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Radical technological breakthroughs in drugs and drug markets: The cases of cannabis and fentanyl

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ABSTRACT

Background: Cannabis legalization and the arrival of nonmedical fentanyl are fundamentally altering North American drug markets. An essential part of that change is the ability to produce large quantities of these drugs at low costs, which is like a technological breakthrough in their production technology. This essay explores possible future consequences of these trends.

Methods: Descriptive statistics, historical analogy and economic reasoning.

Results: In North America, wholesale prices for cannabis and opioids – in the form of illegally manufactured fentanyl and other new synthetic opioids – are radically lower than they were a decade ago. Retail prices for cannabis have fallen commensurately, but not yet for opioids. Historical analogies suggest that very large declines in price can have effects on use that go beyond just an expansion of traditional patterns of consumption.

Conclusion: For cannabis and opioids in North America, conditions are ripe for significant changes in not only quantities consumed, and associated harms, but also in the roles these drugs and their control play in society. The overall situation with these drugs may look more different in 2040 compared to today, than today looks different from 2000. There are no obvious reasons why these trends will not spread to other continents.

Introduction

The thesis of this essay is that sharp declines in production costs for cannabis and opioids could dramatically reduce the price-per-dose for consumers in ways that alter patterns of use and dependence, first in North America but perhaps also on other continents.

It is important to acknowledge that speculating about the future cannot be done with the same degree of certainty as can the reporting of findings rooted in experimental data. As Yogi Berra said "Prediction is very hard, especially about the future", and experts' long-run predictions are often inaccurate, sometimes terribly so (Tetlock, 2017).

In an earlier drug futuring exercise I participated in, the futuring experts suggested focusing on drivers, maintained assumptions, and wildcards (Caulkins, Iguchi, Reuter, & Chiesa, 2003). Drivers are fundamental factors that appear set to change, in this case, production costs.

The maintained assumption is that drugs are ultimately consumer goods that are produced, distributed, and sold in markets (Reuter, 2014; Reuter & Kleiman, 1986). Hence, it makes sense to draw on economists' wisdom concerning fundamental behaviors of markets. In particular, some basic relationships between production costs, prices, and consumption have held up in market after market over centuries. Those market considerations are the focus here, which is not to say that cultural, sociological and political changes will not be equally influential, e.g., as a source of wildcards.

I draw on two key ideas from economics. The first is that prices in competitive markets fall to match the marginal cost of production. The logic for this is simple. If everyone else is charging more than the cost of production, then a firm can profitably offer a lower price. Customers will shift to the supplier offering the lower price, so that firm's sales increase, but the price is still higher than the cost of production, so the firm profits. Seeing that, someone else will bid lower. Then another firm can undercut that price and so on, until price has fallen to equal the cost of production.

By and large the markets for the major illegal drugs, including cannabis and opioids, are competitive in economists' sense of the term (Reuter, 2014). Journalists may speak informally of drug "cartels" but true cartels are the exception not the rule. Even the (in)famous Medellin and Cali cocaine cartels presided over falling prices (ONDCP, 2004), the opposite of what one would expect if they truly could block entry and maintain artificially inflated prices. Markets appear to have become even more fragmented since then (Golz & D'Amico, 2018).

The second key idea is that when prices fall, consumption rises; in elementary economics, this idea is captured by a downward sloping demand curve. Some might question whether that pattern applies

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to psychoactive drugs. However, an abundant empirical literature finds that consumption of drugs (and alcohol) does increase when prices fall and vice versa. Pacula and Lundberg (2013) examine the evidence for cannabis. Gallett (2014) provides a classic review for all drugs. Payne, Manning, Fleming, and Pham (2020) recent review suggests that a 10% change in price can trigger a 9% change in consumption.

It is important to note that many studies in that literature assess effects on use-related harms (e.g., emergency room mentions) not just use per se, so declining prices can push up population-level use-related harms, not just consumption.

Having sketched the basic logic, the next section reviews evidence for declines in production costs for cannabis and, more briefly, opioids. It seems likely, that those declines will percolate through to lower retail prices, at least for no-frills versions of the drugs. This should lead to greater consumption, but with declines in production cost that are so large, the effects may go beyond just an uptick in use. That idea is illustrated by reference to historical analogies, and I close by speculating about some possible consequences of the substantial price declines.

Changes in production costs

This section describes recent sharp declines in production costs for cannabis and illegal opioids that have occurred in both Canada and the United States.

North American cannabis production costs have already fallen by 90–95%

Cannabis policy in North America has been liberalizing for over 20 years, at least since California's Proposition 215 or Compassionate Use Act. There is an important distinction, though, between reducing or eliminating penalties for people who use drugs, or even small-scale growing for personal use, and giving a green light to large-scale production. The latter began in earnest in the U.S. with a series of memos issued by the U.S. Justice Department under the Obama Administration, starting with the Ogden Memo in 2009. These were interpreted as saying that federal law enforcement would not interfere with cannabis production or sale that complied with state laws. Canada's steps toward legalizing supply began later, with the election of Justin Trudeau in 2015, but have gone farther, with federal legalization of supply taking effect in October, 2018.

One of the myths about legalizing cannabis supply was that production would continue more or less as before, just without the arrests. In reality, the structure, conduct, and performance of the cannabis industry had been heavily shaped by prohibition, so much has been changing rapidly since legalization. That has manifest in various ways, including a proliferation of product forms, but perhaps the clearest effects have been on production costs and wholesale prices.

The wholesale price of sinsemilla in California in 2010 was $2000 - $6000 per pound (WSIN, 2010), and generally higher in other parts of the U.S. (Caulkins & Bond, 2012). Given inflation, $4000 per pound then is equivalent to $4650 per pound in 2019 USD. By November 2019, Cannabis Benchmarks reported a U.S. spot index price of $1428 per pound. That 70% fall is equivalent to an average annual decline of 12%.

The price per unit of THC has fallen even faster because potency has risen (Cascini, Carola, & Di Tanna, 2012; Chandra et al., 2019; Niesink, Rigter, Koeter, & Brunt, 2015). ElSohly et al. (2016), p. 613) report that nationwide "the potency of illicit cannabis plant material has consistently risen … from approximately 4% in 1995 to approximately 12% in 2014″. That is the year state-licensed recreational stores opened in Colorado and Washington. Those stores were soon selling flower with average potency over 20%, and extract-based products with potencies exceeding 60% (Smart, Caulkins, Kilmer, Davenport, & Midgette, 2017).

Since California's sinsemilla in 2010 had a potency of about 14% (Kilmer, Caulkins, Liccardo Pacula, MacCoun, & Reuter, 2010), the 70% decline in price per pound over 9 years becomes an 80% decline in the price per unit of THC.

Prices could fall further. The Canadian industry is driving production cost below $1 CAD per gram (Willis, 2019), which is less than $350 USD per pound, or about 7.5% of the inflation-adjusted 2010 price. Factoring in changes in potency, that translates to THC production costs falling by 95% in less than a decade.

Reasons for declines in cannabis production costs

There are multiple reasons why a licensed for-profit industry can produce at much lower cost than criminal producers could during prohibition.

Elimination of the enforcement "tax": Arrest, incarceration, and seizures impose costs on drug producers and distributors that are passed along to consumers as higher prices (Reuter & Kleiman, 1986). People facing the risk of criminal sanction may demand higher compensation than people performing similar tasks in other industries, a principle called "compensating differentials" in economics. For example, Caulkins (2010) notes that circa 2008 people growing cannabis paid unskilled and semi-skilled labor far more than other agricultural workers were paid.

Economies of scale: For various products, unit production costs decline as the scale of production increases. This can be measured as an elasticity of cost with respect to scale. An elasticity less than 1.0 means that cost increases less than proportionally, so cost per unit declines as production scale increases.

Hawken and Prieger (2013) assumed that economies of scale in cannabis production would be modest, suggesting an elasticity of 0.913 as midway between Schumacher and Marsh's (2003) estimate of 0.827 for greenhouse floriculture and no economies based on Kislev and Peterson's (1996) arguments about farming generally.

That might seem insignificantly below 1.0 until one recognizes the enormous changes in scale that have occurred. The average size of the 186 firms in Hawken and Prieger's sample was just under 1000 square feet, but multiple Canadian firms operate 1000,000 square foot grows (Williams, 2018), and Aurora had plans for a 1600,000 square foot facility.[1]

Fig. 1 shows that even with an elasticity of 0.913, a thousand-fold increase in scale implies unit production costs fall by almost half, and Schumacher and Marsh's estimate of 0.827 would imply a decline of 70%.

Furthermore, cannabis can be grown outdoors. Duffy (2009) discusses economies of scale in outdoor agriculture, contrasting a larger 1500-acre farm with a "small" 100-acre farm, but even 100-acres is still over four million square feet.

Harnessing new and improved technologies: The "internal" economies just discussed pertain to doing things differently because the facility is larger. Legalization also encouraged changes in production technology that were driven by the size of the industry, not a particular facility. That includes development of higher yielding strains, and a professionalization of the business. Older accounts of gray market growing often describe amateurish efforts by "plant lovers" (e.g., Donahue, 2012), but modern cannabis corporations fully embrace science-based industrial agriculture. When there were 1000 firms each growing on 1000 square feet, those firms' master growers could have varying skill levels. When one firm grows on 1000,000 square feet, that firm can hire the most skilled of those 1000 master growers to oversee the entire operation.

Extracting cannabinoids: Traditionally growers harvested cannabis buds ("flowers"), but discarded other parts of the plant that contained cannabinoids in lower concentrations. Since most of the plant's weight was in leaves, trim, and stems, the total amount of cannabinoids discarded was not small. Now those materials can be fed into extraction

[1] Schneider (2019) reports that the largest greenhouse in the United States will be a 2.76 million square foot facility in Kentucky that will be used to grow vegetables.

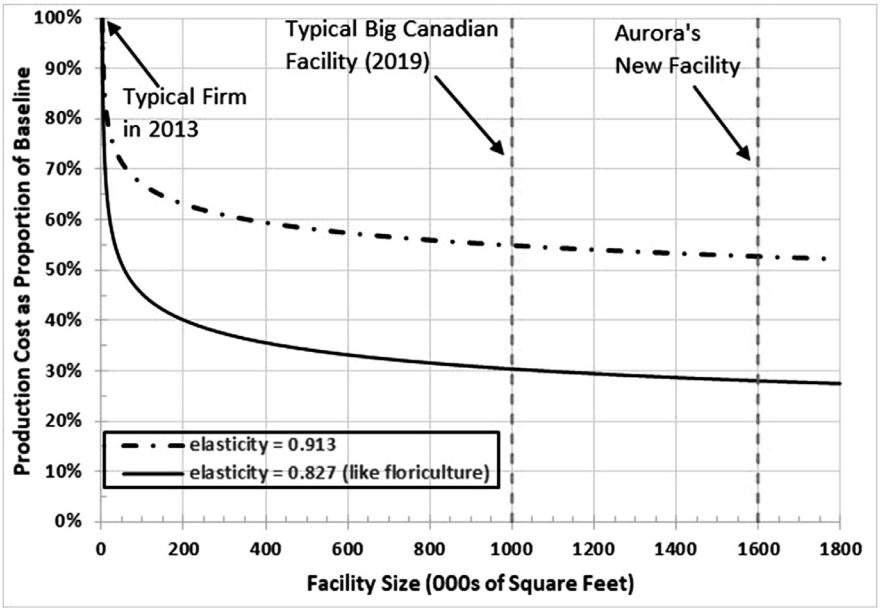

Fig. 1. One model of economies of scale in greenhouse based growing.

machines to produce other cannabis products. Indeed, the market-share of extract-based products has risen sharply (Smart et al., 2017).

Declines in wholesale prices for illegal opioids

Illegal opioid markets in Canada and the United States had long been dominated by heroin, but around 2014 fentanyls and other novel synthetic opioids began to make substantial inroads. There had been previous fentanyl outbreaks that sputtered out, but for various reasons, fentanyl took root this time. At least initially the fentanyl was produced primarily in China. It appeared first as an adulterant in heroin. Later it began to show up in counterfeit prescription drugs, and also stimulants, including cocaine. Although as of 2019 it was still somewhat regional (oddly, concentrated in Western Canada and the Eastern United States), in certain markets it had essentially displaced heroin. See Pardo et al. (2019) for details.

The principal public health concern with fentanyl is that it is much, much more potent than heroin, so overdose rates increased sharply (e.g., Baldwin et al., 2018; Spencer, Warner, Bastian, Trinidad, & Hedegaard, 2019). For present purposes, though, the focus is on the fact that fentanyl is enormously cheaper than heroin per morphine equivalent dose (MEDD).

Pardo et al. (2019), Appendix B) and Reuter, Taylor, & Pardo (2021) describe this chasm between the traditional wholesale prices of heroin and those for newly emergent fentanyl in the United States. Fentanyl costs about one-tenth as much per kilogram, is about twice as pure, and gram-for-gram is about 20 times as potent in terms of morphine equivalent doses. Putting that together, heroin is at least 100 times more expensive per morphine equivalent dose, so fentanyl can cut wholesale opioid dealers' raw materials costs by over 99%.

From people who use opioids, how much cheaper is cheap fentanyl?

The calculations in Table 1 are rough because data on fentanyl prices are scarce and also because MEDD equivalency factors over-simplify; converting between opioids is not just a units conversions akin to converting dollars to euros (Fudin, Cleary, & Schatman, 2016; Knotkova, Fine, & Portenoy, 2009).

MEDD conversions pertain to analgesic effects. Even if one milligram of fentanyl provides as much pain relief as 20 mg of heroin, that doesn't mean that people who use opioids find one milligram of fentanyl to be as appealing as 20 mg of heroin. Both are mu-opioid receptor agonists, but there are differences. Notably, fentanyl's duration of effect is shorter. If switching to fentanyl increases the number of use sessions per day, the dollar cost per day of use might not fall as much as cost per MEDD.

Furthermore, if fentanyl leads to more injection-use sessions, that could increase health risks, or it could increase time spent traveling to a safe injection facility. If more use sessions also meant more frequent purchases, that could increase the "search time" costs of purchasing (Rocheleau & Boyum, 1994).

In sum, the decline in the total or effective cost of using fentanyl may not match the decline in the cost per MEDD, but that would only soften the magnitude of the decline, not negate it.

By how much will declines in production costs affect retail prices?

Retail prices for illegal drugs are often much higher than are wholesale prices. E.g., even though heroin sells in the U.S. for $50,000 per pure kilogram, or $50 per gram, Midgette, Davenport, Caulkins, and Kilmer (2019) describe retail heroin prices as being $750 per pure gram. I will use a more conservative figure of $300 per pure gram. Either way, a long-discussed question is: If the wholesale price falls, say from $50 to $1 per gram, how does that affect retail prices? An additive model predicts a roughly equivalent decline in price per gram, from $300 to $251 per gram at retail. A multiplicative model predicts a proportional reduction, from $300 per gram to $6 per gram. Conventional products would be expected to follow an additive model, but drugs may be different, e.g., because of their high value to weight ratio (Caulkins, 1990).

Cannabis price declines have been broadly consistent with a multiplicative model. Caulkins et al. (2018) show that in Washington State's legal market, as retail prices fell from $22 per gram to a little below $10 per gram between the 3rd quarter of 2014 and the 4th quarter of 2016, they were consistently triple the price at the processor level.

Longer-run declines have also been comparable, in percentage terms, to declines in wholesale prices. The median price for a gram of sinsemilla in California in 2010 was $20, or $23 in 2019 dollars (WSIN, 2010). If retail prices fell by the same 70% that wholesale prices did through 2019, they would be $7 per gram. As noted, Washington State's retail prices had fallen below $10 per gram by the end of 2016, and they continued to fall after that (Davenport, 2019). An industry report described average flower prices in Colorado and Washington as having fallen be-

Table 1
Comparison of wholesale costs per morphine equivalent dose of heroin and fentanyl.

				Cost per kg of MED	
	Price per kg	Purity	MEDD conversion	Low MED Factors	High MED Factors
Heroin	**$25,000**	**50%**	**2–5**	**$25,000**	**$10,000**
Fentanyl	**$2000–5000**	**95%**	**50–100**	**~$40-$100**	**~$20-$50**
			Ratio H to F Price	**~100–600**	**~200–500**
			Fent Price as a%	**0.16–1.0%**	**0.2–0.5%**

low $5 per gram, although prices were higher in California and Nevada (Headset, 2019).

There may always be premium brands commanding higher prices, but no-frills products could become extremely cheap, akin to mass-market vs. craft beers or, for that matter, everyday vs. premium chocolates (Caulkins, Kilmer, & Kleiman, 2016).

As of yet, there is no indication that fentanyl has put substantial downward pressure on retail opioid prices (Reuter, Taylor, & Pardo, 2021), although for technical reasons monitoring retail opioid prices is difficult. The reason may be that most of the value-add in traditional drug distribution represents compensation for dealers' labor (Caulkins & Reuter, 2010; Reuter & Kleiman, 1986). Even if the drug were free at the wholesale level, if distribution continues in its present format, that distribution might still require about the same amount of labor and carry about the same amount of risk to connect wholesale dealers to customers.

However, drug distribution can happen in other ways. For example, even when it was illegal, most cannabis was distributed through social networks, without professional dealers or large price markups (Caulkins & Pacula, 2006; Hathaway, Mostaghim, Erickson, Kolar, & Osborne, 2018). It is interesting to ask why was (relatively cheap) cannabis distributed through social networks and (relatively expensive) heroin distributed by "professional" dealers? The answer may indicate whether cheaper fentanyl could transform opioid distribution, perhaps in ways that shrink the wholesale to retail price markup.

Price declines matter; radical price declines matter radically

Falling prices affect consumption, but the effects of precipitous declines may not be just a bigger version of the effects of modest price declines, as some historical analogies show.

Typical price declines

A considerable literature has developed estimating the elasticity of demand for various illegal drugs, and for tobacco and alcohol. The degree of price responsiveness can vary from one setting to the next, and from one outcome variable to the next. As Payne et al. (2020) note, the elasticity of consumption will generally be greater, in absolute value, than the elasticity in prevalence, because higher prices can reduce the intensity of consumption, not just the number of people who are consuming.) On the whole though the elasticity estimates were traditionally thought to be roughly −0.5 for cannabis (Pacula and Lundberg, 2013) and −0.75 for heroin (Gallett, 2014), but recent estimates are higher. Payne et al. (2020) suggest −0.8 for cannabis and −0.9 for heroin.

That consumption of addictive drugs responds to price changes surprises some until one remembers that people care a lot about the prices of things they spend most of their money on. For example, housing is a big ticket item, and people living in expensive real estate markets tend to have smaller residences than do those living where housing is cheap. Toothpaste, by contrast, accounts for a very modest share of consumer spending, so most people don't adjust tooth brushing habits in response to changes in the price of toothpaste. People who use drugs heavily dominate consumption, and for them drugs can be more like housing than toothpaste in terms of accounting for a significant share of disposable income.

Thinking about very big price declines

This picture of how consumers respond to small price changes may not extend to behavior in the face of very big price declines. Consider the familiar example of taking pictures. Back in 1990, every picture was expensive. One had to buy film, pay for it to be developed, and incur the hassle of traveling to a Fotomat or other developer.

By contrast, taking digital pictures with a cell phone is all but free. Not surprisingly, the total number of pictures taken has soared. Googling turns up claims that film photography peaked in 2000 with 85 billion photos, but an estimated 1.2 trillion digital photos were taken in 2017, or fourteen times as many.[2]

The change is not just about volume. It's not that families once went to portrait studios to have pictures taken for Christmas letters, but now also have portraits taken for Easter, Memorial Day, and National Absurdity Day. (That's November 20th.) Nor do they sit for 14 times as many poses.

Rather, people use cameras in ways that were unthinkable a generation ago. People snap pictures to help them remember interesting presentation slides at conferences, where they parked their car at the airport, and details of the household objects they plan to replace while out shopping.

So the very low cost of taking photographs not only increases the number of photos taken, it also altered the place of photography in daily life. That in turn has wider social ramifications, like selfies, scanning QR codes, the death of privacy, and citizens fighting against police misconduct by taking photos (and videos) with their cell phones.

Historical examples of radical price declines

There are many examples of products whose meaning in society changed when production costs fell radically. Cultured pearls have forever rendered pearls ordinary. When U.S. President Hoover promised "a chicken in every pot", chicken was a sign of wealth; modern farming has made chicken the cheapest and most commonly consumed protein in the US.

An obvious example is that the prices of computer processing and memory have decayed exponentially as chips' performance doubled every 18 months (Moore's Law). Cheaper computing has not just enabled the adding of longer columns of numbers. The information revolution has transformed society.

The cost of producing electricity from sunlight has also decayed exponentially by about 10% per year over at least 40 years, and volume doubles with every 20% decline in price (Swanson's Law). This not only increased production volume, it changed the way photovoltaic cells are used. Originally they were restricted to exotic applications, like solar powered satellites. Then they powered terrestrial objects that could not be plugged into the grid, like watches, calculators and toys, but now are used to produce electricity for the grid.

Lighting offers another example. Fouquet and Pearson (2012) assembled data on UK lighting prices dating back to 1300, spanning multiple

[2] These websites offer those figures: https://petapixel.com/2011/09/16/film-photography-peaked-in-2000-with-85-billion-photos-taken-then-plummeted/ and https://en.wikipedia.org/wiki/Digital_photography#Number_of_photos_taken.

technological eras including tallow candles, kerosene lamps, "town gas", and electricity. They report that price fell from 8000 pounds per million lumen-hours in 1800 to 250 in 1900 and 2.5 in 2000. Consumption grew from 20 billion lumen-hours in 1800 to 10,000 billion in 1900 and 800,000 billion in 2000, a 40,000-fold increase. That cheap lighting transformed society. According to Fouquet and Pearson (2012, p.88) "Before the mid-eighteenth century, at night, most people lived in near-complete darkness and only ventured out in the presence of moonlight." Now society hums 24/7.

Tobacco may offer the most relevant analogy (Proctor, 2004; Proctor & Proctor, 2011). Before the late 19th century, tobacco was mostly smoked in pipes and cigars; the smoke was not drawn into the lungs, so lung cancer was not so common. Three innovations changed that. Flue curing (invented in the 1830s) eliminated the alkali sting and let smoke be comfortably inhaled into the lungs. Safety matches (patented in 1855) made it easier to light a cigar or cigarette. And the Bonsack automated cigarette rolling machine increased productivity 500-fold relative to traditional hand rollers.

The ensuing growth in smoking and cancer are well-known. The changes to industry less so. In the 19th century tobacco firms were small and regional, but rolling machines created economies of scale, and reduced production costs made nationwide marketing and branding more important. The industry consolidated, gained political clout, and intentionally altered the place of tobacco in society. For instance, whereas tobacco use had once been male dominated, at least in the U.S., strategic industry marketing opened up the market for female smokers in the 1930s ("Reach for a Lucky instead of a Sweet").

Possible future implications

It does not take great vision to predict that cannabis policy liberalization may be fundamentally changing the place of cannabis in society. Cannabis corporations are listed on the NASDAQ (e.g., Tilray) and Toronto stock exchanges (Aprhia, Aurora, and Canopy). Legalization promotes product diversification, including extract-based products. Edibles make consumption convenient for those who do not want to smoke, and even vaping is odorless, convenient and easier on the lungs than smoking. Legalization opened the door to aggressive advertising, including dubious health-claims; e.g., the majority of Colorado dispensaries contacted by Dickson et al. (2018) recommended cannabis to pregnant women as a treatment for morning sickness. Cannabis has changed from an occasional recreational drug to a part of daily "wellness" regimens.

More changes may be coming. Production costs could fall to pennies per joint (Caulkins et al., 2016), allowing cannabis to be used as a loss leader (e.g., convenience stores selling at cut rate prices to get people to come in to buy gas). If cannabis gives people the munchies, restaurants might find it profitable to give out cannabis the way that bars comp patrons salty nuts to get them to drink more. Hotels could help anxious travelers sleep better by leaving THC-infused chocolates on pillows.

Radical declines in wholesale opioid prices could also have unexpected effects. If novel synthetic opioids drive out heroin – as has happened in Vancouver, New Hampshire and parts of Ohio—that could cut demand for opium poppies, which are an important source of income for poor farmers in certain regions. It could also undermine the power of Drug Trafficking Organizations (DTOs) that produce and distribute heroin made from those poppies (Felbab-Brown, Caulkins, & Humphreys, 2018). Aggressive interventions to suppress drug production in source countries might be deterred when fentanyl is produced by a nuclear armed superpower.

Fentanyl's potency per kilogram and tendency to be distributed by parcel may reduce the value of criminal organizations' skills at cross-border smuggling. If domestic distribution moves online with orders fulfilled by mail, that might make distribution less violent.

Sharply falling opioid prices might favor oral over intravenous routes of consumption, reduce spending on drugs and associated economic-compulsive crime, and take market share away from stimulants. Synthetic opioids' tendency to produce extraordinary numbers of overdose deaths, and the existence of effective opioid pharmacotherapies, may further the shift toward seeing illegal drugs through a medical not a criminal lens.

Legalization transformed cannabis from more or less a single drug (smoked "herbal" cannabis, plus hashish) into a broad category of cannabis plant products, a change akin to expanding beyond milk to the entire dairy industry with cheese, yogurt, ice cream, etc. The same could happen with opioids. Where once there was just black tar and powder heroin, now there is also not only fentanyl but dozens of other new synthetic opioids.

I give only passing mention to these possible and important changes, even though each could be developed into an essay of its own, because I do not want to bet that this or that particular change will happen. The future is unknown, and any of these specific speculations may well be proven wrong, but I will stand by this more general prediction. I predict that if someone in 2040 makes a list of the major changes in drug markets, use, and dependence that occurred since 2020, there will be items on that list that pertain to the declines in production costs brought about by cannabis legalization and the spread of synthetic opioids.

In terms of policy implications, it is too soon to react to any of these specific speculations, since it is not clear which will come to pass. It is not too soon, however, to invest more in market monitoring in order to stay abreast of the diverse ramifications that may flow from these radical reductions in production costs.

Declarations of Interests

None to declare.

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