CONTEMPORARY ECONOMIC POLICY

WEAI

THE WAR ON DRUGS 2.0: DARKNET FENTANYL'S RISE AND THE EFFECTS OF REGULATORY AND LAW ENFORCEMENT ACTION

JACOB N. MILLER*

U.S. overdose deaths attributed to synthetic opioids, such as fentanyl, have increased from under 3,000 in 2013 to nearly 20,000 in 2016, making up half of all opioid-related overdose deaths. Using web scrapes of darknet markets from 2014 to 2016, I provide historical prices for fentanyl and its most popular analogues and find that fentanyl vendors priced fentanyl in 2014 at a 90% discount compared to an equivalent dose of heroin. Using regression discontinuity, I evaluate the effects of two major law enforcement and regulatory events. I find minimal lasting effects of U.S. legal actions intended to disrupt darknet markets, but there are statistically significant indications of a price increase corresponding with regulatory action in China. Despite these indications of some regulatory success, fentanyl prices remained approximately 90% cheaper than heroin. (*JEL* I18, K42)

I. INTRODUCTION

Drug overdose has become the number one cause of death in the United States for adults under age 50 Drug Enforcement Agency (Department of Justice (DOJ) 2017). Opioids are primarily responsible for the rise in overdose deaths, ending nearly 40,000 lives in 2016. In 2013 a sub-class of opioids, synthetic opioids, became the catalyst in accelerating overdoses to new heights. Opioid overdose deaths broke from the previous trend and grew exponentially between 2013 and 2016, increasing from 20,000 to 40,000 in just 3 years. Figure 1 demonstrates the progression of opioid and synthetic opioid deaths from 1998 to 2016. Reported deaths from synthetic opioids more than tripled between 2010 and 2015 and doubled in 2016 alone (Center of Disease Control (CDC) WONDER 2017).

Fentanyl is the primary synthetic opioid associated with this increase in overdose deaths. Fentanyl's potency—approximately 25–50 times more powerful than heroin—and inexpensive precursors contribute to its illicit production and smuggling (CDC 2016). The estimated lethal dose for a non-opioid-tolerant individual is 2–3 mg (milligrams) (European Monitoring Center for Drugs and Drug Addiction (EMCDDA) n.d.). Because of this potency, production and distribution mistakes or error by the end user can easily lead to overdose and death.

Opioids are inherently addictive, and demand for this category of drugs is widely considered price inelastic. However, researchers have found that the demand for specific opioids is elastic. To estimate elasticity, researchers have used U.S. Drug Enforcement Agency (DEA) estimates, surveys, theoretical models, and other sources to estimate the demand and elasticities of specific drugs. For example, Saffer and Chaloupka (1995) used DEA data and the National Household Survey of Drug Abuse to estimate the price elasticity for heroin at −1.80 to −1.60. Unick et al. (2014) estimated that a $100 USD decrease in the price per gram of pure heroin resulted in a 2.9% increase in the number of heroin overdose hospitalizations. Alpert, Powell, and Pacula (2017) demonstrated that users switched from OxyContin to heroin when the former became unavailable. Finally, Hempstead and Yildirim (2013) showed that price elasticity for heroin is

ABBREVIATIONS

API: application programming interface
CDC: Center of Disease Control
DEA: Drug Enforcement Agency
DOJ: Department of Justice
EMCDDA: European Monitoring Center for Drugs and Drug Addiction
UNODC: United Nations Office on Drugs and Crime

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Miller: Professor, Economics and Finance, Southern Utah University, Cedar City, UT 84720, Phone (435) 865-8206, Fax (435) 586-5493, E-mail jacobmiller21@suu.edu

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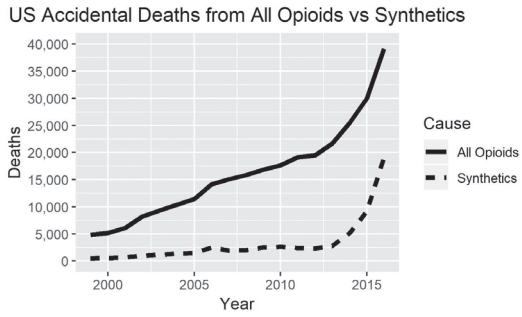
FIGURE 1

Synthetics Are a Sub-Category of all Opioids and Are Included in the all Opioids Calculation



Source: CDC WONDER.

elastic when close substitutes, like prescription opioids or fentanyl, are readily available. All of these examples indicate a high degree of price elasticity for specific opioids and a willingness to turn to other opioids as substitutes.

The first objective in this study is to explicitly address fentanyl's wild surge in popularity. While fentanyl-linked deaths have received attention, fentanyl prices have not been as heavily scrutinized. The descriptive data from fentanyl pricing on darknet markets provides compelling evidence as to why users and vendors switched to fentanyl in such a short period. Darknet markets are found on the dark web, and they facilitate the connection of buyers and sellers of contraband while maintaining users' anonymity. Using heroin pricing from the United Nations and fentanyl pricing from darknet markets, this study uniquely identifies the pricing differential and degree to which both users and vendors are incentivized to switch from other opioids to fentanyl. The United Nations Office on Drugs and Crime (UNODC) (2014) estimated the price of retail heroin at approximately $5.40 USD per 10 mg pure dose. Using data from darknet markets, I find the retail cost of an equivalent effective dose of fentanyl in 2014 was $0.41 USD. An opioid user can obtain an equivalent dose of fentanyl at a discount exceeding 90% compared to heroin. Furthermore, fentanyl's retail price declined by 50% to $0.21 USD between 2014 and 2016, exacerbating this difference.

Opioid users' demand is considered price inelastic due to opioids' addictive nature, while demand for specific opioid substitutes has been found to be price elastic as users have been willing to switch among opioids. While a 90% relative discount for an equivalent opioid is outside the range of existing price elasticity studies, one would expect that the size of fentanyl's relative discount would quickly lead to market saturation for the segment of consumers who are willing to switch.

Furthermore, this same 90% discount creates an economic incentive for vendors and wholesalers to fraudulently substitute heroin, oxycodone, and other costlier products with fentanyl. However, fentanyl's extreme concentration contributes to errors in uniform mixing and precise dosing, creating a greater potential for lethality. This fraudulent substitution by wholesalers has contributed to overdose deaths (United States Drug Enforcement Agency 2016), most famously the popstar Prince, who took fake Vicodin tablets made of fentanyl (Coscarelli and Eldred 2018).[1] Both users and drug distributors face enormous incentives to switch to fentanyl despite its greater degree of overdose risk. Given these incentives to switch from other opioids to fentanyl, the increase in synthetic opioid overdose deaths from 3,000 to 19,000 in just 3 years is unsurprising.

The second objective of this study is to examine two law enforcement and regulatory actions intended to reduce its availability. The first event was intended to disrupt distribution, while the second event was intended to disrupt production. This study evaluates the effectiveness of these two events by observing the corresponding market reaction on darknet market fentanyl. Fentanyl's demand inside North America is uniquely popular compared to the rest of the world. Furthermore, China's share of global illicit fentanyl production is disproportionately high (EMCDDA n.d.; USCC 2017). Accordingly, demand shocks within North America and supply shocks within China should appear in the global darknet market for fentanyl. Additionally, although demand for fentanyl has steadily increased over time, the demand for an addictive drug like fentanyl should not vary significantly during a short window of time. Assessing the impact of fentanyl's market prices within a restricted window surrounding a law enforcement or regulatory event that is intended to disrupt supply should reveal itself in higher prices if it achieves its intended effect.

1. See Appendix S1 for an illustration of the increasing public interest in fentanyl over time. The first news reports of fentanyl and counterfeit tablets linked to Prince's death were reported in 2016.

The first event is Operation Onymous, an international law enforcement initiative carried out in November 2014 intended to disrupt the distribution of illicit goods. Operation Onymous took down three of the five largest darknet markets (Department of Justice (DOJ) 2014). In theory, this event could have disrupted markets, increasing both transaction costs and prices. Décary-Hétu and Giommoni (2016) discovered that darknet drug prices did not generally increase following Operation Onymous. For the fentanyl market, I found a temporary increase in prices due to the market disruptions and shutdowns from Onymous, but the general downward trend in prices reversed the temporary increase over the 2 months following the event. This specific finding for the fentanyl darknet market is consistent with Décary-Hétu and Giommoni's conclusions concerning the market generally. The market recovered quickly following a law enforcement event intended to disrupt the distribution of illicit substances.

The second event of interest is a regulatory change in China regarding the manufacturing of fentanyl. On September 25, 2015, the Chinese government declared that starting on October 1, 2015 (1 week later) production and possession of fentanyl analogues acetyl and butyr fentanyl were illegal, and also signaled a general increase in enforcement to curb illicit synthetic opioid production and distribution. After this regulatory crackdown fentanyl analogue producers moved away from prohibited analogues and toward analogues that were not yet prohibited. Additionally, I found that the previous downward trend in prices halted, reaching $0.21 USD per dose for retail amounts and $0.08 USD per dose for bulk purchases. These responses in price indicate that Chinese regulatory action to curb production of fentanyl may be able to influence illicit fentanyl markets in the intended direction. However, despite the positive evidence of this regulatory action having some effect, the overall magnitude of the impact was insufficient to meaningfully change the relative discount of fentanyl to other substitutes, and the incentives for both distributors and users to switch to or remain with fentanyl persisted.

II. DATA

The dark web is a term used to describe web sites that are not indexed, can only be accessed using a special web browser, and mask the IP address of both visitor and host. Users can communicate and interact anonymously on the dark web. This anonymity is an essential element for darknet markets to exist.

Darknet markets are marketplace platforms on the dark web. Darknet markets allow users to buy and sell digital and physical products while maintaining a greater degree of anonymity than they can on the traditional internet. In the darknet market drug trade, buyers will generally select a product from a reputable vendor, directly send or escrow cryptocurrency (e.g., Bitcoin, Monero, etc.), and provide a mailing address for the sender. The vendor receives the cryptocurrency and usually ships the product through the postal system. The buyer then receives the goods and has the opportunity to leave public seller feedback.

Drugs that are highly concentrated and easy to ship, such as MDMA, LSD, and fentanyl, are ideally suited to darknet market distribution and make up a large portion of darknet market transactions. For example, 5 g of fentanyl, or 50,000 standard doses, is the highest standard amount sold on darknet markets and is routinely sold for over $1,000 USD. MDMA, LSD, and fentanyl's relatively compact size and potency reduce shipping costs and the probability of detection by law enforcement.

With the recent advent of darknet markets, troves of data emerged that facilitate the evaluation of illicit markets on a grander scale. Darknet markets are a valuable source of information and likely one of the best sources to analyze prices of illicit drugs. Many researchers have been scraping data off darknet markets since the beginning days of the first darknet market, Silk Road. With periodic scraping, a longitudinal view and study of prices of illicit goods—from drugs to stolen credit cards—is now possible. Aldridge and Décary-Hétu (2014) estimated the size and rapid growth of Silk Road and its impact on illicit drug markets. Soska and Christin (2015) estimated the revenue of darknet markets, seller survivability, and the market's recovery after law enforcement successfully shut down Silk Road.

An independent researcher who goes by the name Gwern Branwen made public the dataset used in this analysis. He has compiled and made available his own scraped datasets as well as those from other sources. Torrents to access the datasets are available on his website. The specific source of the data for this analysis stems from the Grams data set. Grams, which purported to be the "Google of the darknet,"

provided Gwern Branwen with "near-daily CSV exports of the current state of listings in their search engine" (Branwen et al. 2016). The crawls from some markets were sourced directly using an application programming interface (API), ensuring a higher degree of accuracy. I used this specific darknet market dataset for this analysis because it contained information regarding the two events of interest concerning fentanyl regulatory and law enforcement changes.

For all of its benefits, the Grams dataset is not without its drawbacks. First, because of scraping timing and occasional unsuccessful scrapes, the data is not collected at identical intervals or an equal number of times per month. Some months have many more successful scrapes than others do. Second, there are some gaps in the data. The first significant gap is mid-January 2015 to mid-February 2015. The second significant gap occurred in the beginning of October 2015. This second significant gap is unfortunate, as it took place immediately after the fentanyl regulation in China. However, if the impact of the China regulation is both large and persistent, evaluation of the event should still be possible when comparing prices before the event and beginning 3 weeks after the ban took place.

To simplify the analysis, focus on the primary research question, and address the scraping timing issue, I cleaned the individual market listings further. Only a single listing by unique product and vendor is included at each 10-day interval. The advantage of this approach is that scraping timing and frequency issues are mitigated, as only unique listings for a larger time period are considered.

The dataset contains the product description, vendor, market, shipping location, and Bitcoin price. However, the dataset does not clearly break out the product or amount. Accordingly, I developed algorithms to transform product descriptions into product categories and amounts. A random sampling and manual test demonstrated perfect accuracy of the algorithm for the fentanyl products and quantities.[2] The code for both the algorithm and analysis is publicly available.[3]

Vendors distribute fentanyl in many forms including nasal sprays, liquids, patches, lollipops, powder, or disguised as other drugs in pill form. Patches, lollipops, nasal sprays, and other forms intended to sell directly to consumers were excluded. Furthermore, fentanyl in pill form was excluded. While the market for fentanyl in pill form is important, fentanyl pills are intended for either the end-consumer or a distributor closer to the end-consumer. Pills are generally sold at the later stages in the drug distribution process after the fentanyl has already been imported, diluted, pressed, and sometimes manipulated to appear like other drugs. The focus of this analysis is the first stage of importation with only the most concentrated forms of fentanyl, primarily powders.

A total of 447 unique vendors offered fentanyl on the primary darknet markets from June 2014 to April 2016. Of these 447 vendors, 187 unique fentanyl vendors sold fentanyl in the doses, analogues, and physical form of interest for this study. In comparison, during this same period there were 3,272 unique MDMA vendors, and 1,609 unique MDMA vendors who sold it in its purest form. LSD had 1,334 unique vendors. The fentanyl market does not make up a large percentage of darknet market vendor activity. However, the increased degree of concentration and the number of doses provided per sale makes fentanyl more comparable to other popular high-volume products.

For the purposes of this analysis, only fentanyl and the three most popular darknet market fentanyl analogues were considered. Although other analogues exist and some became popular for illicit use, these other analogues either made up a very small portion of listings or became popular after the period analyzed in this study. A total of 117 vendors offered fentanyl in its traditional form and was the most popular form throughout the period. Acetyl fentanyl was second popular with 58 unique vendors, but its popularity tapered off after China's regulation. Furanyl fentanyl had just 20 vendors, but furanyl was first made available in June 2015 and became the most popular fentanyl analogue by January 2016. Butyr fentanyl had 20 vendors as well, but its popularity remained low throughout the period analyzed, with only a handful of vendors by the end.

Vendors sell darknet market fentanyl in concentrated form at five primary quantities: 100 mg, 250 mg, 500 mg, 1 g, and 5 g. 100 mg of pure fentanyl converts into approximately 500 standard 200 mcg (microgram) doses, while 5 g of fentanyl converts into approximately 25,000,200 mcg doses. A volume of 100 mg sales are generally considered for personal use or social dealing amounts (an amount appropriate for a small network of drug users), while large

2. See Appendix S2.

3. Source code for both cleaning and analysis stored at: https://github.com/jakenmiller/GramsAnalysis

distributors would make up the bulk of the 1 and 5 g higher volume purchases.

Shipping pricing policies varied by vendor. Some vendors offered free shipping while others did not. While this does add some noise to the data, the impact on this type of analysis should be minimal for three reasons. First, even the heaviest amounts of fentanyl sold, 5 g, could be shipped easily in a small envelope. This kept postage costs to a minimum. Second, general postage costs to ship small parcels did not vary significantly compared to the purchase price of the product. Third, overall shipping costs generally added a few percent to the overall purchase price. However, this effect would be most pronounced for the smallest purchase amounts analyzed.

III. METHODS

To test the hypotheses regarding the two potentially disruptive events, I use a regression discontinuity model for each of the events of interest while controlling for the amount and type of fentanyl analogue sold.

$$\ln(\text{Price}_{ij}) = \beta_0 + \beta_1(\text{Trend}) + \beta_2(\text{Event}) + \beta_3(\text{Trend} * \text{Event}) + \lambda_i + \theta_j + \varepsilon_{ij}$$

The ln(Price) of fentanyl for each amount (i) and type (j), acts as the dependent variable. The following act as independent variables: a linear time trend (Trend) measured in days with zero set at the time of the event, a dummy variable if the event—Operation Onymous or the fentanyl China regulation—has occurred (Event), and an interaction between trend and the event (Trend * Event). For comparisons to MDMA and LSD, similar models were generated for each. λ_i and θ_j are fixed effects for the amount and type of fentanyl analogue, respectively.

Binscatter (Stepner 2013) was used for aggregating the thousands of listings into a straightforward visualization to better comprehend the shifts in prices for each drug around the events of interest. Through this binning visualization technique, large shifts in both the level and slope at the point of interest should be apparent.

In order to properly evaluate whether the intended effects of each event persisted beyond the initial shock, a 120-day window on each side of the event was selected. In order to determine the appropriate window size, three elements were considered. First, the window should be long enough to evaluate if the event persisted, not just detect the initial shock. Second, the window should be limited to minimize the impact of capturing other events that occurred during roughly the same period. Third, the window should be long enough to provide sufficient power to detect economic significance. A 120-day window balances these three concerns. If the policies' effects have enduring power of economic significance, it should still be evident 2 to 4 months after the fact. This is also short enough to avoid many events that occurred disrupting darknet markets and the international drug trade. Concerning power, for Operation Onymous the 120-day window for the fentanyl market detects a price shock of at least 19%, and a change in trend of 0.25% per day at an α of 0.05. For China's fentanyl regulation the 120-day window for the fentanyl market detects a price shock of 14% and a change in trend of 0.2% per day at an α of 0.05. The power for MDMA and LSD are higher, as both of those markets are thicker with more vendors and listings.

The primary identifying assumption in the regression discontinuity model is constant trends over time and the exogeneity of the two law enforcement and regulatory events.

To evaluate constant trends over time, a few different approaches are utilized. First, there are approximately 3 months within the data that is outside of the 120-day window of either event. This period may be used as a robustness check to evaluate the frequency to which price shifts may have occurred. The model is applied at 10-day intervals during these 3 months to evaluate the prevalence of statistically significant shifts in price in terms of both level and trend. Second, 90- and 60-day windows are used as a secondary robustness check against the 120-day window selection.

Concerning exogeneity, Operation Onymous was a surprise raid and unanticipated by vendors, consumers, and the markets themselves. Darknet markets typically end in one of three ways: (1) exit scam by the marketplace creator, (2) shutdown by law enforcement, or (3) orderly shutdown by the marketplace creator. It is natural to assume that law enforcement would like to shut down all darknet markets. However, the dark web is used specifically for the reason of maintaining anonymity and avoiding capture. Law enforcement shutdowns typically occurred through mistakes by the marketplace leaking a username, email, metadata, or another piece of data that could be linked back to the real world, although Operation Onymous specifically may have been linked to an exploit in the dark web itself (Gallagher 2014). Many darknet markets

continued for years and remained outside of law enforcement's abilities to remove them. Assuming that market participants did not anticipate the shutdown of specific markets is reasonable in light of these facts.

The Chinese government implemented the fentanyl regulation with little warning; the announcement came less than a week before implementation (National Health Commission of the People's Republic of China 2015). Chinese government agencies and news sites provided little indication that the fentanyl regulation would be forthcoming. Furthermore, this was the first fentanyl regulation of its type implemented by the Chinese government (see Appendix S3, Supporting Information). While the Chinese government sometimes collaborates with the United States Drug Enforcement Agency and drug bans are expected to some degree, this was the third year that the U.S. government was focused on curbing illicit fentanyl. The unknown timing and suddenness of implementation created a largely exogenous event affecting darknet market Chinese fentanyl.

To assist validating the identifying assumptions, the price movements of other drugs on darknet markets may be used for comparison. Both MDMA and LSD are popular drugs on darknet markets and could serve as useful comparisons. MDMA and LSD are prevalent on darknet markets, highly concentrated substances, not direct substitutes or complements to fentanyl, and China is not the primary origin of production for either drug (Drug Enforcement Agency n.d.-a, n.d.-b). If Operation Onymous disrupted darknet markets generally, those effects should also be seen for LSD and MDMA as well. However, if Chinese fentanyl regulation disrupted darknet market fentanyl specifically, those effects should not be apparent in the market for LSD or MDMA.

By restricting the window of the model, checking against alternate windows of time, and comparing to other drugs, the effects of the two events should be discoverable with high confidence. If the effects of each event intended to disrupt these markets are significant, they should break through the noise and natural market trends within the model.

IV. RESULTS

Because the primary features of this analysis are time and discrete events, visually inspecting the data and data tables already provides some insights.

First, illicit fentanyl is inexpensive (see Table 1). In 2014, a 200 mcg dose purchased in bulk cost approximately $0.08 USD. A lethal dose for an opioid-naïve individual, or someone with no history of taking opioids, purchased in bulk cost approximately $1 USD, compared to a 75 mg dose of heroin with an estimated purity-adjusted bulk price of $8 (UNODC 2018a, 2018b). When buying retail amounts of darknet fentanyl in 2014, a 200 mcg dose cost approximately $0.20 USD. A retail lethal dose cost approximately $2.60 USD, compared to a price of more than $40 for an equivalent retail lethal dose of 75 mg of heroin.

At the retail consumer level, fentanyl offers a discount of more than 90% compared to heroin. Considering the price elasticity of specific opioids, one expects a major shift in overdose deaths toward fentanyl at the moment illicit fentanyl hits the market in 2013. One also expects the number of overdose deaths related to fentanyl to continue increasing until the market for fentanyl saturates. At the distributor level, fraudulent substitution of fentanyl for heroin reduces product costs by at least 80% while maintaining relatively the same effect. Because most illicit opioid users evaluate

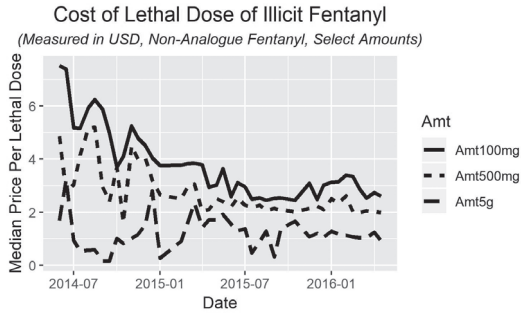
TABLE 1
Median Fentanyl Prices by Type and Quantity Purchased: July 2014 Versus April 2016 (Measured in US Dollars)

	Median Price 100 mg			Median Price 250 mg			Median Price 500 mg		
	Acetyl	**Butyr**	**Fentanyl**	**Acetyl**	**Butyr**	**Fentanyl**	**Acetyl**	**Butyr**	**Fentanyl**
Jul-14	110	75	207	130	149	559	250	268	606
Apr-16	54	64	104	75	80	226	121	130	403
% change	−51%	−15%	−50%	−42%	−46%	−59%	−52%	−51%	−34%

Note: Traditional fentanyl is more potent per dose than either acetyl or butyr fentanyl. Furanyl fentanyl is omitted, as its first listings did not appear until 2015. *Source*: Grams darknet market scrapes.

FIGURE 2

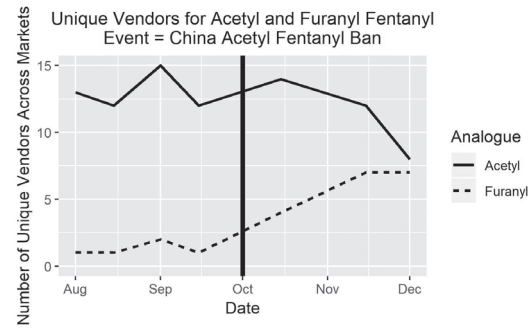
Lethal Dose of 2.5 Mg Is Assumed. Prices Do Not Include Shipping Costs or Other Surcharges



Source: Grams darknet market scrapes.

FIGURE 3

China's Fentanyl Regulation Occurred on October 1, 2015 and Targeted Acetyl Fentanyl, but Not Furanyl Fentanyl. China's Regulatory Agency Later Added Furanyl Fentanyl in 2017



Source: Grams darknet market scrapes.

quality by effect rather than using chemical tests to compare the product to advertised content, opioid dealers have an opportunity to increase profitability through sustained product alteration.

Second, the market price for fentanyl and its analogues trends downward from 2014 to 2016. Figure 2 tracks the evolution of prices for one fentanyl analogue, showing a general decline in prices, especially for smaller amounts, and a general decline in volatility. Prices have fallen across nearly every category during the period analyzed, some of which exceeded 50%, such as 100 and 500 mg listings of traditional fentanyl. The most significant price decreases occurred in the social dealing quantities (500 mg or less). This fall in prices occurred simultaneously with a tripling in synthetic opioid overdose deaths. Falling prices in the presence of increasing demand provide some evidence of increasing returns to scale and market maturity in the nascent illicit fentanyl industry.

Third, traditional fentanyl maintained a premium over other analogues. Fentanyl has a stronger effect per microgram than the fentanyl analogues that were popular on darknet markets at the time. Fentanyl's market premium is consistent with its greater potency.

Fourth, Figure 3 shows that the China ban of acetyl and butyr fentanyl coincided with a decrease in the number of acetyl fentanyl vendors and an increase in the number of furanyl fentanyl vendors, suggesting a migration from the prohibited substance to the similar still legal substance. Furanyl fentanyl was not included in the list of drugs the Chinese government prohibited in October 2015. Additionally, a closer look at the type of vendors before and after the China ban reveal that vendors that had listed shipping country as "China" completely disappeared from the banned analogue markets. However, the number of vendors from "Undeclared" and "Worldwide" increased significantly during this same period.

TABLE 2

Operation Onymous Fixed Effects Model for Fentanyl Prices

	Estimate	Standard Error	*p* Value
Trend	−0.003	(0.001)	.0006***
Onymous	0.280	(0.097)	.0040**
Trend * Onymous	0.001	(0.001)	.6235
Analogue: Butyr	0.366	(0.077)	.0000***
Analogue: Traditional	0.948	(0.053)	.0000***
Amount: 250 mg	0.632	(0.073)	.0000***
Amount: 500 mg	0.965	(0.071)	.0000***
Amount: 1 g	1.270	(0.067)	.0000***
Amount: 5 g	1.890	(0.080)	.0000***
(Intercept)	4.121	(0.092)	.0000***

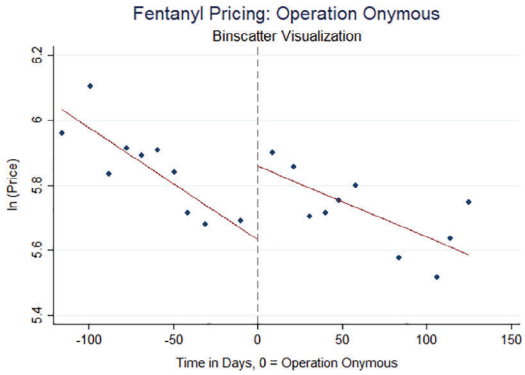
Note: Fixed effects included for the amount and fentanyl analogue type 100 mg of Acetyl Fentanyl is the omitted baseline $\ln(\text{Price}_{ij}) = \beta_0 + \beta_1(\text{Trend}) + \beta_2(\text{Event}) + \beta_3(\text{Trend} * \text{Event}) + \lambda_i + \theta_j + \varepsilon_{ij}$.

*$p < .05$, **$p < .01$, ***$p < .001$.

The first modeled event examined was Operation Onymous, when law enforcement shut down three of the five largest darknet markets simultaneously. The model results are found in Table 2. The initial shock increased price

FIGURE 4

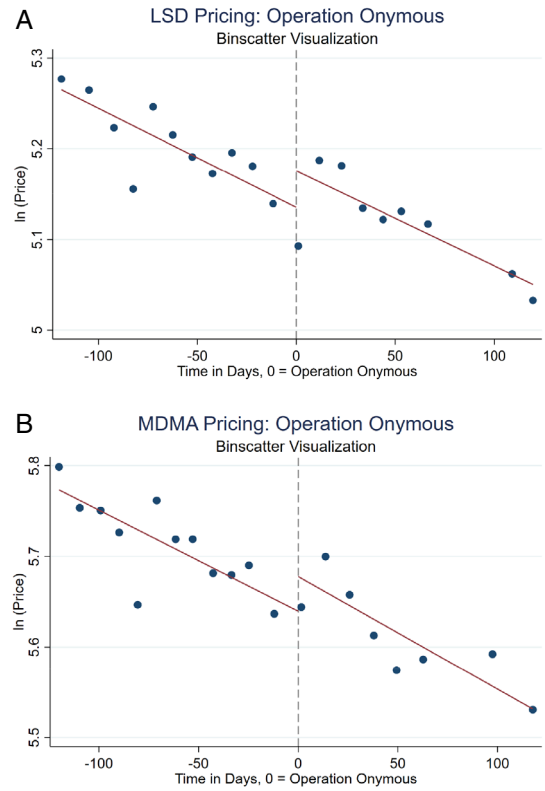
Operation Onymous Occurred on November 6, 2014 and Acts as the Zero Day Reference Point. Figure Displays 120-Day Window on Each Side of Event



Source: Grams darknet market scrapes.

FIGURE 5

Darknet Market MDMA and LSD Are Used as Comparisons to Fentanyl. Operation Onymous Occurred on November 6, 2014 and Acts as the Day Zero Reference Point. Figure Displays 120-Day Window on Each Side of Event



Source: Grams darknet market scrapes.

at a statistically significant level, but the overall downward trend did not change. Figure 4 demonstrates this temporary disruption and continuation of the downward trend. Figure 5 shows a similar temporary effect in the MDMA and LSD markets. In Table 3 the change in ln(price) when Operation Onymous occurred was 0.28 (or a 32% increase in prices), 0.078 (8%), and 0.048 (5%) for fentanyl, LSD, and MDMA, respectively. However, without a change in the previous trend, prices reached their previous levels within 60 days.

Performing the same model with 90- and 60-day windows resulted in nearly identical results for fentanyl, except the initial shock of Operation Onymous increased from 32% to 35% and 44%, respectively. The change in trend linked to Operation Onymous was statistically insignificant for all three windows of time.

These results showing a temporary price increase in fentanyl, LSD, and MDMA are consistent with Décary-Hétu and Giommoni's (2016) conclusion that Operation Onymous did not result in a lasting general disruption across darknet markets, as vendors and users transitioned to surviving or new darknet markets in the ensuing months.

The second modeled event examined was the first fentanyl analogue regulation implemented by the Chinese government, prohibiting two of the most popular fentanyl analogues. The model results are found in Table 4. Fentanyl prices

TABLE 3

Operation Onymous Impact Summary: Comparing Across Drugs

Drug	Type of Change	Effect (Log)	Standard Error	*p* Value
Fentanyl	**Change in Price**	**0.280**	**0.097**	**.001**
Fentanyl	Change in Trend	0.001	0.001	.623
LSD	**Change in Price**	**0.078**	**0.011**	**.000**
LSD	Change in Trend	−0.001	0.000	.641
MDMA	**Change in Price**	**0.048**	**0.021**	**.021**
MDMA	Change in Trend	0.000	0.000	.450

Note: For each drug a similar fixed effects model was created surrounding the Operation Onymous event. The key coefficients around the change in price and the change in trend are included for each model below.

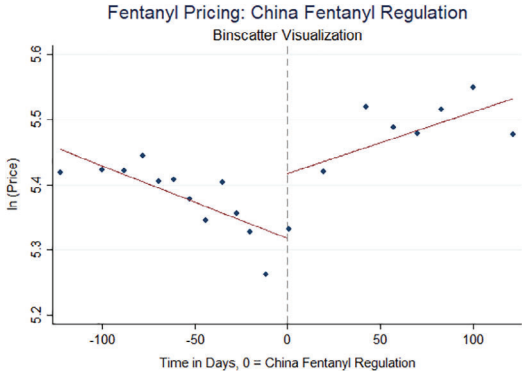
TABLE 4
China Fentanyl Regulation Fixed Effects Model for Fentanyl Prices

	Estimate	Standard Error	*p* Value
Trend	−0.0024108	(0.000)	0.000***
ChinaBan	0.2352078	(0.070)	0.001***
Trend * ChinaBan	0.0030152	(0.001)	0.001***
Analogue: Butyr	0.1497304	(0.056)	0.007**
Analogue: Traditional	1.0936281	(0.031)	0.000***
Analogue: Furanyl	0.313321	(0.046)	0.000***
Amount: 250 mg	0.6405325	(0.039)	0.000***
Amount: 500 mg	1.135128	(0.038)	0.000***
Amount: 1 g	1.4735829	(0.037)	0.000***
Amount: 5 g	2.5293025	(0.047)	0.000***
(Intercept)	3.5208845	(0.046)	0.000***

Note: Fixed effects included for the amount and fentanyl analogue type 100 mg of Acetyl Fentanyl is the omitted baseline $\ln(\text{Price}_{ij}) = \beta_0 + \beta_1(\text{Trend}) + \beta_2(\text{Event}) + \beta_3(\text{Trend} * \text{Event}) + \lambda_i + \theta_j + \varepsilon_{ij}$.
*$p < .05$, **$p < .01$, ***$p < .001$.

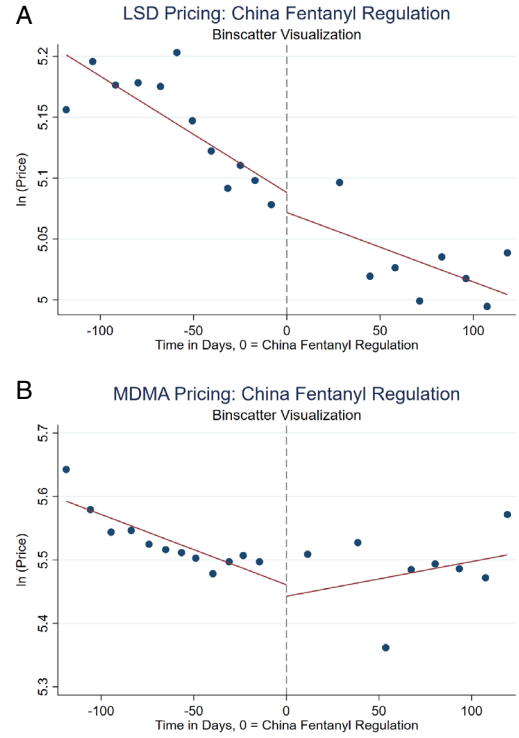
increased at the time of event and the downward trend in prices reversed at a statistically significant level. Figure 6 visually demonstrates this shift in both price level and trend. This change occurred at the same time as the regulation's implementation. Figure 7 shows no effect in the LSD market. The MDMA market does show a

FIGURE 6
China's Fentanyl Regulation Was Announced on September 24, 2015, and Implemented October 1, 2015. October 1st Date Is Used as Day Zero. Figure Displays 120-Day Window on Each Side of Event



Source: Grams darknet market scrapes.

FIGURE 7
Darknet Market MDMA and LSD Are Used as Comparisons to Fentanyl. China's Fentanyl Regulation Was Announced on September 24, 2015, and Implemented October 1, 2015. October 1st Date Is Used as Day Zero. Figure Displays 120-Day Window on Each Side of Event



Source: Grams darknet market scrapes.

TABLE 5
China Fentanyl Regulation Impact Summary: Comparing Across Drugs

Drug	Type of Change	Effect (Log)	Standard Error	*p* Value
Fentanyl	**Change in Price**	**0.235**	**0.070**	**.001**
Fentanyl	**Change in Trend**	**0.003**	**0.001**	**.001**
LSD	Change in Price	−0.013	−0.028	.642
LSD	Change in Trend	0.000	0.000	.210
MDMA	Change in Price	0.004	0.027	.892
MDMA	**Change in Trend**	**0.001**	**0.000**	**.005**

Note: For each drug a similar fixed effects model was created surrounding the China fentanyl regulation event. The key coefficients around the change in price and the change in trend are included for each model below.

TABLE 6
Iterative Model Robustness Check

Beginning Window	Event Date	End of Window	Event *p* Value	Event * Trend *p* Value
15-Nov-14	15-Mar-15	13-Jul-15	0.927	.258
25-Nov-14	25-Mar-15	23-Jul-15	0.613	.618
5-Dec-14	4-Apr-15	2-Aug-15	0.293	.626
15-Dec-14	14-Apr-15	12-Aug-15	0.079	.715
25-Dec-14	24-Apr-15	22-Aug-15	0.053	.803
4-Jan-15	4-May-15	1-Sep-15	0.506	.325
14-Jan-15	14-May-15	11-Sep-15	0.620	.075
24-Jan-15	24-May-15	21-Sep-15	0.413	**.047**
3-Feb-15	3-Jun-15	1-Oct-15	0.271	.054

Note: As a robustness check, the specified model was applied at 10-day intervals to the 3-month period that existed outside of the ranges of the two events of interest.

change in trend, but not price. However, upon closer examination this change in trend appears to have occurred 60 days prior to the Chinese fentanyl regulation and does not exhibit the sharp change at the time of the event like the fentanyl market exhibits. In Table 5 the change in ln(price) when the China fentanyl regulation occurred was 0.235 (or a 27% increase in price), and the downward trend reversed at a statistically significant level. No statistically significant change in LSD was detected, and the only statistically significant change in MDMA was the trend occurring earlier in the window. A closer examination of the descriptive statistics of specific analogues showed that traditional fentanyl increased in price the least, with acetyl and furanyl fentanyl increasing the most.

Performing the same fentanyl model with 90- and 60-day windows produced similar results. The shock measured by the model at the time of the event for these two narrower periods increased by 21% and 29%, respectively. The downward trend reversed at a statistically significant level for the 90-day window. Although the 60-day window had a similar coefficient, its power was insufficient to show a statistically significant change in trend with the narrower window.

As a final evaluation of both the model and evaluating price shifts in fentanyl prices, the model was also implemented at 10-day intervals for the 3 months that occurred between the events and outside their respective evaluation periods. The Event variable was not significant at .05 level in any of the iterations. The Event * Trend variable was statistically significant in one iteration. A table of the *p* values for both the Event and Event * Trend has been included (Table 6).

Despite the 27% increase in prices that occurred in late 2016, overall fentanyl prices remained lower than 2 years earlier (Table 1), and the significant relative discount to heroin remained.

V. CONCLUSION

Understanding consumer demand and elasticity is essential to understanding the effectiveness of regulation and prohibition (Becker, Murphy, and Grossman 2004). Effective regulatory response to fentanyl affects the survival of tens of thousands of people in North America every year, and understanding why fentanyl has grown in popularity should guide policy makers to improved regulatory outcomes. Fentanyl's extreme cost efficiency compared to close substitutes, and opioid consumers and distributors' willingness to switch may explain its rapid rise and the seeming inefficacy of law enforcement and regulatory actions intended to slow the increase in overdose deaths.

Two legal and regulatory events were evaluated: one addressed the distribution of fentanyl while the other addressed fentanyl manufacturing. The effects of disrupting distribution were short-lived, as market participants could move on to other channels and markets. Regulatory actions in China intended to curb the manufacturing of fentanyl did coincide with a general halt in the downward trend in fentanyl prices. Regulatory actions in China may have dampened the rapidly expanding supply to stay at pace with rising demand in North America. However, the low price per dose remained and opioid drug overdose deaths continued to climb.

These policies intended to reduce overdose deaths can be considered as part of a larger policy framework: (1) frustrate distribution, (2) reduce production, (3) directly reduce demand, and (4) indirectly reduce consumer demand through substitutes. The effects of frustrating distribution in this case were short-lived, while reducing production appears to have worked to some degree. While reducing production may assist in reducing overdose deaths, in terms of policy the third and fourth options should be considered more fully.

For example, demand for fentanyl could be reduced by providing fentanyl testing strips as a part of harm reduction. This would increase the reputational costs for vendors mixing or substituting other products with fentanyl, potentially leading to a reduction in unintentional fentanyl consumption and overdose deaths.

Concerning opioid substitutes, opioid users face an increased danger of overdose deaths. Because of this increase in users' risk, drug addiction detoxification and maintenance drugs, such as methadone, suboxone, and buprenorphine, may be more enticing to current opioid users than previously if these maintenance drugs were more readily accessible.

One area with important research potential is better understanding the cost structure of drug dealing intermediaries and assessing the profit motive to mix fentanyl into other products. As fentanyl initially became available and then fell in price, the profit incentive increased for distributors to defraud customers by diluting or completely substituting fentanyl into more expensive opioids, like oxycodone, Vicodin, and heroin. A fuller understanding of heroin dealer cost structures would provide the magnitude of the increased profitability for substitution. With a proper understanding of the degree and incentives of fraudulent substitution, policy makers could more fully differentiate legal penalties associated with dealing illicit drugs versus defrauding customers and contributing to higher mortality rates.

Finally, further research into darknet markets has become an essential element for illicit drug regulation. The elimination of darknet markets has thus far proven unsuccessful. While darknet markets may make certain illicit drugs more readily available, they can also cut out violent intermediaries and online vendor reputation effects may lead to more accurate product descriptions and doses than street vendors. The optimal methods of dealing with these emerging markets require further study.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1 Fentanyl Popularity—Google Trends
Appendix S2 Fentanyl Classification Confusion Matrix
Appendix S3 China Regulatory Announcements for Fentanyl