditional SA [Colombian] heroin markets... This is likely an indication that the current retail heroin market in each of these cities is in transition and that Mexican drug trafficking organizations (DTOs) continue to expand their role in white heroin markets." (DEA 2016, p. 1)

The report indicated this heroin was likely created by Mexican DTOs mimicking the Colombian DTOs' processing methods or mixing in their own products with Colombian white powder heroin (DEA 2016). It was not until May 2015 that the DEA developed the capacity to chemically identify Mexico-originating white powder heroin. They retroactively applied the tests to 2014 seizures. By that time, 79 percent of all heroin seized nationwide originated in Mexico (see Appendix Figure A.2). By 2015, when tests were first used prospectively, the share of all heroin originating in Mexico had increased to 93 percent (see Appendix Figure A.2). City data reveal that once this testing was applied from 2014 to 2016, Mexican white powder heroin was the dominant type of heroin sold in eastern markets (see Panel D of Appendix Figure A.1). Critically to the identification strategy that we present below, western markets were unaffected by the takeover, and black tar heroin from Mexico continued to comprise the bulk of heroin sold there (see Panel C of Figure Appendix A.1).

2.3 Increased white powder heroin potency

As new Mexico-originating white powder heroin came on the market, heroin potency went up with it; see Appendix Figure A.3. This was largely due to the Mexico-originating white powder

[5] Personal communication with Bernie Malone, a retired heroin detective in New York and DEA agent.
[6] To our knowledge, the 2012 Heroin Domestic Monitoring Program report has not been publicly released.

heroin coming in at a higher potency than the Colombia-originating white powder heroin it was replacing in years prior. However, the potency of Colombia-originating white powder heroin also rose over the period, even as it became a small share of supply. Leading up to 2010, the potency of both major types of heroin was on a downward trend. While the entry of Mexican DTOs reversed this trend for white powder heroin, the decline continued for black tar heroin. This led to substantial differences in potency between white powder and black tar heroin, with white powder heroin being roughly twice as potent as black tar heroin by 2013.

These trends caused heroin in cities with white powder heroin markets to become more potent and variable, as seen in Figure 4. In the left figure of Panel A, we observe that the average purity in both black tar and white powder heroin markets is declining over time. Then, in 2012, there is a large increase in purity only in white powder heroin markets. The right figure of Panel A shows that the distribution of purity across cities also widened from 2011 to 2013, the years before and after the Mexican DTO takeover of white powder heroin production.[7] Panel B of Figure 4 shows that the cities that experienced these heroin purity changes experienced much sharper increases in heroin mortality than cities that did not (left). Further, this division (and especially the sharp break in trends) was even sharper than if we divide our sample of cities into those with high vs. low OxyContin shipments pre-reformulation (right), the main explanation for the trend break in heroin mortality in the literature (Evans et al. 2019).

2.4 Supplier substitution of fentanyl for white powder heroin

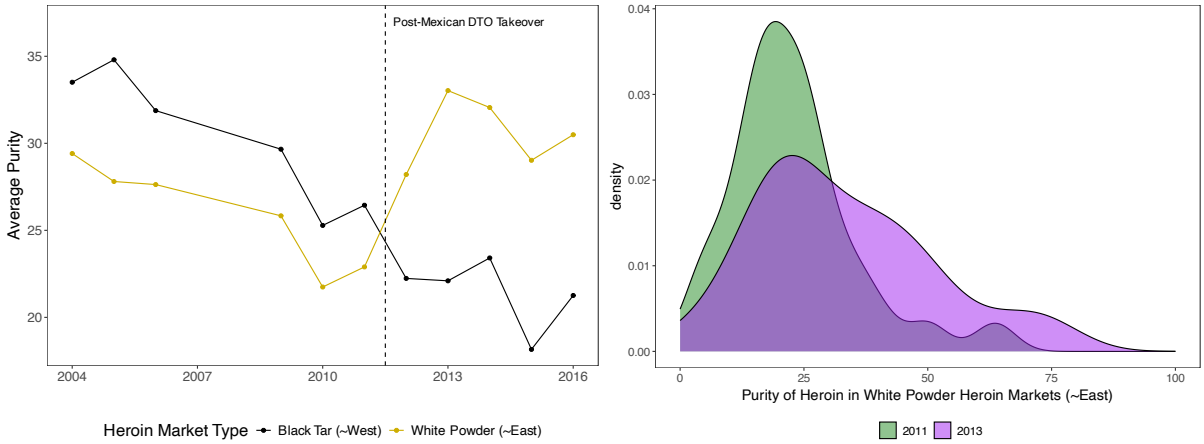
The next and likely more consequential change that we observe is the increasing presence of fentanyl in white powder heroin supply after Mexican DTOs took over the market. Why this only occurred starting in 2012-2013 and after the takeover by Mexican DTOs is unclear, but it is generally believed to be the result of a supplier- rather than user-driven shift (Mars et al. 2018, 2019). To understand this, it is important to note that heroin and other illicit drugs are classic examples of experience goods. Buyers are not able to observe the purity of drugs or what they are adulterated with until after they have consumed them, and there are no institutions to enforce quality in the illicit market. This creates a supplier moral hazard problem. Drug traffickers choose between maximizing instantaneous profits from adulterating drugs with lower-cost products but risk losing future profits if consumers perceive to have been ripped off and switch to other suppliers (Galenianos et al. 2012; Galenianos and Gavazza 2017).

At the import level, fentanyl is roughly 99 percent cheaper than heroin (Pardo and Reuter 2020). Thus, traffickers stand to profit considerably from substituting fentanyl for heroin. However, because fentanyl is roughly 20 times more potent than heroin, it is also more lethal (Comisssion 2022, Table B.1). Just 2 milligrams of fentanyl is considered a lethal dose for most individuals, leading small variations in quality across batches to cause an overdose (DEA 2024). The duration of fentanyl's effects is also shorter and requires people to take fentanyl more frequently, making it more addicting (Comisssion 2022). Thus, some consumers may wish to use heroin rather than fentanyl or fentanyl-adulterated heroin.

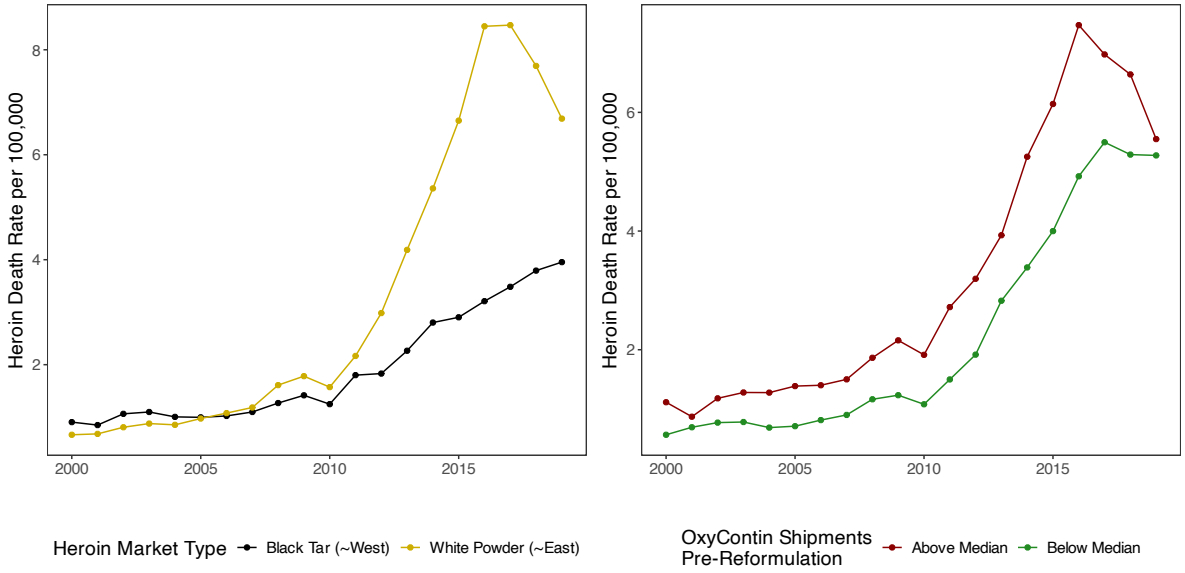
[7] Unfortunately, our data do not allow us to observe the variability of purity within cities. Variability across cities likely understates the true underlying variability of heroin supply since the observations for each city are an average of roughly 10 to 20 purchases in a given year.

Figure 4: Heroin Purity and Mortality Over Time

Panel A: Changes in Heroin Purity and Variability



Panel B: Changes in Heroin Mortality by Market Type and OxyContin Shipments



Notes: The data for Panel A are from the Heroin Domestic Monitoring Program (HDMP). The left figure in Panel A plots the yearly average heroin purity separately for white powder and black tar markets. The right figure of Panel A shows the distribution of purity one year before and one year after the Mexican DTO takeover for the white powder heroin market. The data for Panel B are from the National Vital Statistics System, where the left figure plots the yearly heroin overdose death rate for each type of heroin market and the right figure splits these same markets by their OxyContin shipments from 2008 to 2009 (i.e., pre-reformulation). Appendix Figure A.4 shows the distribution of changes in illicit opioid overdose deaths by heroin market type.

The supply-side moral hazard problem concerning fentanyl would have been especially significant white powder heroin markets. Fentanyl is also a white powder, making it more difficult to know if white powder heroin is adulterated with fentanyl before using it (especially relative to black tar heroin). Appendix Figure A.5 uses pictures of these different drugs to illustrate this. Ethnographic studies also indicate this and the supplier-driven shift to cutting heroin with more potent fentanyl starting in 2012 (Ciccarone et al. 2017; Mars et al. 2018, 2019). For example, one study asked a 30-year-old man who had been using heroin for 18 years about changes to heroin supply in Massachusetts (Ciccarone et al. 2017, p. 148):

> Q: So the heroin that is out there right now, how long has that been around? Have there been any changes?
>
> *A: It's been changing, like 3-1/2 years ago, maybe 4. 2012–2013, it's like that's when like the bullshit started coming in. Like mother-fucker's realized, if I got 3 grams of dope I can put 3 grams of bullshit on it.*
>
> Q: What do you mean by bullshit?
>
> *A: Like cut. Well, the fake cut or fentanyl or whatever [. . .]*

The first DEA data validating user reports of fentanyl contaminating white powder heroin supply appeared in the 2014 combined HDMP and HSP report. The report noted that 21 total heroin samples purchased through the program in 2014 contained fentanyl, and retroactively noted that 7 exhibits from 2013 contained fentanyl (DEA 2015, p. 23).[8] The report also noted that all samples containing fentanyl were purchased in eastern cities where white powder heroin was prevalent. Later HSP reports note the shares of different types of heroin that contained fentanyl. By 2018, fentanyl was detected in roughly one-quarter (23 percent) of all white powder heroin samples but still fewer than 1 percent of black tar heroin samples (DEA 2020, p. 10).

Two facts help explain why the Mexican DTO takeover of eastern heroin markets sparked the switch to fentanyl. First, expanding production to supply heroin to the entire U.S. market would have required large amounts of heroin. Mexican DTOs increased production in the early 2000s in advance of their takeover, but their heroin production stalled and declined in the early 2010s (see Appendix Figure A.6), even as Mexican DTOs' heroin market share was expanding and the number of heroin users was growing as a result of people substituting from prescription opioids to heroin (Compton et al. 2016) (see also Figure 2). Substituting fentanyl for heroin would have eased production constraints. Second, Mexican DTOs had already demonstrated their intent to sell fentanyl in white powder heroin markets when they were a much smaller supplier (as noted above and shown in Appendix Figure A.7). After Mexican DTOs became the sole supplier of white powder heroin, such moves would be more consequential.

3 The Effects of Heroin Market Changes on Overdose Mortality

In this section, we both describe the methodology used to estimate the causal effects of the supply-side changes to heroin markets discussed in Section 2 and present our results. We

[8] The lack of noting fentanyl in the 2013 report highlights the clear lag between changes to heroin markets and what shows up in the DEA documents.

conduct our analysis only in commuting zones where we know the heroin purity, source, and type, based on the 31 cities that are tracked in the DEA's HDMP reports.

We begin by estimating an event study model of the form

$$Y_{ct} = \sum_{t=-12, t\neq -1}^{7} \rho_t(\text{White_Powder_Market}_c \times 1\{\text{year}=2012+t\}) + \lambda_c + \gamma_t + \nu_{ct}, \quad (1)$$

where Y_{ct} are overdose death rates per 100,000 in commuting zone c in year t. In our main specification, we define a commuting zone with a white powder heroin market as one that has 30% or more of its pre-Mexican DTO takeover heroin seizures being white powder, but we also present results for cutoffs of 1%, 5% and 50%, as well as a continuous version. λ_c and γ_t are commuting zone and year fixed effects, respectively, and regressions are population-weighted. Standard errors are clustered at the commuting zone. The coefficients of interest are therefore ρ_t, which capture the year-by-year differences in within-changes among commuting zones that are exposed to the DTO takeover relative to ones that are not.

We also estimate an average effects version of Equation (1) with

$$Y_{ct} = \beta(\text{White_Powder_Market}_c \times \text{Post_Mexican_DTO_Takeover}_t) + \lambda_c + \gamma_t + \varepsilon_{ct}, \quad (2)$$

where all variables are defined as before except for Post_Mexican_DTO_Takeover, which is an indicator variable for the period from 2012 to 2019. The coefficient of interest is therefore β, which captures the average mortality impact among commuting zones that are exposed to the Mexican DTO takeover relative to ones that are not.

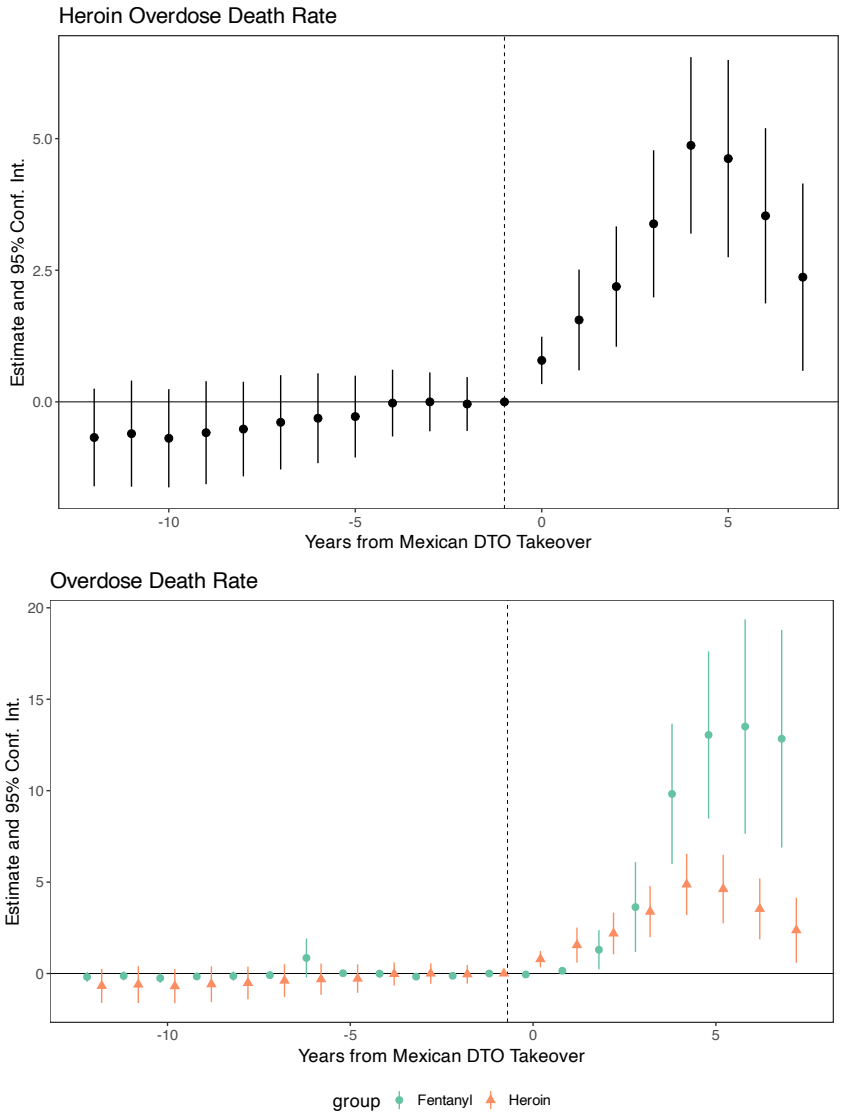
The top panel of Figure 5 provides the event study for heroin overdose deaths from estimating Equation (1).[9] First, we do not observe a significant pre-trend in heroin mortality between commuting zones with white powder versus black tar heroin markets for over ten years prior to the Mexican DTO takeover. Then, we see an immediate and dynamic increase in the heroin death rate in white powder heroin markets relative to black tar heroin markets that coincides with the Mexican DTO takeover of white powder heroin markets and lasts for approximately five years. Afterwards, it slowly declines but remains significant. The bottom panel shows that as the heroin death rate declines in white powder heroin markets, those same markets experience a dynamic and large increase in fentanyl overdose death rates.

We next estimate Equation (2) and present the average mortality impacts of the takeover of white powder heroin markets in Table 1.[10] The average effect from the top panel of Figure 5 is in Column (1), namely an increase in heroin overdose deaths of 3.256 per 100,000 (108% change from the mean). The average effect for fentanyl from the bottom panel of Figure 5 is in Column (2), which shows an increase of 6.813 overdose deaths per 100,000 (236%). The last two columns of Table 1 show that the increase in overdose mortality is unique to opioids and is specifically driven by heroin and fentanyl, as Columns (1) and (2) sum approximately

[9] Appendix Figure A.8 re-estimates Equation (1) for heroin overdose death rates but with alternative treatment definitions of white powder heroin markets, while Appendix Figure A.9 repeats the event study analysis for additional outcomes, namely mortality from heroin and fentanyl, only fentanyl, and only heroin.

[10] Appendix Table B.2 provides additional outcomes of interest, namely mortality from heroin and fentanyl, only fentanyl, and only heroin.

Figure 5: The Dynamic Mortality Impacts of the Mexican DTO Takeover



Notes: These figures present the ρ_t coefficients from estimating Equation (1). The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes 31 commuting zones where we have HDMP data on heroin type. The top panel is only heroin overdose deaths, while the middle panel presents both heroin and fentanyl overdose deaths.

to Column (3), and Columns (3) and (4) are almost identical. Appendix Tables B.3 and B.4 repeat this exercise but replace our binary treatment indicator with a continuous and quartile version, respectively, and arrive to the same conclusions.

Table 1: The Average Mortality Impacts of the Mexican DTO Takeover

	Heroin (1)	Fentanyl (2)	Any Opioids (3)	Any Drug (4)
(White Powder Market)X(Post-Takeover)	3.256***	6.813***	11.68***	11.13***
	(0.6198)	(1.322)	(1.872)	(2.329)
Dependent variable mean	3.0180	2.8879	9.2226	16.072
R^2	0.80428	0.65074	0.75079	0.77956
Observations	620	620	620	620

Notes: This table presents the β coefficients from estimating Equation (2). The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data.

We then explore alternative explanations in Figure 6 by again estimating Equation (2), but we now add various controls to examine the stability of our results. We first test for the possibility that previously studied legal market interventions may impact our results. We control for pre-reformulation OxyContin shipments using ARCOS data (see section 1) in a commuting zone (as a continuous and binary variable in two separate specifications) and interact it with an indicator variable for the post-2010 period (i.e., after OxyContin was reformulated), and we do not see any significant attenuation of our results. Next, we add a triple interaction term between pre-reformulation OxyContin, being in a white powder heroin market, and post-reformulation (as well as the double interactions between these variables). This is to control for the possibility that OxyContin and white powder heroin are closer substitutes than OxyContin and black tar heroin, leading to more substitution in white powder than black tar heroin markets. We again do not see attenuation of our results. Moreover, Appendix Table B.5 shows that the coefficient on the interaction term between OxyContin shipments, white powder heroin markets, and post-reformulation is negative, showing differentially greater substitution from OxyContin to white powder heroin cannot explain any of the differential rise in heroin death rates in these cities.

Next, we include indicators for the period after a state passes either a Prescription Drug Monitoring Program or a pill mill law, which are state-level policies intended to prevent prescription opioid diversion that prior literature argues increased illicit opioid death rates (Mallatt 2018; Kim 2021; Balestra et al. 2021; Mallatt 2022). These exercises show that our main coefficient of interest, the β for heroin overdose death rates, is very stable and suggests that our results are not affected by policies intended to reduce prescription opioid misuse. The remainder of Appendix Figure 6 explores whether enforcement or trade affects our main results. More specifically, we first control for the yearly number of officers per 100,000 in a given commuting zone using Law Enforcement Officers Killed and Assaulted (LEOKA) data. This is our best nationwide measure of whether enforcement changed during our sample period. Second, we use the same trade data as in Moore et al. (2023), namely those from the U.S. Census' Trade Online portal on imports in 2008 based on the "state of destination" code. This is meant to capture

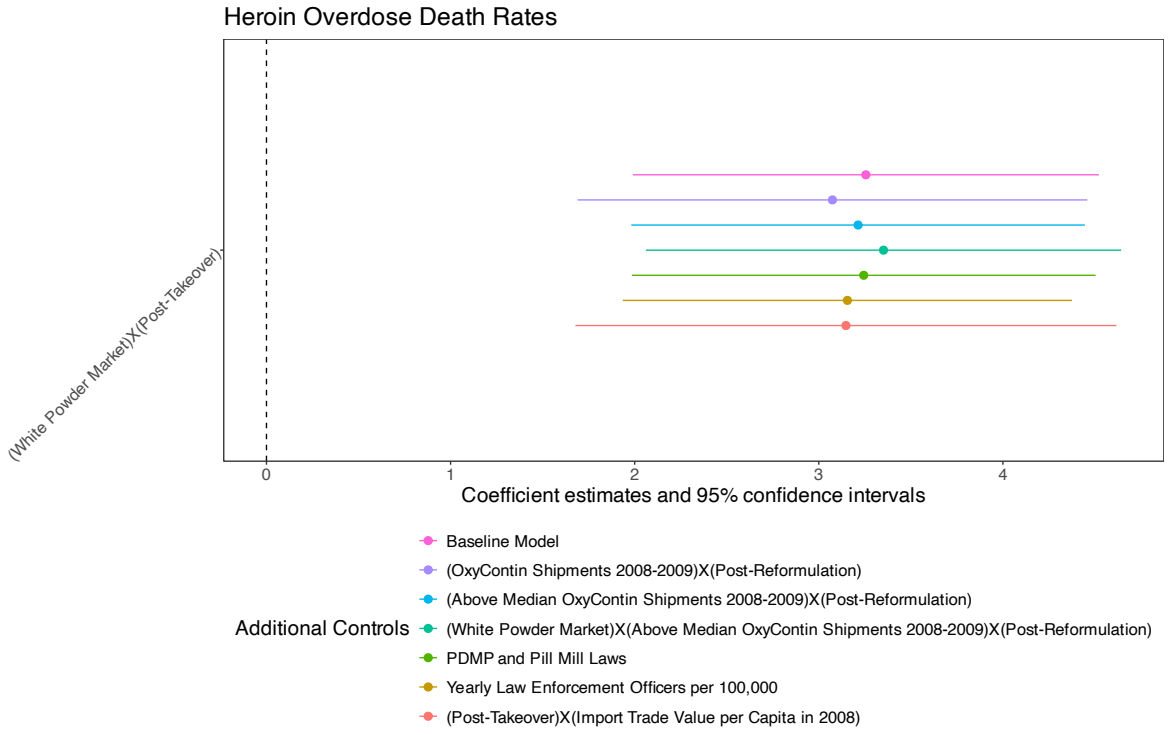


Figure 6: The Average Mortality Impacts of the Mexican DTO Takeover (HDMP Markets)

Notes: This figure presents the β coefficients from estimating Equation (2) with different control variables. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data. Appendix Table B.5 is the table version equivalent.

smuggling of fentanyl via legal trade packages. We interact it with a post-takeover indicator variable. Both of these exercises show that our main coefficient of interest is again very stable.

As a final robustness exercise, we conduct several permutation tests in Appendix Figure A.10. For each outcome of interest, we randomize with replacement which commuting zone that participated in the HDMP gets "treated," then run Equation (2) 1,000 times using a new sample each time. The figures present the distribution of coefficients obtained from these regressions, where the dotted vertical red line is our estimated coefficient. This exercise suggests that our results are very extreme relative to random variability of increases in heroin and fentanyl death rates across cities over this period.

4 The National Importance of the Takeover

In this section, we present additional results to frame the national implications of our findings in the previous section, which uses data for 31 cities. First, we show that we obtain similar results if we expand our HDMP market analysis nationwide by using longitude to define likely exposure to the takeover (Section 4.1). Second, we show the takeover had larger effects in commuting zones with higher pre-takeover heroin use (as proxied by death rates), consistent with a shock that increased the death rate of existing heroin users (Section 4.1). Third, we show the takeover had large impacts on death rates among non-Hispanic Black Americans and can explain the recent demographic transition of the epidemic (Section 4.2). Finally, we extend the literature on OxyContin reformulation to assess the separate contribution of user substitution and the takeover of white powder heroin markets to illicit opioid mortality after 2010 (Section 4.3).

4.1 Nationwide Analysis

Our results from Section 3 focused on markets where we have data on heroin purity, source, and type. We now first turn to a nationwide analysis, which is similar to Equations (1) and (2), but the treatment variable is now Longitude_c instead of $\text{White_Powder_Market}_c$, and we use all contiguous U.S. commuting zones instead of only ones that we have HDMP data for. The decision to use longitude is driven by what we observe in Figure 3: a clear geographic segmentation of the U.S. heroin market at around -91 degrees. Longitude_c captures the longitude of the commuting zone centroid, and we use both continuous and binary versions when estimating

$$Y_{ct} = \sum_{t=-12, t\neq -1}^{7} \rho_t(\text{Longitude}_c \times 1\{\text{year}=2012+t\}) + \lambda_c + \gamma_t + \nu_{ct}. \tag{3}$$

For the binary version, we use -91 degrees as the longitude cutoff that splits the U.S. heroin market so that areas east of -91 degrees (more positive longitudes) are treated while those west of it are not, but the results are not sensitive to this choice. We also estimate an average effects version of Equation (3) with

$$Y_{ct} = \beta(\text{Longitude}_c \times \text{Post_Mexican_DTO_Takeover}_t) + \lambda_c + \gamma_t + \varepsilon_{ct}, \tag{4}$$

where all variables are defined as before except for Post_Mexican_DTO_Takeover, which is an indicator variable for the period from 2012 to 2019. The coefficient of interest is therefore β, which captures the average mortality impact among commuting zones that are east of -91 degrees longitude relative to ones that are west of it. As in Section 3, we cluster standard errors on commuting zones and population weight the regressions.

We begin by estimating Equation (3), the parallel to Equation (1), in Appendix Figure A.11. Similar to Figure 5, we observe large and significant dynamic increases in heroin overdose deaths that begin to decline as fentanyl takes off. Appendix Figure A.12 re-estimates Equation (3) for heroin overdose death rates but with alternative treatment cutoffs for longitude.

Table B.6 presents the results from estimating Equation (4), the parallel to Table 1 and Equation (2). Columns (1) to (4) utilize a binary treatment measure for longitude, where commuting zones east of -91 degrees are treated while those west are not. Columns (5) to (8) are the continuous version. These two treatment definitions show qualitatively similar results both to each other and to Table 1, namely large increases in heroin and fentanyl overdose deaths and that the increase in overdose mortality is primarily driven by these two opioids. The main difference is that the magnitudes are larger for the nationwide analysis relative to the HDMP-market analysis. Similar to the conclusions of Appendix Figure 6, our coefficient estimates for heroin overdose death rates in Appendix Figure A.13 remain stable when we control for policies intended to curtail opioid prescribing, enforcement, and trade.[11]

Next, we extend our national analyses by taking advantage of additional variation in exposure to treatment based on pre-takeover heroin use. The intuition is that commuting zones with more heroin users would have been more susceptible to a shock to heroin markets that increased death rates conditional on use. We proxy pre-takeover use with pre-takeover heroin death rates (an average from 2005 to 2011) and estimate

$$\begin{aligned} Y_{ct} =& \beta(\text{Heroin OD}_{c,2005-2011} \times \text{Post_Mexican_DTO_Takeover}_t \times \text{Longitude}_c) + \\ & \delta(\text{Post_Mexican_DTO_Takeover}_t \times \text{Longitude}_c) + \\ & \alpha(\text{Heroin OD}_{c,2005-2011} \times \text{Post_Mexican_DTO_Takeover}_t) + \lambda_c + \gamma_t + \varepsilon_{ct}, \end{aligned} \tag{5}$$

where all variables are defined as before except we now add Heroin $\text{OD}_{c,2005-2011}$, the heroin overdose death rate from 2005 to 2011.[12] The results from estimating Equation (5) are in Table 2. They show that heroin death rates increased by 1.797 deaths per 100,000 (185%) in likely white powder heroin markets in the average year after the Mexican DTO takeover, and by an additional 0.1453 deaths per 100,000 (15%) per each additional heroin death per 100,000 in the pre-takeover period. Effects are even larger for fentanyl and total opioid/drug overdose deaths. Appendix Table B.8 shows similar results if we instead use heroin death rates from 2005 to 2009 at baseline. Thus, the shock had larger effects on death rates in areas with more heroin use even prior to OxyContin being reformulated. This evidence strongly suggests an exogenous shock to existing heroin users/markets over this period and is also consistent with heroin death rates increasing sharper than heroin use rates (as shown in Figure 2).

[11] Appendix Table B.7 is the table version equivalent of Appendix Figure A.13 and Appendix Figure A.14 suggests that our results are not driven by chance.

[12] We also estimate Equation (5) with Heroin $\text{OD}_{c,2005-2009}$, the heroin overdose death rate from 2005 to 2009.

Table 2: The Average Mortality Impacts of the Mexican DTO Takeover (Nationwide)

	Heroin (1)	Fentanyl (2)	Any Opioids (3)	Any Drug (4)
(2005-2011 Heroin Death Rate)X(Post-Takeover)	0.0717**	0.0250	0.1257**	0.1720**
	(0.0312)	(0.0159)	(0.0606)	(0.0810)
(Longitude Binary)X(Post-Takeover)	1.797***	3.611***	6.968***	7.015***
	(0.3605)	(0.6045)	(0.9676)	(1.232)
(2005-2011 Heroin Death Rate)X(Post-Takeover)X(Longitude Binary)	0.1453***	0.3970***	0.5502***	0.6237***
	(0.0533)	(0.0900)	(0.1553)	(0.1888)
Dependent variable mean	0.97026	1.7834	5.6437	9.6917
R^2	0.74754	0.65606	0.74451	0.76352
Observations	13,820	13,820	13,820	13,820

Notes: This table presents the β coefficients from estimating Equation (5). The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States.

4.2 Explaining the Opioid Epidemic's Demographic Transition

In this section, we estimate Equation (4) and show results separately for non-Hispanic Black and non-Hispanic White individuals. For Black individuals, we observe an increase in the illicit opioid (heroin or fentanyl) death rate of 8.764 deaths per 100,000 (283%). The increase for White individuals is 10.69 deaths per 100,000 (302%). Thus, this shock helps explain why the heroin and fentanyl death rate increased similarly for Black and White individuals despite Black individuals having lower exposure to the prescription opioid wave (as shown in Figure 2).

Table 3: The Average Mortality Impacts of the Mexican DTO Takeover (Nationwide)

	Illicit Opioids (1)	Black (2)	White (3)
(Longitude Binary)X(Post-Takeover)	9.399***	8.674***	10.69***
	(0.7122)	(1.535)	(0.8490)
Dependent variable mean	2.7537	3.0969	3.5428
R^2	0.69044	0.57967	0.69996
Observations	13,820	13,600	13,820

Notes: This table presents the β coefficients from estimating Equation (4). The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are illicit opioid overdose deaths per 100,000 (heroin or fentanyl) and the sample includes all commuting zones in the contiguous United States.

4.3 Decomposing Deaths into Substitution and Takeover Effects

In this last section, we reconcile our findings that a large share of the increases in illicit opioid death rates since 2012 have been due to supply changes with prior literature that suggests all of these increases are attributable to substitution following OxyContin being reformulated to be abuse deterrent in August 2010 (Alpert et al. 2018; Evans et al. 2019; Powell and Pacula 2021). To do so, we replicate Alpert et al. (2018) whose study design allows for straightforward incorporation of additional controls for the white powder heroin takeover based on the longitude

variable defined above in Section 4.1 (east of -91 degrees longitude).[13] Aggregating our mortality data to the state-level, as in Alpert et al. (2018), we estimate

$$Y_{st} = \alpha_s + \gamma_t + \delta_1(Post_t^R \times Oxy_s^{Pre}) + \delta_2(t \times Oxy_s^{Pre}) + \delta_3(Post_t^R \times (t-2011) \times Oxy_s^{Pre}) + \gamma_1(Post_t^T \times Long_s^{Pre}) + \gamma_2(t \times Long_s^{Pre}) + \gamma_3(Post_t^R \times (t-2012) \times Long_s^{Pre}) + \epsilon_{st},$$

(Extension of Eq. 2, Alpert et al. 2018)

where the first half of this equation is the same as the baseline specification in Alpert et al. (2018) and uses the same state-level pre-Reformulation OxyContin misuse rate from 2004 to 2009 from the National Survey on Drug Use and Health. The specification controls for pre-existing trends and allows for a level shift and trend break in states with higher pre-Reformulation OxyContin use after 2011 (Alpert et al. 2018, p.19).[14] The second half adds in the same terms for our indicator of likely exposure to heroin supply changes (i.e., the state centroid having a longitude of greater than -91 degrees), interacted with a pre-trends term and terms allowing for a level shift and post-trend after 2012. We follow Alpert et al. (2018) and weight regressions by population and cluster standard errors at the state level.

We start by estimating this equation using data from 1999-2013 as in Alpert et al. (2018). After estimating it, we report the 3-year effect of OxyContin reformulation that is reported in Alpert et al. (2018): $(\hat{\delta}_1 + 2\hat{\delta}_3)$, which gives the effect of having 1 percentage point higher OxyContin misuse prior to reformulation on heroin death rates through 2013. We use this to benchmark our estimates against the results reported in Alpert et al. (2018)'s paper. We then adjust this estimate to reflect the effect for the average state: i.e., $\bar{p}\hat{\delta}_1 + 2\bar{p}\hat{\delta}_3$, where $\bar{p}$ denotes the average state's pre-reformulation OxyContin misuse prevalence (0.57 percent). We compare this to the effect of heroin supply changes in the average area (i.e., the increase in deaths solely attributable to being a white powder heroin market over the same time frame): $\mu\hat{\gamma}_1 + \mu\hat{\gamma}_3$, where μ denotes the share of states with longitude greater than -91 degrees. This directly compares how much of the increase in illegal opioid death rates is due to larger increases in death rates in states with higher pre-reformulation OxyContin misuse rates versus states exposed to the takeover described in Section 2 using the same methods in prior literature.

Results are reported in Table 4, where Column (1) replicates the baseline specification in Alpert et al. (2018). As in their study, we find no pre-trend in heroin mortality in states with higher pre-Reformulation OxyContin use and a jump in mortality after reformulation as well as a trend break. The coefficients imply that for each 1 percentage point higher OxyContin use pre-reformulation, heroin deaths increased 0.82 deaths per 100,000 on average after 2011 and by an additional 0.71 deaths per 100,000 each year after 2011 (though the latter term is imprecisely estimated). Using the equation noted above, we obtain approximately the same estimate for the 3-year effect of OxyContin reformulation that is reported in (Alpert et al. 2018,

[13] Evans et al. (2019) estimate a national trend break specification, which they use to argue the timing of the national trend break in heroin death rates coincided with the month after OxyContin was reformulated (September 2010). Though the month they identify for a trend break could be influenced by the effects of the supply changes we study (their models include data from 2012-2014), it is conceptually difficult to extend their analysis to incorporate controls for heroin supply changes due to the lack of cross-sectional variation in their main model. Thus, we focus on extending Alpert et al. (2018) who use cross-sectional variation instead.

[14] Though OxyContin was reformulated in mid-2010, Alpert et al. (2018) use 2011 rather than 2010 for their post-reformulation period due to 2011 being the first full year after reformulation. We follow their approach.

Table 2 col. 1) (2.25 vs. 2.21). After our adjustment for OxyContin misuse prevalence, we find OxyContin reformulation caused heroin death rates to increase by 1.28 deaths per 100,000 in the average state based on this baseline specification. This is close to the average increase in heroin death rates over this period (1.57 deaths per 100,000, shown in Table 4), showing why prior literature concluded that all of the heroin epidemic was due to OxyContin reformulation.

Column (2) adds in the same set of time-series variables, interacted with a binary variable for each state being east of -91 degrees longitude. Starting with the OxyContin variables, we do not see any attenuation of the post-effect. However, the post-trend-break term ($\hat{\delta}_3$) attenuates significantly (by 64%). Consistent with prior sections, we also observe large and significant increases in heroin mortality post-2012 attributable to being a likely heroin market. The coefficients imply heroin death rates increased by 0.68 more deaths per 100,000 on average in white powder markets after 2012, and an additional 0.72 deaths per 100,000 annually. The effects in the average area show the heroin wave through 2013 was approximately equally driven by the OxyContin reformulation and heroin supply changes.

Table 4: Decomposing heroin overdose increase into supply shift and substitution components (Alpert et al. (2018) Extension)

	Heroin (1999-2013)		Heroin + fentanyl (1999-2019)	
	(1)	(2)	(3)	(4)
Initial Oxy × pre-trend	-0.06	-0.05	0.16*	0.14
	(0.10)	(0.12)	(0.09)	(0.08)
Initial Oxy × post-2011	0.82***	0.82***	-0.28	0.40
	(0.28)	(0.29)	(0.79)	(0.72)
Initial Oxy × post-2011-trend	0.71	0.28	2.23***	1.02*
	(0.46)	(0.35)	(0.91)	(0.57)
Long. (≥ -91) × pre-trend		-0.01		0.04
		(0.06)		(0.05)
Long. (≥ -91) × post-2012		0.68***		0.38
		(0.17)		(0.50)
Long. (≥ -91) × post-2012-trend		0.72***		2.09***
		(0.21)		(0.32)
Oxy reform 3-year effect: (as reported in Alpert et al.)	2.25	1.54		
Effect in average area:				
OxyContin reformulation	1.28	0.79	10.01	4.87
	[0.24, 2.31]	[-0.04, 1.62]	[2.14, 17.87]	[-0.13, 9.88]
Mexican DTO takeover		0.83		8.94
		[0.47, 1.20]		[6.27, 11.61]
Average change (2011-last year)	1.57	1.57	13.63	13.63
N	306	306	1,071	1,071

Notes: State-level two-way fixed effects regressions on overdose death rates. *(**)*** denotes statistical significance at $p < 0.1(0.05)0.01$.

Columns (3) and (4) repeat this exercise but extends the sample through 2019 and also

examine effects on deaths from any illegal opioid (heroin or fentanyl). This is similar but not identical to Powell and Pacula (2021).[15] As before, we find including controls for heroin supply changes significantly attenuates the estimated effects of OxyContin reformulation. However, the attenuation of the effects of OxyContin reformulation is more severe (roughly 51%). We find heroin supply effects explain roughly 77% of the rise in illegal opioid death rates after 2012.

Consistent with prior literature, we continue to find an effect of the OxyContin reformulation in causing substitution to illegal opioids and leading to increased heroin and fentanyl death rates. However, we extend this literature to show that the magnitude of this is less than previously thought and conclude that changes in heroin supply are the main factor driving the epidemic in recent years.

5 Conclusion

This paper shows that changes to U.S. heroin markets since 2012 played a major role in driving the opioid epidemic and transition of death rates from prescription to illegally produced opioids. Policies and interventions to expand harm reduction services, stem the flow of highly potent opioids, and relay intelligence about changing drug supply conditions to public health organizations may be needed to prevent further harms and similar crises from recurring in the future. Responses to the epidemic should also consider new populations that have been impacted by supply shocks to the illicit market, particularly non-Hispanic Black individuals, whose pathways to opioid use may be occurring through other mechanisms than opioid prescribing. Preventing opioid abuse among newly affected populations may require a different policy focus than tightening opioid prescribing practices.

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[15] Powell and Pacula (2021) restrict the sample to 2006 to 2017 and exclude 2010 from estimation, due to it being only partially treated (OxyContin was reformulated in August). We instead use yearly data from 1999 to 2019, and use 2011 as the post-reformulation period as in Alpert et al. (2018). We also examine deaths from any illegal opioid (heroin or fentanyl), where as Powell and Pacula (2021) examine these deaths separately.

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A Additional Figures

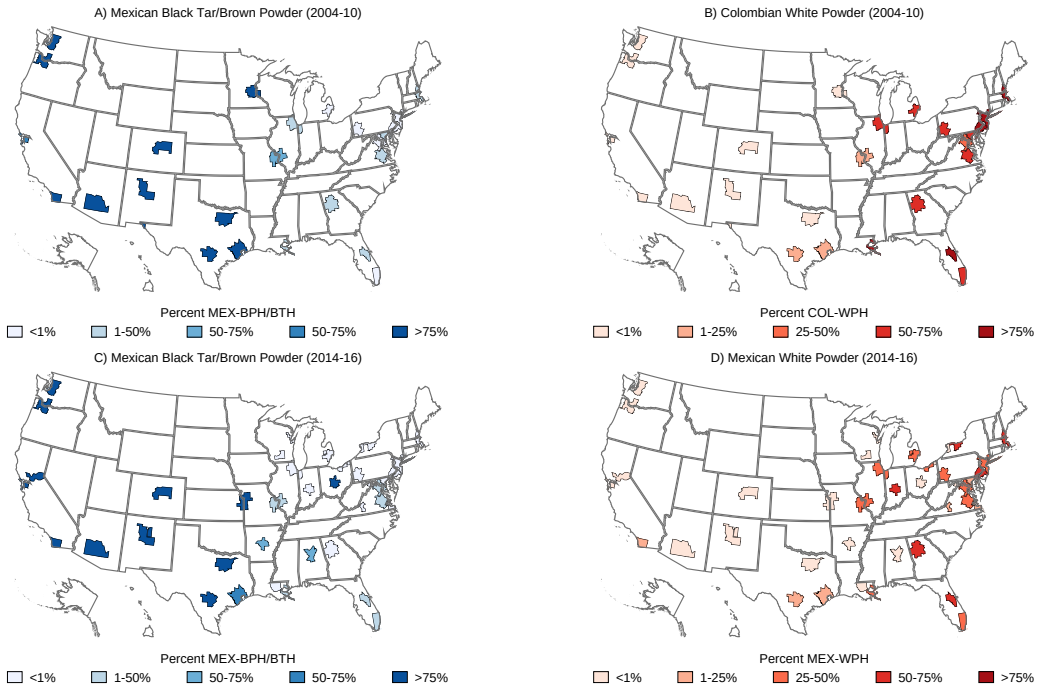


Figure A.1: Geographic divisions in U.S. heroin supply, 2004-2010 vs. 2014-2016.

Notes: Data are from chemical analysis of retail heroin seizures published in the the Drug Enforcement Administration's 2004-2010 and 2014-2016 Heroin Domestic Monitoring Program Reports.

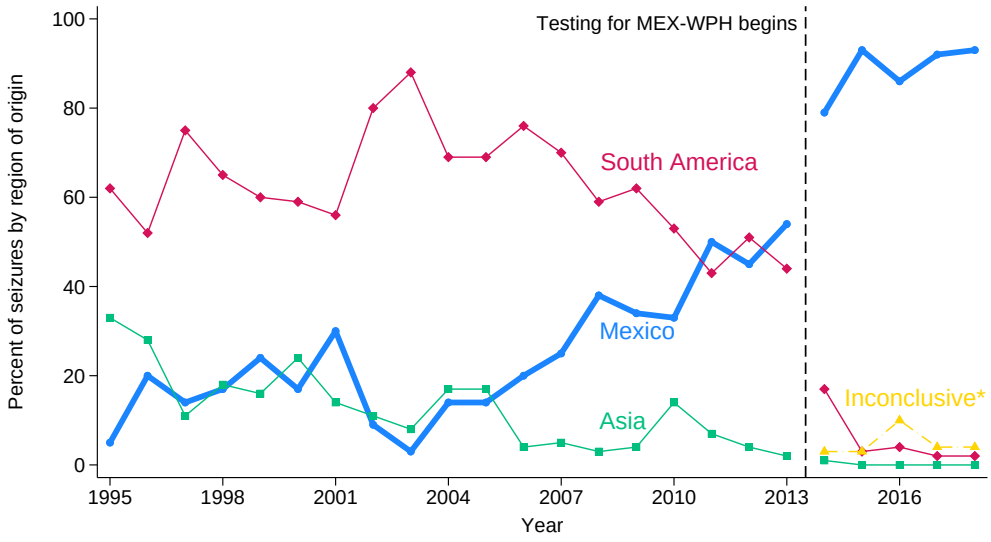


Figure A.2: Trends in country/region of origin of U.S. heroin seizures, 1995 to 2018

Notes: Data are from the 2018 Heroin Signature Program Report. South American heroin was primarily produced in Colombia. Chemical analyses to distinguish Mexican white powder heroin were first developed in 2015, and applied retroactively to 2014 data, leading to the jump in the share of heroin from Mexico in that year. * Inconclusive heroin resembled Mexican or Colombian white powder heroin, but the presence of adulterants or other issues prevented confirmation of the specific country of origin.

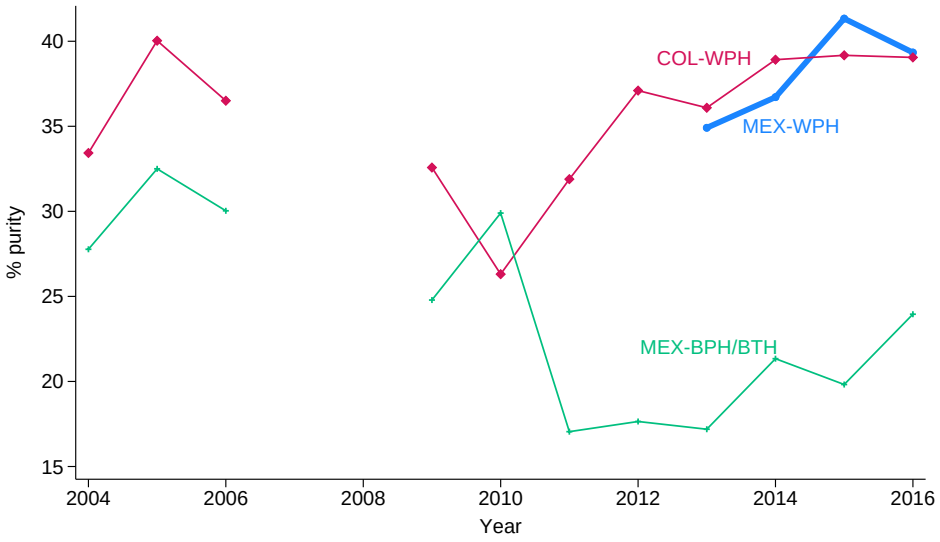


Figure A.3: Trends in heroin purity by type and origin

Notes: Data are from the 2004-2016 Heroin Domestic Monitoring Reports. Data are not available from 2007-2008. COL-WPH = Colombian White Powder Heroin; MEX-BPH/BTH = Mexican Brown Powder/Black Tar Heroin; MEX-WPH = Mexican White Powder Heroin. Chemical analyses to distinguish Mexican white powder heroin were first developed in 2015, and applied retroactively to 2014 data, leading to no observations for MEX-WPH prior to 2014.

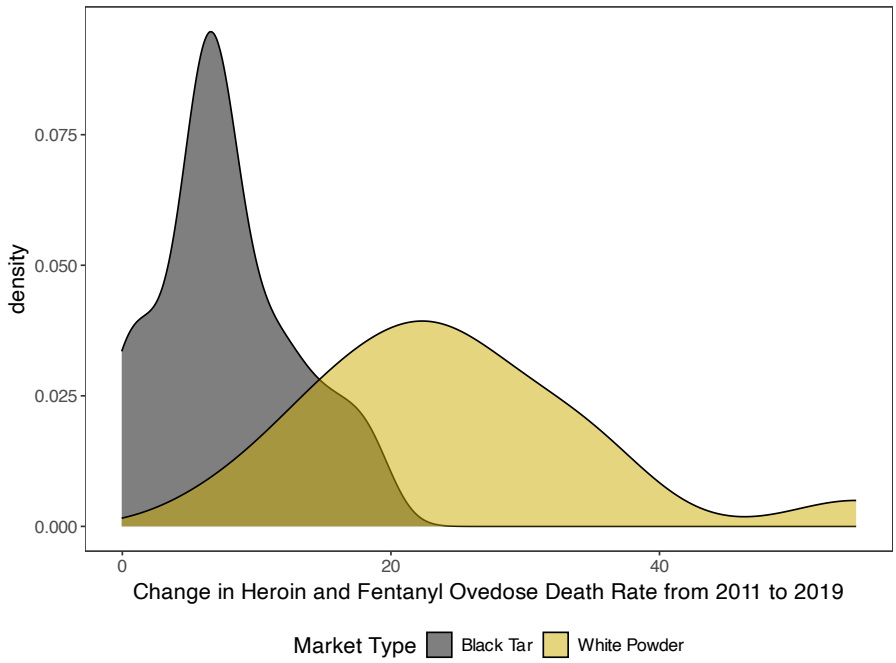
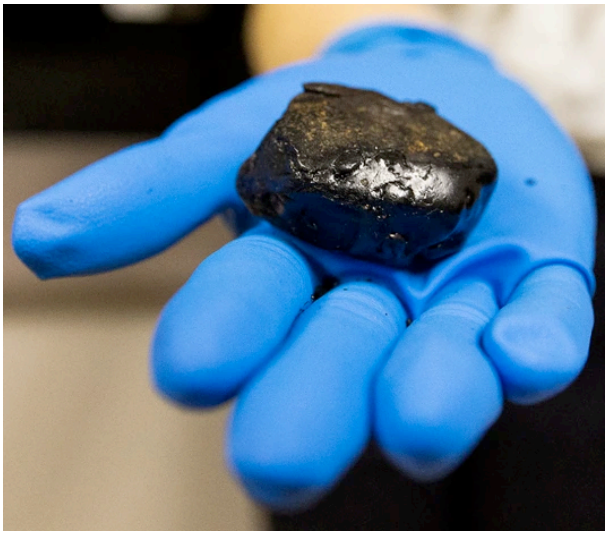


Figure A.4: Change in the Overdose Death Rate For HDMP Markets

Notes: This figure presents the distribution of the changes in heroin and fentanyl deaths from 2011 to 2019 for the Heroin Domestic Monitoring Program (HDMP) markets. For these markets, we know the heroin source, type, and purity, and thus can define them as being either black tar or white powder.

Figure A.5: Images of black tar heroin, white powder heroin, and illicit fentanyl

A) Black tar heroin



B) White powder heroin



C) Fentanyl



Notes: Images are obtained from here, here, and here, respectively.

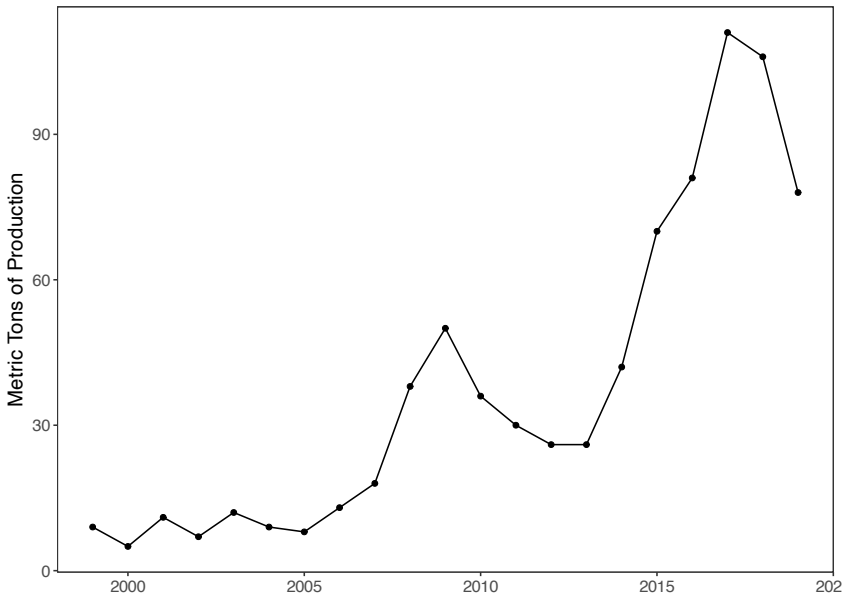


Figure A.6: Yearly Heroin Production in Mexico (Metric Tons)

Notes: Data source is the Office of National Drug Control Policy.

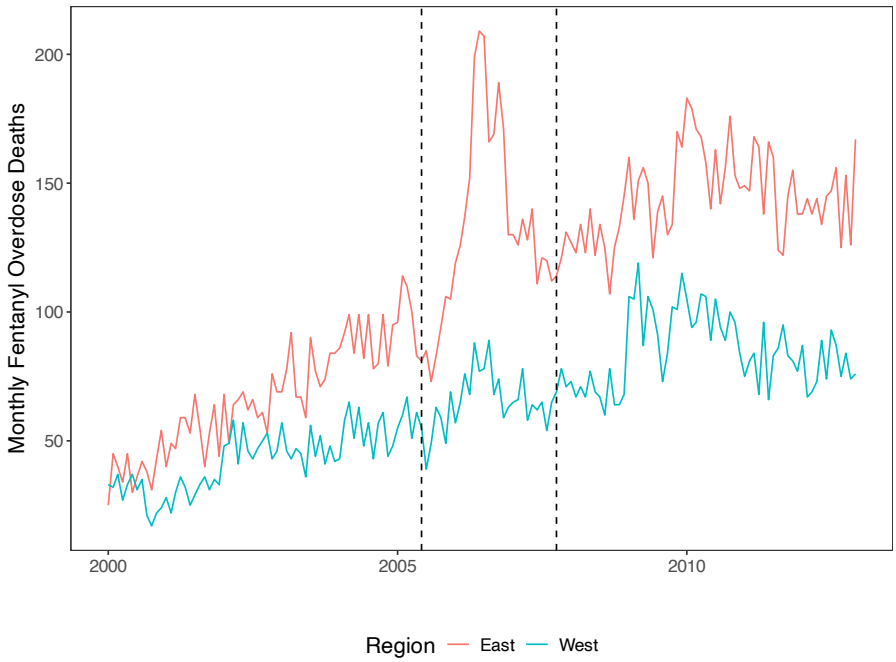


Figure A.7: Monthly Fentanyl Overdose Deaths Before 2013

Notes: Data are from the National Vital Statistics System, where we use the ICD-9 code of T40.4 for fentanyl.

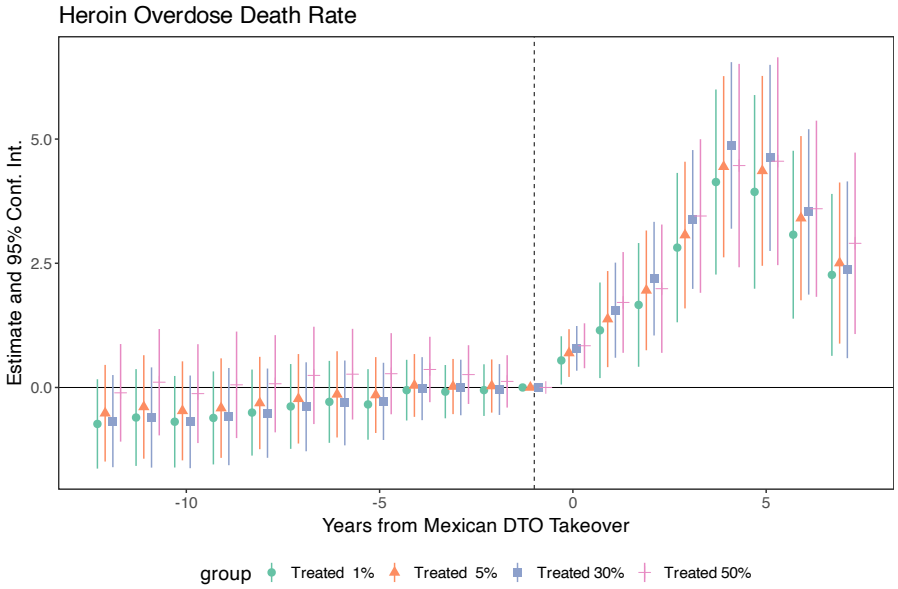
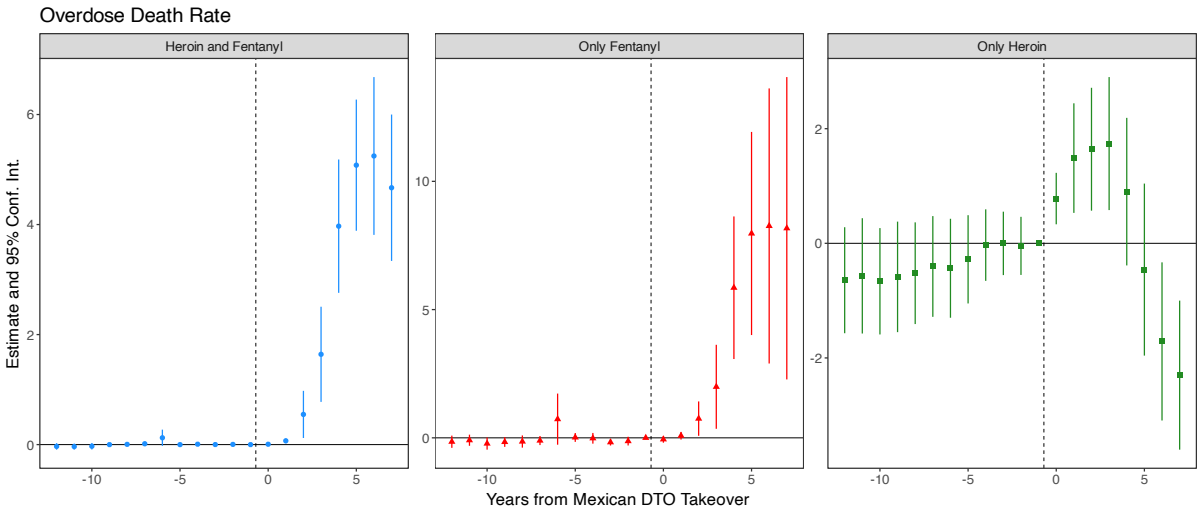


Figure A.8: The Dynamic Mortality Impacts of the Mexican DTO Takeover (HDMP Markets)

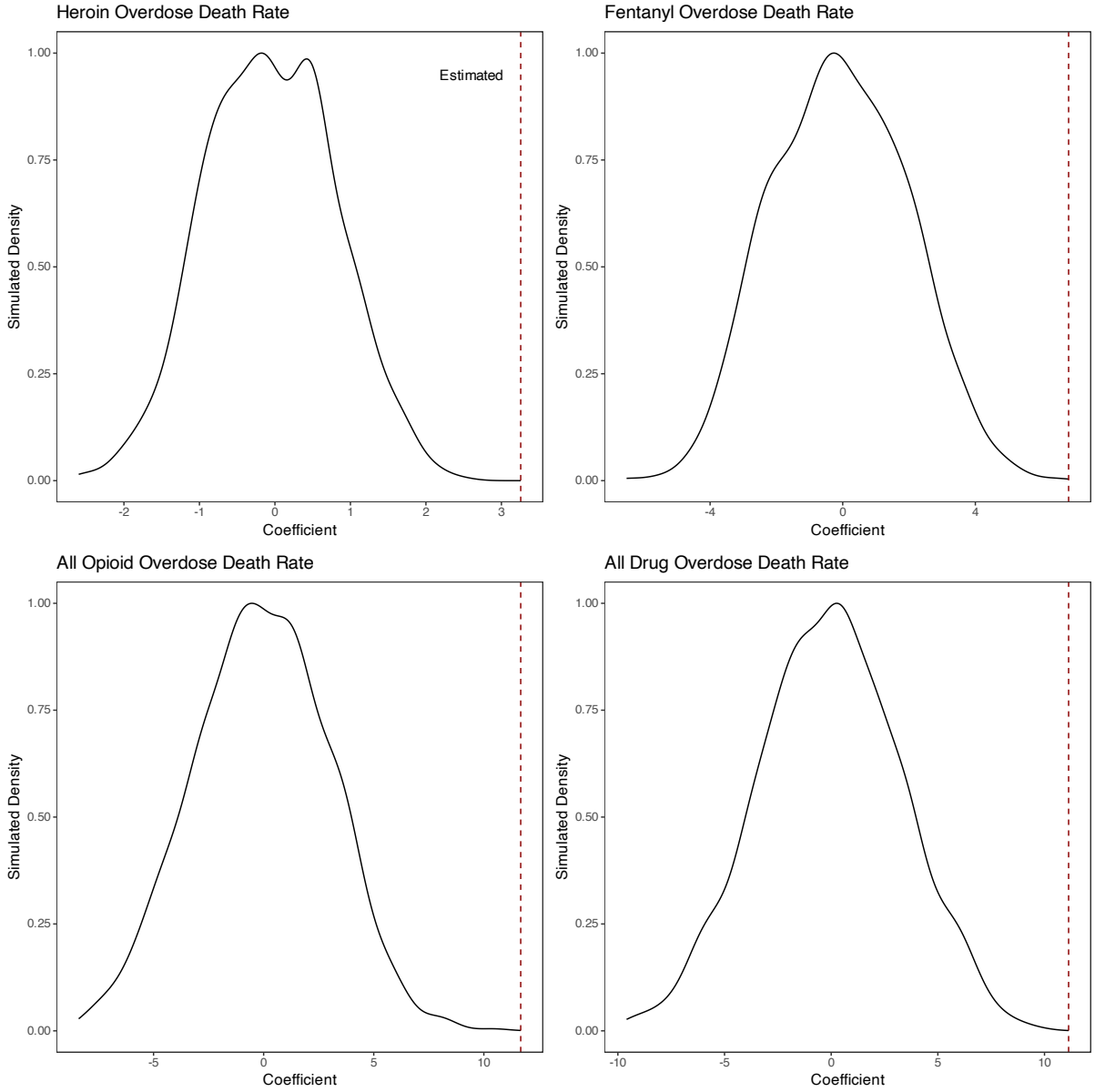
Notes: This figure present the ρ_t coefficients from estimating Equation (1) for different definitions of a white powder heroin market; our main specification uses 30% or more of the heroin seizures pre-DTO takeover being white powder. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. The outcome is heroin overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data.

Figure A.9: The Dynamic Mortality Impacts of the Mexican DTO Takeover



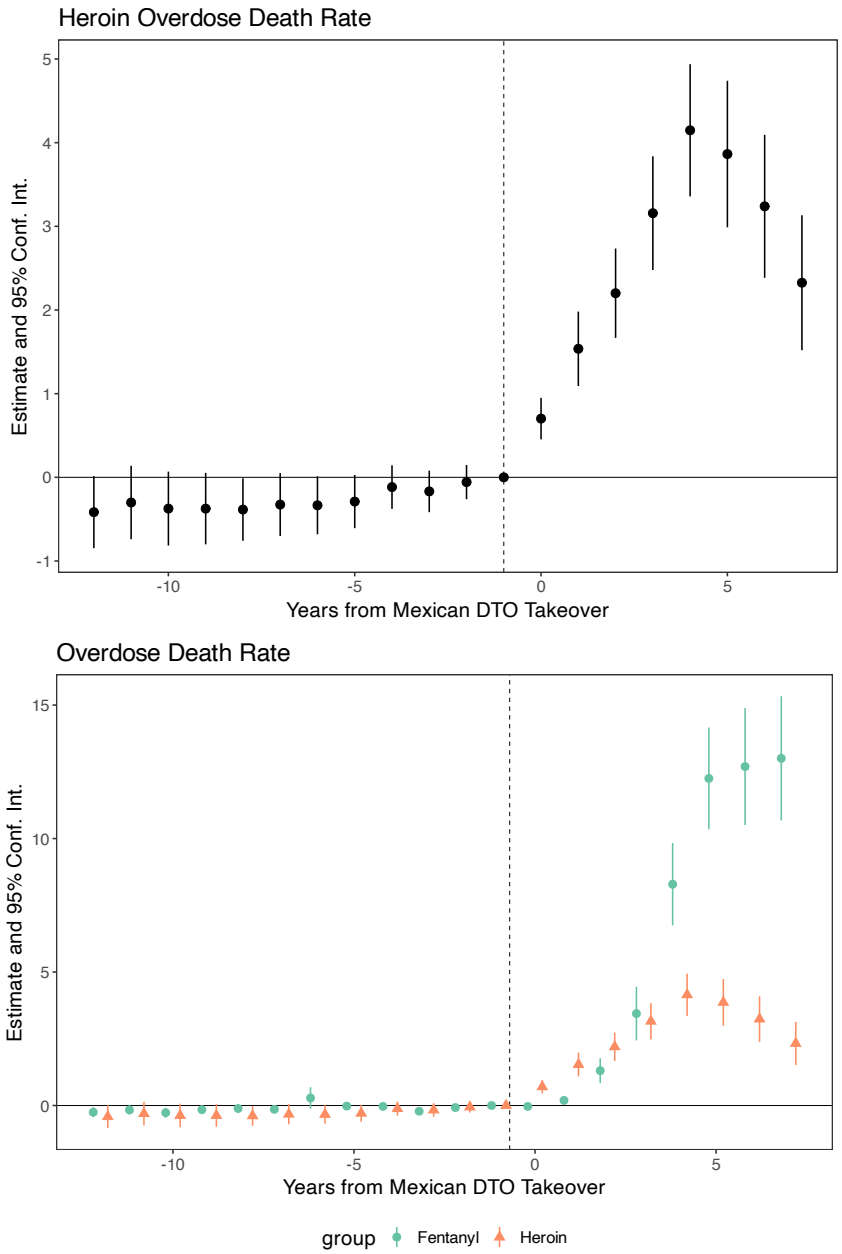
Notes: These figures present the ρ_t coefficients from estimating Equation (1). The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 for heroin and fentanyl, only fentanyl, and only heroin, and the sample includes only commuting zones where we have HDMP data.

Figure A.10: Permutation tests for HDMP market analysis



Notes: For these tests, we randomize which commuting zone gets "treated" and then run Equation (2) 1000 times using a new sample each time. The figures present the distribution of coefficients obtained from these regressions. The dotted vertical red line is the estimated coefficient.

Figure A.11: The Dyanmic Mortality Impacts of the Mexican DTO Takeover (Nationwide)



Notes: These figures present the ρ_t coefficients from estimating Equation (3). The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States. The top panel is only heroin overdose deaths, while the bottom panel presents both heroin and fentanyl overdose deaths.

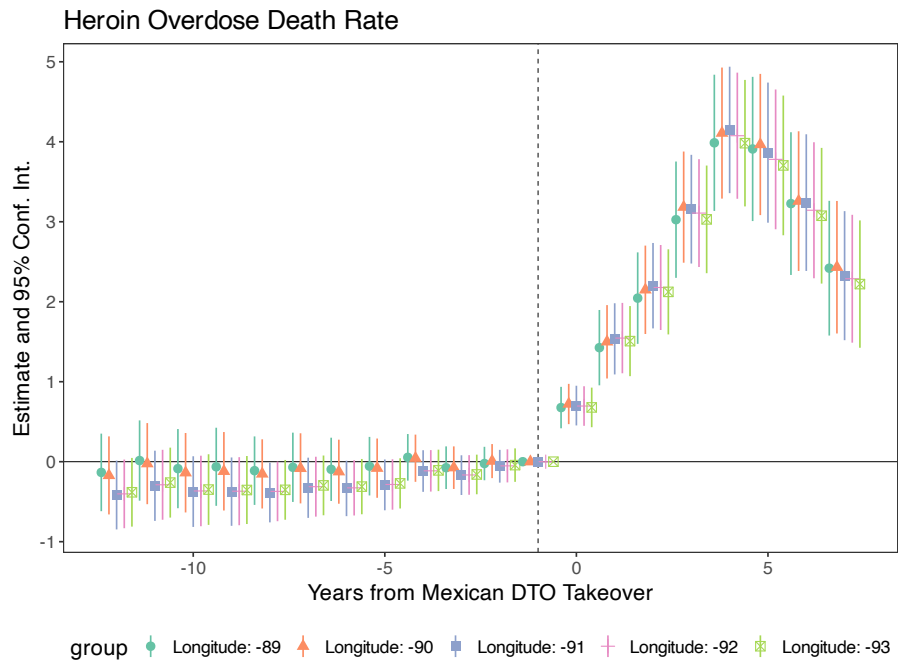


Figure A.12: The Dynamic Mortality Impacts of the Mexican DTO Takeover (Nationwide)

Notes: This figure present the ρ_t coefficients from estimating Equation (3) for different longitude cutoffs; our main defines treatment as commuting zones east of -91 degrees. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are heroin overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States.

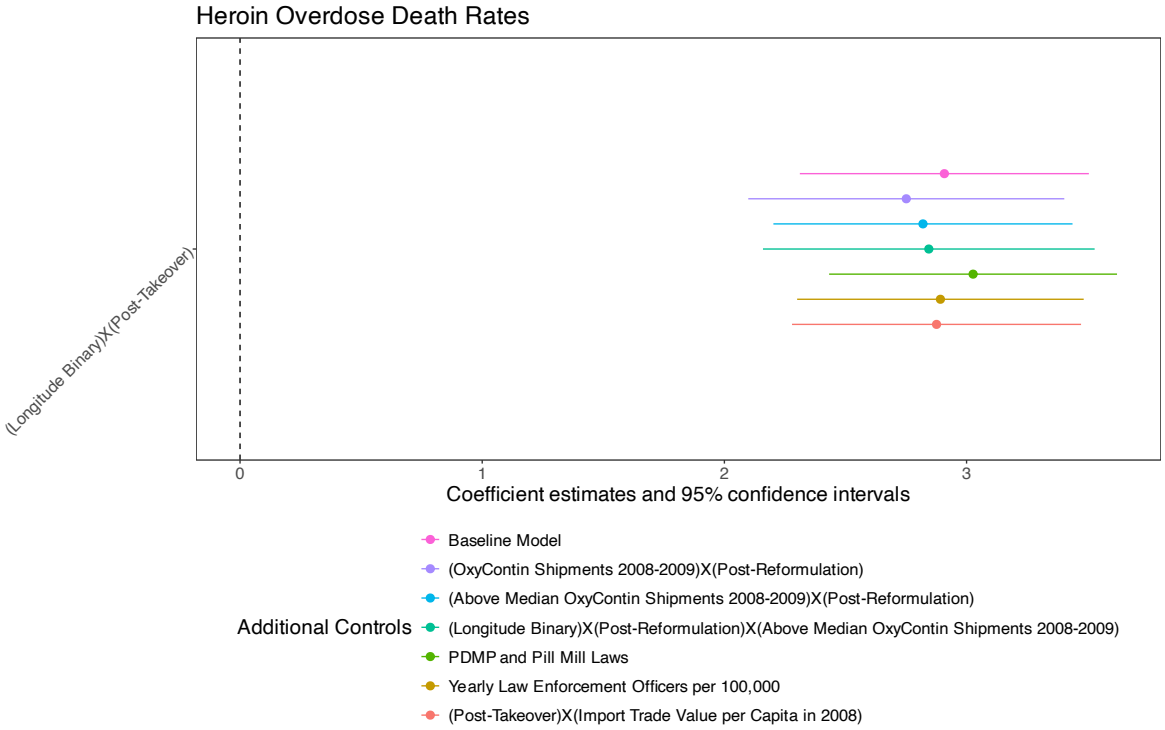
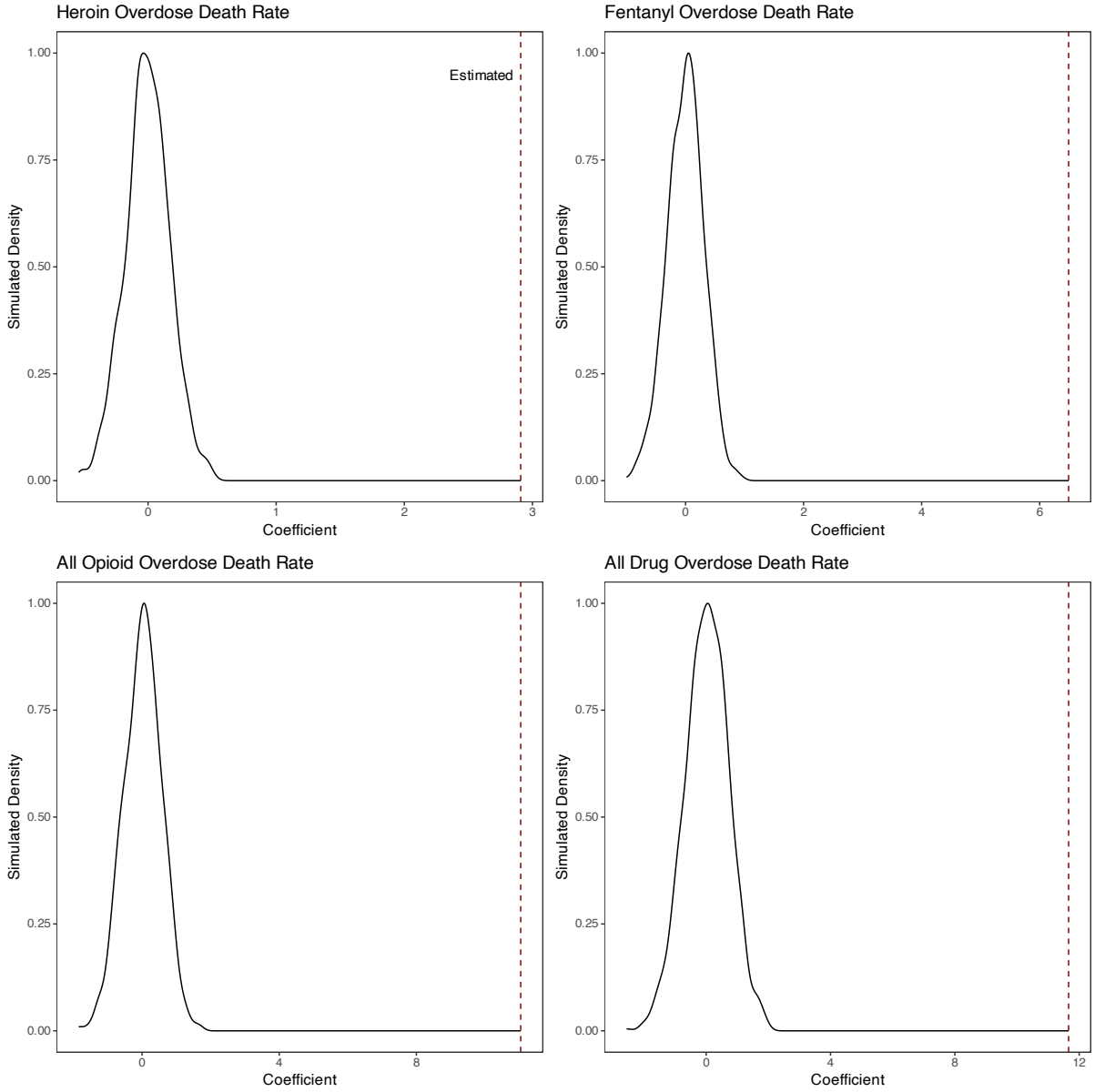


Figure A.13: The Average Mortality Impacts of the Mexican DTO Takeover (Nationwide)

Notes: This figure presents the β coefficients from estimating Equation (4) with different control variables. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States.

Figure A.14: Permutation tests for nationwide analysis



Notes: For these tests, we randomize which commuting zone gets "treated" and then run Equation (4) 1000 times using a new sample each time. The figures present the distribution of coefficients obtained from these regressions. The dotted vertical red line is the estimated coefficient.

B Additional Tables

Table B.1: Quotes describing Colombian DTOs' reliance on Mexican DTOs to traffic heroin.

Source	Quote
NDTA, 2003, p. 49-50	"DEA reports that in 2002 a significant number of Mexican nationals intending to board flights to Mexico were arrested at airports in Central and South America with South American heroin in their possession... Increased airport security since September 11, 2001, may result in fewer heroin couriers on commercial flights to the United States. To compensate, Colombian traffickers may rely more heavily on Mexican criminal groups to transport heroin across the U.S.-Mexico border."
NDTA, 2005, p. 68	"The amount of South American heroin seized in the U.S. Arrival Zone along the Southwest Border—particularly Texas—increased significantly in 2003... South American heroin typically is smuggled into the United States by couriers aboard commercial flights to international airports in New York and Miami. However, law enforcement reporting indicates that traffickers are transporting increasing amounts of South American heroin across the Southwest Border. Law enforcement reporting indicates that Colombian DTOs are increasingly relying on Mexican DTOs and criminal groups to transport South American heroin to the United States much as they rely on Mexican DTOs to transport cocaine."

Notes: Quotes are from national reports by the Drug Enforcement Administration.

Table B.2: The Average Mortality Impacts of the Mexican DTO Takeover

	Heroin (1)	Fentanyl (2)	Any Opioids (3)	Any Drug (4)	Heroin and Fentanyl (5)	Only Heroin (6)	Only Fentanyl (7)
(White Powder Market)X(Post-Takeover)	3.256***	6.813***	11.68***	11.13***	2.649***	0.6067	4.164***
	(0.6198)	(1.322)	(1.872)	(2.329)	(0.2863)	(0.4911)	(1.167)
Dependent variable mean	3.0180	2.8879	9.2226	16.072	0.71312	2.3049	2.1748
R^2	0.80428	0.65074	0.75079	0.77956	0.66420	0.65765	0.57935
Observations	620	620	620	620	620	620	620

Notes: This table presents the β coefficients from estimating Equation (2). The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data.

Table B.3: The Average Mortality Impacts of the Mexican DTO Takeover

	Heroin (1)	Fentanyl (2)	Any Opioids (3)	Any Drug (4)
(Pre-Takeover White Powder Heroin Share)X(Post-Takeover)	0.0366***	0.0856***	0.1406***	0.1360***
	(0.0100)	(0.0207)	(0.0316)	(0.0367)
Dependent variable mean	3.0180	2.8879	9.2226	16.072
R^2	0.77816	0.63771	0.72852	0.76924
Observations	620	620	620	620

Notes: This table presents the β coefficients from estimating Equation (2) using a continuous treatment measure of white powder heroin in the pre-takeover period. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data.

Table B.4: The Average Mortality Impacts of the Mexican DTO Takeover

	Heroin (1)	Fentanyl (2)	Any Opioids (3)	Any Drug (4)
(Post-Takeover) × WhitePowderQuartile = 2	-0.6530	0.7123	-0.5360	0.2205
	(0.8112)	(1.056)	(2.026)	(2.286)
(Post-Takeover) × WhitePowderQuartile = 3	3.104***	6.142***	10.88***	10.13***
	(0.9098)	(1.905)	(2.758)	(3.307)
(Post-Takeover) × WhitePowderQuartile = 4	2.044**	6.956***	9.710***	10.01***
	(0.7879)	(1.826)	(2.307)	(2.955)
Dependent variable mean	3.0180	2.8879	9.2226	16.072
R^2	0.79617	0.63574	0.73416	0.76916
Observations	620	620	620	620

Notes: This table presents the β coefficients from estimating Equation (2) using a binned treatment measure of white powder heroin in the pre-takeover period. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data.

Table B.5: The Average Mortality Impacts of the Mexican DTO Takeover (HDMP Markets)

	Heroin						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(White Powder Market)X(Post-Takeover)	3.256***	3.074***	3.213***	3.351***	3.244***	3.155***	3.147***
	(0.6198)	(0.6779)	(0.6032)	(0.6320)	(0.6166)	(0.5975)	(0.7193)
(OxyContin Shipments 2008-2009)X(Post-Reformulation)		0.9100					
		(0.6510)					
(Above Median OxyContin Shipments 2008-2009)X(Post-Reformulation)			0.6566	0.8859			
			(0.5731)	(0.6075)			
(White Powder Market)X(Post-Reformulation)X(Above Median OxyContin Shipments 2008-2009)				-0.4178			
				(0.9389)			
Post-Pill Mill Reform					1.035*		
					(0.5562)		
Post-PDMP Reform					0.0556		
					(0.4500)		
Yearly Law Enforcement Officers per 100,000						-0.0074*	
						(0.0043)	
(Post-Takeover)X(Import Trade Value per Capita in 2008)							-4.88×10^{-6}
							(6.98×10^{-6})
Dependent variable mean	3.0180	3.0180	3.0180	3.0180	3.0180	3.0180	3.0180
R^2	0.80428	0.81034	0.80757	0.80798	0.81023	0.80782	0.80483
Observations	620	620	620	620	620	620	620

Notes: This table presents the β coefficients in the first row from estimating Equation (2) with different control variables. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data.

Table B.6: The Average Mortality Impacts of the Mexican DTO Takeover (Nationwide)

	Heroin	Fentanyl	Any Opioids	Any Drug	Heroin	Fentanyl	Any Opioids	Any Drug
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(Longitude Binary)X(Post-Takeover)	2.908***	6.490***	11.04***	11.66***				
	(0.3039)	(0.5351)	(0.8293)	(1.053)				
(Longitude Continuous)X(Post-Takeover)					0.0799***	0.1958***	0.3212***	0.3324***
					(0.0092)	(0.0211)	(0.0280)	(0.0351)
Dependent variable mean	0.97026	1.7834	5.6437	9.6917	0.97026	1.7834	5.6437	9.6917
R^2	0.70405	0.61588	0.70684	0.73496	0.69022	0.60945	0.69529	0.72641
Observations	13,820	13,820	13,820	13,820	13,820	13,820	13,820	13,820

Notes: This table presents the β coefficients from estimating Equation (4). The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States.

Table B.7: The Average Mortality Impacts of the Mexican DTO Takeover (Nationwide)

	Heroin						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(Longitude Binary)X(Post-Takeover)	2.908***	2.751***	2.820***	2.844***	3.027***	2.892***	2.876***
	(0.3039)	(0.3323)	(0.3145)	(0.3487)	(0.3027)	(0.3013)	(0.3039)
(OxyContin Shipments 2008-2009)X(Post-Reformulation)		0.6599*					
		(0.3655)					
(Above Median OxyContin Shipments 2008-2009)X(Post-Reformulation)			0.4915	0.5257**			
			(0.3096)	(0.2647)			
(Longitude Binary)X(Post-Reformulation)X(Above Median OxyContin Shipments 2008-2009)				-0.0555			
				(0.4052)			
Post-Pill Mill Reform					0.7054*		
					(0.3636)		
Post-PDMP Reform					0.3892*		
					(0.2104)		
Yearly Law Enforcement Officers per 100,000						-0.0019	
						(0.0012)	
(Post-Takeover)X(Import Trade Value per Capita in 2008)							$-2.35 \times 10^{-7***}$
							(6.39×10^{-8})
Dependent variable mean	0.97026	0.97026	0.97026	0.97026	0.97026	0.97026	0.97026
R^2	0.70405	0.70715	0.70573	0.70573	0.70878	0.70454	0.70503
Observations	13,820	13,820	13,820	13,820	13,820	13,820	13,820

Notes: This table presents the β coefficients in the first row from estimating Equation (4) with different control variables. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are heroin overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States.

Table B.8: The Average Mortality Impacts of the Mexican DTO Takeover (Nationwide)

	Heroin	Fentanyl	Any Opioids	Any Drug
	(1)	(2)	(3)	(4)
(2005-2009 Heroin Death Rate)X(Post-Takeover)	0.0873**	0.0271	0.1529*	0.2229**
	(0.0423)	(0.0206)	(0.0821)	(0.1111)
(Longitude Binary)X(Post-Takeover)	1.921***	3.782***	7.246***	7.482***
	(0.3487)	(0.6179)	(0.9382)	(1.168)
(2005-2009 Heroin Death Rate)X(Post-Takeover)X(Longitude Binary)	0.2137***	0.6020***	0.8353***	0.9151***
	(0.0726)	(0.1388)	(0.2251)	(0.2620)
Dependent variable mean	0.97026	1.7834	5.6437	9.6917
R^2	0.73770	0.65194	0.73929	0.75855
Observations	13,820	13,820	13,820	13,820

Notes: This table presents the β coefficients from estimating Equation (5). The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States.