Estimating Canadian Cannabis Consumption Using Markers in the Wastewater

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Abstract
In the fall of 2018, Canada legalized cannabis for recreational use. Given this major change in policy, Statistics Canada wanted to update and improve their estimates of cannabis consumption. However, estimating drug use with traditional surveys presents a challenge because respondents are likely to under-report their consumption.

To supplement surveys, Statistics Canada piloted the emerging science of wastewater-based epidemiology (WBE), which involves measuring wastewater in the sewers for trace concentrations of a cannabis metabolite that is created and excreted after consuming cannabis. This same approach can also be applied to other drugs of interest, including methamphetamine, cocaine, and opioids. In this paper, we validate the WBE measurements and evaluate their utility for estimating various quantities relating to societal drug use.

WBE is particularly well-suited to direct comparisons of the wastewater at different times or locations. It detected large temporal patterns for some of the drugs, including cannabis. It also identified geographical patterns of drug consumption that were distinct for each drug, revealing different drug-use profiles for the five cities in the study.

However, WBE estimates of annual drug consumption were of mixed quality, depending on the drug. Methamphetamine and cocaine consumption estimates were reasonably precise. The cannabis estimate was more variable, primarily due to uncertainty in the amount of cannabis metabolite excreted after consuming cannabis. Estimates of individual opioids were not attempted at this time because too many distinct drugs leave the same trace in the wastewater, making them impossible to distinguish.

This project demonstrated that wastewater contains information about societal drug use. While WBE does have some limitations that should be evaluated when considering a specific application, it could provide a valuable source of information when used in concert with surveys.

Key Words: Cannabis, Drugs, Wastewater-Based Epidemiology, Official Statistics, Illicit Drug Monitoring, Response Burden

Disclaimer
This article describes theoretical approaches and does not reflect currently implemented methods at Statistics Canada.

1. Introduction

Societal use of recreational drugs is of interest to National Statistical Offices (NSO), including Statistics Canada. This information is important from the perspectives of health, economics, justice, society, and for the creation and evaluation of drug-related policies, such as the nation-wide legalization of recreational cannabis that took place in Canada on October 17, 2018.

However, drug use is difficult to measure accurately using surveys, the most common instrument used by NSOs for data collection, for several reasons. First, respondents may not be willing to divulge their drug use to a government agency, leading to systematic under-reporting. This problem is likely more severe with more stigmatized drugs, such as cocaine, methamphetamine, and heroin, but it is likely still present with cannabis as well. An interesting product of this problem is that if the stigma around a drug changes, as could happen with the legalization of cannabis, then the degree of intentional under-reporting could change and lead to a change in survey estimates even if there was no change in drug consumption. A second reason why surveys may struggle to accurately measure drug consumption is that respondents may honestly not know or remember the amount of drug they consumed in the past three months. They may not count a joint shared with friends; they may not know the amount of cannabis in a brownie they ate; and they may forget to include a weekend of atypically heavy use that happened several months ago, near the beginning of the reference period. Instead, they may respond with their consumption for "a typical period", which may not account for atypical events and therefore also systematically underestimates their consumption. In addition to these measurement issues, drug users may be more likely to be missing from a survey frame, depending on the drug, if they are more likely to be living without an address or a phone number.

Because of these challenges, Statistics Canada began testing the use of wastewater-based epidemiology (WBE) to supplement surveys for estimating drug consumption. WBE is based on the principle that each drug is processed in the body into metabolites, which are excreted and flushed into the sewer system (Figure 1). WBE involves sampling untreated wastewater to measure the concentration of the drug metabolites, which can be used to estimate the total amount of that drug consumed within the area serviced by the sewer system. WBE has been used for estimating drug use since the early 2000s (European Monitoring Centre for Drugs and Drug Addiction, 2016), mostly in Europe but with labs all around the world. It remains an active area of research, especially with respect to how the molecules behave in the complex environments of the body and the sewer system (where they may react with other chemicals, heat, or microbes), and the chemical analysis of the drug metabolite concentrations in the challenging wastewater matrix where a wide array of other molecules are also present. Most of the WBE analysis has taken place at academic institutions, although the Australian government has also launched a WBE project to track drug consumption across time and locations (Australian Criminal Intelligence Commission, 2019).

The WBE approach to estimating drug consumption has several advantages over surveys. It is more impartial because it is not subject to recollection or under-reporting biases. It eliminates response burden for residents. It is an aggregate measurement of typically tens of thousands to hundreds of thousands of people, so even the raw data does not identify people who consumed drugs or even city blocks where the drugs were consumed, alleviating privacy concerns. Additionally, it has the potential to provide information quickly and inexpensively compared to surveys with the same population coverage.

However, WBE does have its limitations. WBE cannot identify who consumed the drug or how it was consumed, which makes it impossible to know even the drug's prevalence (how many people consumed), let alone demographic characteristics of consumers such as age, gender, education, ethnicity, and religion, or the most common methods of consuming the drug. Additionally, WBE is limited to the geographies defined by the architecture of the sewer systems, which may not align to desired geographical definitions, and the measurement always relates to drug consumption with no flexibility to ask about related concepts such as drug purchasing. Therefore, WBE does not replace surveys, but can serve as a supplement with a complementary set of strengths and limitations.

Statistics Canada implemented a one-year pilot project to examine the utility of WBE data for estimating consumption of cannabis and other drugs. Section 2 describes the implementation of the pilot project. Section 3 discusses validations of the WBE data. Section 4 tests WBE's ability to estimate three different quantities: total drug consumption, changes in consumption over time, and differences between cities.

2. Pilot Study

The pilot project spanned 12 months, from March 2018 to February 2019. It included 14 wastewater treatment plants from five large Canadian cities: Halifax, Montreal, Toronto, Edmonton, and Vancouver. The selected treatment plants serve 8.4 million people, over 20% of the national population.

For each of the 12 months, the week starting on the second Monday was selected for collection. For each day during a collection week, the wastewater arriving at a treatment facility was sampled with high frequency, approximately every half hour. The timing of the sampling was proportional to the flow rate so that the incoming water volume would be sampled at equal intervals (e.g. every $10{,}000m^3$). The daily samples were frozen at the end of each day, and at the end of the week, they were shipped to external partners at McGill University in Montreal, Canada, for chemical analysis.

At McGill, the samples were thawed and the seven daily samples were combined into a single weekly aggregate, proportional to the flow on each sampling day. The weekly aggregate was then split into several parts to be independently tested. The concentrations of drug metabolites were quantified using liquid chromatography − high resolution mass spectrometry (LC-HRMS) using a process that was certified by the Sewage analysis CORe group Europe (SCORE).

3. Validating the WBE Measurements

WBE is a new measurement instrument for Statistics Canada, so we wanted to validate it. However, we could not simply compare the WBE estimates to a gold-standard estimate of cannabis consumption within the sampled cities because no such estimate exists. Therefore, we validated the measurements in other ways. First, we assessed the consistency of the chemical measurements from the same weekly aggregates of wastewater. Second, we evaluated whether consecutive weeks had similar quantities of cannabis metabolite in the wastewater, which would be expected since it is excreted slowly over the course of several days to a week (Huestis, 2007; Gracia-Lor, Zuccato, and Castiglioni, 2016) and therefore even single doses are likely detectable in consecutive weekly wastewater samples. Third,

we compared the measurements to WBE measurements from other labs in other cities to determine if they are in the same range.

3.1 Chemical Analysis Is Highly Consistent

Each weekly aggregate of wastewater was tested for the concentration of cannabis metabolites three times independently. The three replicates were very consistent with one another, with a correlation of 99% (Figure 2A). This demonstrates that the chemical analysis is highly replicable and not a major source of variability.

3.2 Results for Consecutive Weeks Are Similar

Despite the high consistency of the chemical analysis, there were large differences between monthly loads[1] in the same city (Figure 2B shows Montreal as an example). We wondered if this variability represented errors in the wastewater sampling.

We wanted to validate these measurements, but there was only one sample for each collection week and the next sample was not until a month later. However, in Montreal, research samples were collected on consecutive weeks. We would predict that the amount of cannabis metabolite excreted into the wastewater would be similar on consecutive weeks since it is excreted slowly after consumption, over the course of a few hours to a week or more (Huestis, 2007; Gracia-Lor et al., 2016). The Montreal research data happened to align well with the two spikes in the monthly production data: it was collected during the four weeks of May and the five weeks connecting the November-December regular production samples.

All four weeks in May were similarly high, corroborating the high May measurement. Similarly, the November-December weekly data fell intermediate to the low November measurement and the high December measurement. These results show the expected similarity between consecutive weeks and are inconsistent with the idea that the May and December measurements were high because of errors in the sample collection and preparation steps.

3.3 Wastewater Cannabis Measurements Are Broadly Similar to Other Cities

The first two validations are internal, asking if the data are self-consistent. The third validation is external, comparing the results to other data sources to determine if the estimates are of a reasonable magnitude.

We compared the wastewater measurements of cannabis metabolites to those of 70 cities around the world (Figure 2C) (SCORE, 2017). While different cities have substantial differences in cannabis metabolite loads per capita, the pilot test results fall near the middle of the range of the other cities (Figure 2C, horizontal line is the average of the 12 months and five cities in the pilot project). This suggests the magnitudes of the measurements are reasonable and broadly consistent with previous results.

[1] This comparison was based on cannabis metabolite loads rather than concentrations. Load is an estimate of the mass of the metabolite flowing into the treatment plant during the sampling week. While a rainy week would increase the flow and decrease the concentration, it would not change the load. The rest of the comparisons in this paper are either based on load or load per capita, which standardizes cities with different populations.

In light of these three validations, the WBE data appear to be informative about the amount of cannabis excreted into the wastewater. The next section explores which quantities can be well-estimated by WBE methods.

4. Results

4.1 Estimating Annual Drug Consumption

Estimating cannabis consumption requires knowledge of cannabis plant potency, cannabis metabolism, and stability of the cannabis metabolite. The main psychoactive ingredient in cannabis is tetrahydrocannabinol (THC); its proportion of the dried plant mass is called the potency. Upon consuming THC, the body converts it into a variety of non-psychoactive metabolites, including 11-nor-9-carboxy-tetrahydrocannabinol (THC-COOH), one of the most common and stable metabolites, which is then excreted. THC-COOH is considered quite stable but some may still degrade in the sewer system or after the sample was collected but before it could be analyzed. Therefore, the quantity of THC-COOH in the wastewater sample depends not only on the amount of cannabis consumed, but also on these additional parameters, as follows:

$$\underset{\text{consumption}}{\text{cannabis}} \times \underset{\text{of cannabis}}{\text{THC potency}} \times \underset{\text{excretion rate}}{\text{THC}-\text{COOH}} \times \underset{\text{in sewers}}{\text{degradation}} \times \underset{\text{in sample}}{\text{degradation}} = \underset{\text{in the wastewater}}{\text{load of THC}-\text{COOH}}$$

Cannabis consumption can then be estimated by dividing the wastewater load of THC-COOH by the four parameters: potency, excretion rate, degradation in sewers, and degradation in sample[2].

We characterized each parameter with a probability distribution using the available literature. This method specifies not only the average but also the range of possible values for each parameter. For the specific probability distributions we used, and the literature on which they are based, see Brennan et al. (2019).

We estimated annual cannabis consumption within the entire pilot area, accounting for uncertainty in the parameters and the wastewater measurements. We accounted for wastewater measurement uncertainty using a bootstrap procedure based on across-month variability and accounting for the right-skewed distribution of the monthly measurements (see Brennan et al. (2019) for more information). We combined this with the parameter uncertainties using Monte Carlo simulation: for each of 10,000 repetitions, independent draws from the parameter distributions and the distribution for mean annual load in the wastewater were combined to estimate cannabis consumption. This resulted in a distribution of 10,000 cannabis consumption estimates that are consistent with the wastewater measurements and account for all the relevant uncertainties.

The median estimate of cannabis consumption was 10 grams per person per year, across the 8.4 million people in the sampled cities (Figure 3A). However, there was a wide range of annual consumption values consistent with the wastewater measurements: a 95% confidence interval spanned from 3 to 32 grams of dried cannabis per person per year, representing a coefficient of variation of 64%.

[2] We are estimating the mass of dried cannabis plant that would need to be consumed to account for the THC-COOH in the wastewater. However, some of the cannabis would have been consumed in another form, such as a concentrated product. We are accounting for consumption of these other products by considering them equivalent to a mass of dried cannabis plant that would result in the same excretion of THC-COOH.

As an additional validation of the WBE measurements, the cannabis consumption estimates can be compared to survey-based estimates of cannabis consumption in Canada. Four Statistics Canada publications have estimated recent national cannabis consumption. They are all based on the same 2012 survey, so they are not independent estimates, but they use different methods to account for under-reporting and to project to 2017 or 2018. While the survey and WBE estimates are based on different populations (national for surveys; sampled cities for WBE), we would still expect them to be similar. The available survey estimates range from 18 to 23 grams per person per year (Office of the Parliamentary Budget Officer, 2016; Macdonald & Rotermann, 2017; Cannabis economic account, 2018; Provincial and territorial cannabis economic accounts, 2018; for more details on these estimates, see Brennan and Reedman, 2019). For the estimate that was accompanied by confidence limits, the 90% limits extended from 10 to 27 grams per person per year (Office of the Parliamentary Budget Officer, 2016). While the survey estimates are higher than the WBE estimates, they are contained within the WBE confidence interval, again suggesting that the magnitude of the estimates is reasonable, although highly uncertain at this time.

The high uncertainty of the cannabis consumption estimate arises primarily because the cannabis excretion rate is extremely uncertain (Figure 3B). Excretion rates of 1% to 5% would all be consistent with the available data at this time (Burgard et al, 2019; Brennan et al, 2019). This parameter could be improved with more clinical studies of cannabis metabolism and excretion, especially fecal excretion, which is an important route of elimination for cannabis metabolites (Burgard et al, 2019; Gracia-Lor et al, 2016; Been, Schneider, Zobel, Delémont, & Esseiva, 2016; Khan & Nicell, 2012).

A secondary reason for the uncertainty, accounting for about 25-30% of the uncertainty of the final estimate (versus 65% from the excretion rate), is the high variability between the monthly samples (Figure 4), which may turn out to be due to seasonal variation. In the future, this variation may be explained and controlled by more regular sampling or models of seasonality.

The methods we have described can be applied to other drugs as well. Cocaine and methamphetamine metabolites were both reliably measured in the wastewater[3]. Moreover, their excretion rates and degradation parameter values are better-studied than those for cannabis and are correspondingly more certain (Brennan et al, 2019).

Methamphetamine consumption was estimated to be 0.31 grams per person per year in the five sampled cities, with 95% confidence intervals spanning from 0.19 to 0.56 grams per person per year (Figure 3C). Cocaine consumption was estimated to be 0.37 grams per person per year, with 95% confidence intervals from 0.27 to 0.54 grams per person per year (Figure 3D). These estimates are much more precise than the cannabis estimate, with coefficients of variation of 30% and 19%, respectively.

[3] Like cannabis, cocaine is processed into a distinct metabolite, benzoylecgonine, which indicates that cocaine was consumed within the service area. In contrast, methamphetamine's main trace in the wastewater is methamphetamine itself, excreted unchanged after consumption. We are assuming that the wastewater methamphetamine was excreted after consumption and not dumped. Additionally, there are other drugs that metabolize into methamphetamine and would appear the same in the wastewater. However, in consultation with Health Canada, we determined that these drugs are very rare and account for a negligible portion of the methamphetamine in the wastewater.

Another class of drugs that would be desirable to estimate is opioids. However, WBE estimates of opioid consumption are challenging because the metabolites are the same for several different opioids. For example, the main stable heroin metabolite is morphine, but morphine in the wastewater could also have come from morphine or codeine consumption, both of which are quite common. Heroin's other metabolites are excreted in low doses and are unstable in the wastewater, leaving no other reliable traces. Therefore, an estimate of heroin consumption would need careful accounting of the wastewater morphine attributable to other sources, which is not possible from the wastewater alone.

There would be an additional challenge extending these drug consumption estimates to a national level because they are biased toward large cities. This problem could be partially corrected by including some randomly-chosen smaller cities. However, it could never be eliminated because people who use septic tanks cannot be included. Hence, WBE may be best suited for focusing on large or high-risk cities rather than extending to a larger population of interest.

4.2 Detecting Changes Over Time

Detecting changes over time has an advantage over estimating drug consumption because it does not rely on knowledge of the additional parameters (potency, excretion rate, and degradation). While the parameters are uncertain, they are not expected to change much over time, so differences in wastewater measurements primarily reflect differences in drug consumption[4]. Therefore, wastewater measurements can be compared directly for temporal trends.

We first examined whether there were changes in any of the drug metabolites at the time of cannabis legalization in October 2018. Cannabis legalization could affect cannabis consumption, but it could also affect consumption of other drugs if cannabis replaces them for recreational or medicinal use. However, no statistically significant changes were detected in any of the cannabis, cocaine, or methamphetamine metabolites, nor morphine (metabolite of morphine, codeine, and heroin) or codeine (metabolite of codeine) between the eight months before legalization versus the four months after legalization[5] (Figure 4).

Nevertheless, clear temporal patterns emerged across the 12 months for some drugs[6] (Figure 4). The cannabis metabolite, THC-COOH, was considerably elevated in May, June, and December, with May being 4 times higher than the average of the other months. The cocaine metabolite, benzoylecgonine, was depressed in September and October. Codeine was elevated in March and depressed in the summer. These differences indicate that drug consumption is not a consistent and regular behaviour at a societal level. However, we cannot conclude that these are seasonal effects until there are more years of data since we do not know if they repeat at the same time each year.

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[4] It is possible for the parameters to change slightly over time or in different locations. The cannabis culture may change, resulting in different preferred potencies or methods of consumption, which could affect the excretion rate. Temperature could affect degradation in the sewers and different cities could have different microbial environments or industrial chemicals leading to different degradation. However, those effects are expected to be small while the differences in the metabolite loads can be much larger. For more information, see Brennan and Reedman (2019).

[5] Based on a permutation test of the months before versus after legalization, aggregated across all five cities. All metabolites were $p>0.10$.

[6] Based on an ANOVA of log load per capita, with factors for months and cities. Details on the testing methods and p-values can be found in Brennan et al. (2019).

This high temporal variability has not been observed in surveys of drug consumption, but surveys may not be very sensitive to detecting such effects. Surveys typically ask about long reference periods (e.g. three months) compared to one week for WBE. On top of that, some people may mentally substitute a question about the past three months for a question about what they usually do. People may under-account for large events such as parties. Additionally, surveys often ask about consumption frequency, not quantity, so variation in the dose sizes or doses per day would not be captured. All of these factors would serve to smooth a survey's temporal pattern.

4.3 Different Drug Use Between Cities

The five cities had large, clear differences in wastewater metabolite loads per capita[7] (Figure 5). The cannabis metabolite, THC-COOH, was 2.5 to 3.8 times bigger in Halifax and Montreal than it was in the other three cities[8] . However, methamphetamine showed almost the opposite pattern: Vancouver and Edmonton were over 3.7 times higher than the other three cities, and Halifax had over 6 times less than all of the other cities. Cocaine showed no significant differences between the cities.

Morphine also had large differences between the cities. While we cannot identify which individual opioids were responsible for the morphine in the wastewater, wastewater morphine is still indicative of opioid use within the city. Morphine was 2 to 4 times higher in Halifax, Edmonton, and Vancouver than it was in Montreal and Toronto. Codeine had a similar but distinct pattern, where Edmonton was very high (over 2.5 times higher than the others) and Montreal was very low (over 5 times lower than the others), but Toronto was similar to Vancouver and Halifax. These results demonstrate that cities have distinct drug-use profiles, high in some drugs and low in others (Figure 6).

These differences between cities are extremely large, with multiple times as much drug metabolite in some cities as others, and sometimes even different orders of magnitude. The fact the cities are not uniformly high or low but have their own profiles, high in some drugs and low in others, indicates that the results do not arise from increased degradation in one city's sewer system or problems with the population normalization from tourism or commuting. Instead, the differences in the wastewater measurements likely reflect large differences in drug consumption between the cities.

There are several reasons why WBE is well-suited to city comparisons. Like temporal comparisons, city comparisons avoid the uncertainty of the parameters, such as the body's metabolism of the drugs. To some degree, city comparisons also avoid uncertainty from the high month-to-month variability, since some of that variability is common between the cities. Finally, there seem to be very large differences between the cities, providing ample signal that is easy to detect.

[7] Some nuance is required for interpreting these results because each city had different coverage of their metropolitan areas. Coverage ranged from near-complete (Vancouver, Edmonton), to high (Toronto, Montreal), down to about half (Halifax). If drug consumption is not distributed uniformly around the city, these coverage differences could cause some differences between cities.

[8] Based on the non-parametric Wilcoxon signed-rank test, which is agnostic to the distribution and robust to outliers. Only tests with $p<0.05$ are discussed here. For more information, see Brennan et al. (2019).

5. Conclusion

WBE is able to reliably detect metabolites from several different drugs, including cannabis, cocaine, methamphetamine, and some opioids. The results seem reasonable based on both internal and external validations.

WBE estimates of drug consumption have good precision for methamphetamine and cocaine, which are difficult to estimate with surveys for the reasons outlined in the introduction and also because they are far less commonly consumed than cannabis. However, WBE estimates of cannabis consumption are problematically uncertain due to insufficient research into the cannabis excretion rate. Consumption estimates of individual opioids are not possible at this time because the same metabolite is common to several different drugs.

The cannabis metabolite had surprisingly high month-to-month variability in the wastewater, as did the cocaine and codeine metabolites. More years of data will be required to determine if these are regular, repeating, seasonal patterns. The cannabis metabolite did not show a sharp rise at the time of legalization.

The five cities had clear drug consumption differences, with cannabis higher in the two most eastern cities (Halifax and Montreal) and methamphetamine higher in the west (Edmonton and Vancouver). Opioids were highest in Edmonton, with Vancouver and Halifax also fairly high, and Montreal was very low.

WBE has proved capable of providing valuable information on societal drug consumption, even in a one-year pilot project. The results can likely be further improved by changing the sampling design, extending coverage within some of the sampled cities and to additional cities, and testing for more target compounds in the wastewater. While WBE can struggle with some applications, it seems to be well-suited for monitoring drug use within large or high-risk cities, identifying seasonality in drug consumption, detecting sudden increases in drug consumption so that local health service providers can respond quickly, and providing an early detection system to inform about consumption of new drugs before they become widespread.

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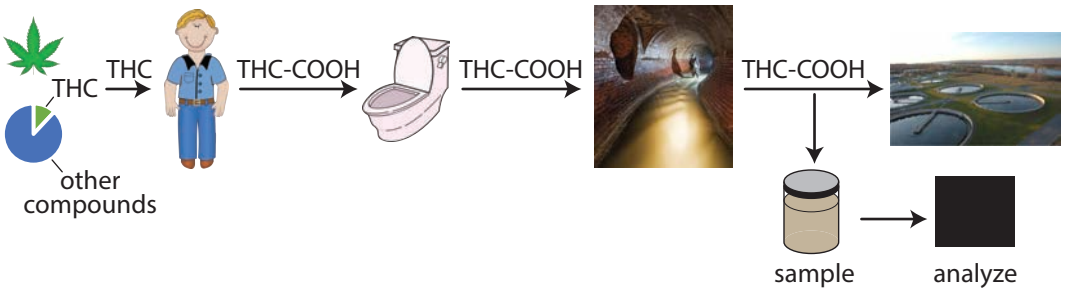

Figure 1: Cannabis consumption results in cannabis metabolites (THC-COOH) in the wastewater. Part of the cannabis plant is the main psychoactive compound tetrahydrocannabinol (THC). When THC is consumed, it is partly converted into a non-psychoactive metabolite 11-nor-9-carboxy-tetrahydrocannabinol (THC-COOH). THC-COOH is then excreted and flushed into the sewer system, where it will eventually be treated at a wastewater treatment plant. The pilot project involved sampling the untreated water coming into wastewater treatment plants in five cities for 12 months. The wastewater samples were chemically analyzed for THC-COOH and the metabolites of methamphetamine, cocaine, and opioids. These metabolites provide evidence of drug consumption within the region serviced by the treatment plant.

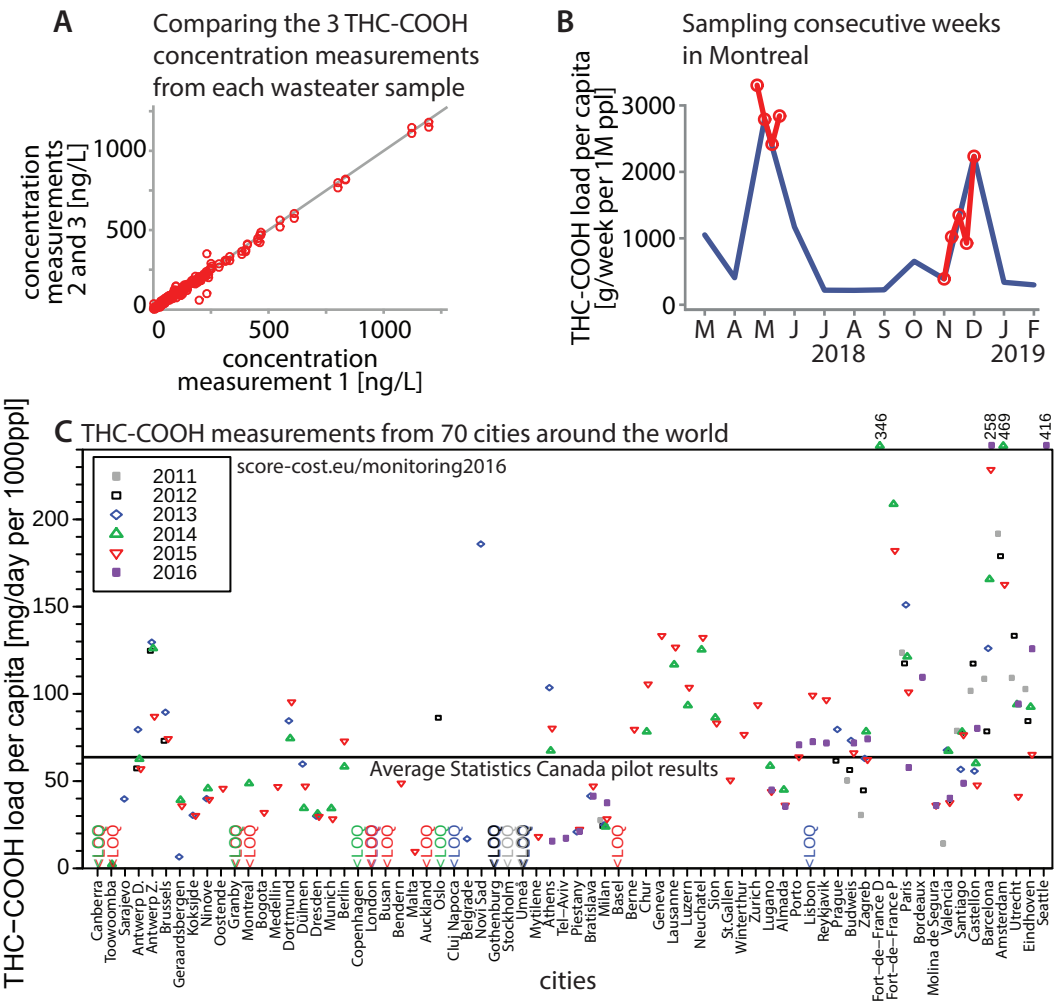

Figure 2: Validating the WBE measurements. (A) Each wastewater sample was divided and chemically analyzed three times independently. The THC-COOH concentration measurements for replicates 2 and 3 are plotted against replicate 1 for each of the wastewater samples (each wastewater treatment plant for each month). Almost all the samples were very close to the unity line, which demonstrates very high replicability of the chemical analysis from the same original sample. (B) Regular sampling was done during the second week of every month (blue line; data for Montreal). At two times during the year, the Montreal wastewater was sampled for consecutive weeks (red lines). The May weekly samples corroborate the high May value found during the second week. The November-December weekly samples were intermediate to the low November measurement and the high December measurement, which supports the validity of the December value. Note that the second weeks of May, November, and December were only sampled once and are included in both the weekly (red) and monthly (blue) time series; the overlap of these points does not represent replication of those values. (C) Comparing the Statistics Canada THC-COOH measurements to 70 cities around the world. The Sewer analysis CORe group Europe (SCORE) compiled results for 6 years of wastewater testing where THC-COOH was measured. There is a lot of variability between the cities: some cities did not have enough THC-COOH to reliably quantify it (<LOQ indicates that the amount detected was below the limit of quantification), while others had THC-COOH in excess of 200mg/day per 1000 people. The one-year average of the five cities in this pilot study (black horizontal line) lies close to the middle of the other cities, indicating that the magnitude of the measurements is reasonable.

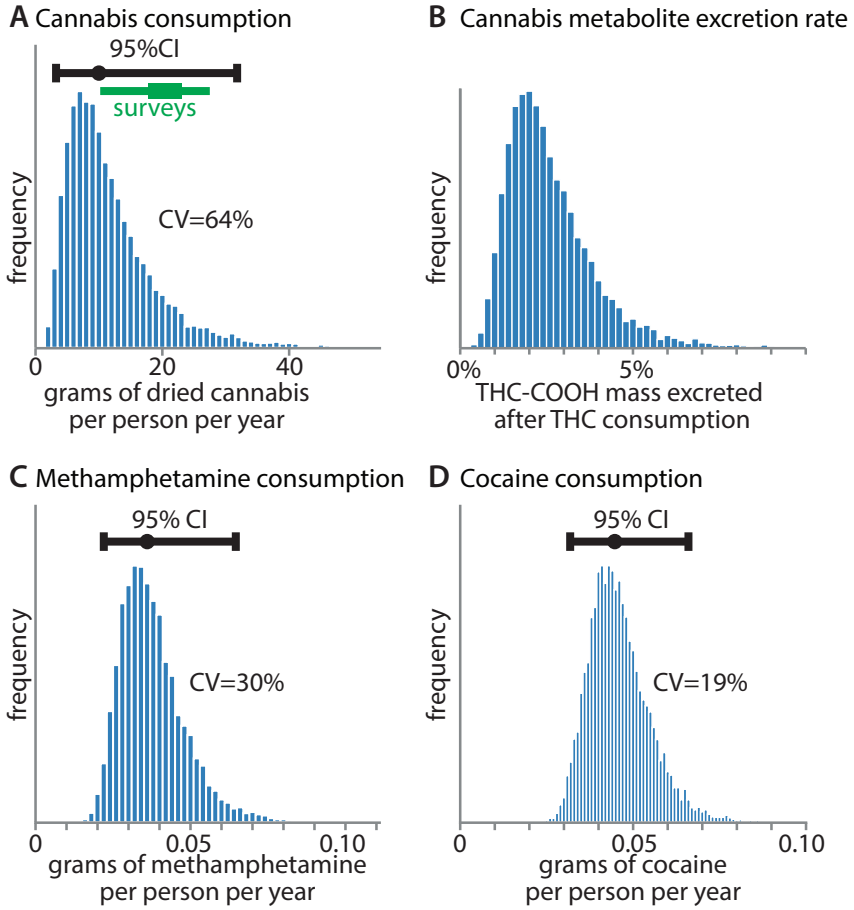

Figure 3: Drug consumption estimates. (A) We estimated cannabis consumption among the 8.4 million residents covered by the pilot study. We accounted for uncertainty from the wastewater measurements as well as from the parameters linking THC-COOH in the wastewater to cannabis consumption, including THC potency, THC-COOH excretion rate, and THC-COOH degradation after excretion. The histogram represents the range of cannabis consumption estimates consistent with the wastewater measurements. The median estimate is 10 grams of dried cannabis per person per year, with 95% confidence limits extending from 3 to 32 g/(person·year). This distribution has a coefficient of variation of 64%. Canadian cannabis consumption estimates from four recent analyses of survey data range from 18 to 23 g/(person·year) (thicker middle section of the green line; see Section 4.1 for details). For the study with confidence intervals available, the 90% confidence interval ranged from 10 to 27 g/(person·year) (full length of the green line). (B) The primary reason for the uncertainty of the cannabis consumption estimate is the excretion rate parameter. Values ranging from 1% to 5% are consistent with the available literature. (C) The same approach can be applied to other drugs. The median estimate of methamphetamine consumption was 0.31 g/(person·year), with 95% confidence intervals ranging from 0.19 to 0.56 g/(person·year), with a coefficient of variation of 30%. This estimate is more precise than the cannabis consumption estimate because the methamphetamine excretion rate is more certain. (D) The median estimate of cocaine consumption was 0.37 g/(person·year), with 95% confidence limits ranging from 0.27 to 0.54 g/(person·year), with a coefficient of variation of 19%. As with methamphetamine, the excretion rate is more certain for cocaine than for cannabis, resulting in a more precise consumption estimate.

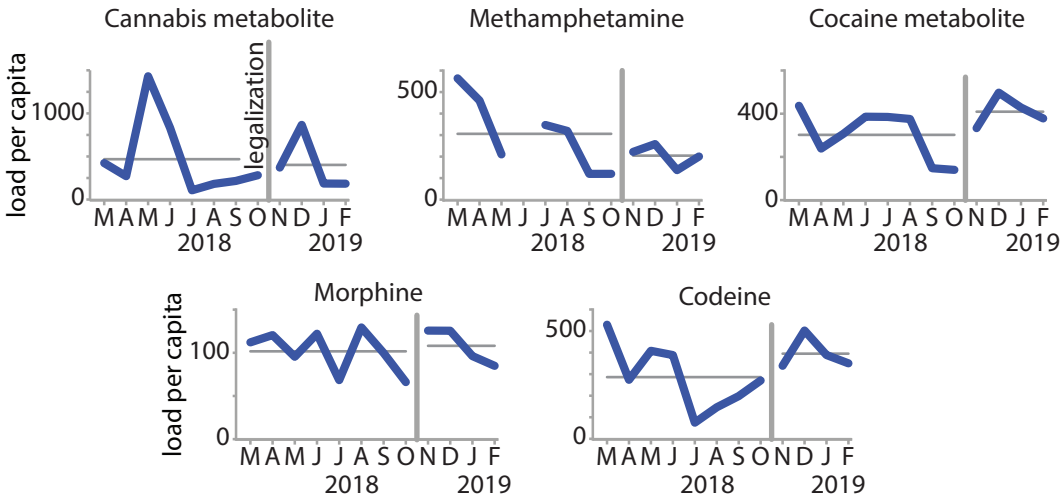

Figure 4: Temporal patterns of drug consumption. Legalization of recreational cannabis took place in Canada on October 17, 2018. We found no significant effect of legalization on any of the drug metabolites. However, we did find large, statistically significant temporal patterns for the cannabis metabolite, cocaine metabolite, and codeine, indicating drug consumption does not occur at a steady rate. The cannabis metabolite is THC-COOH; methamphetamine is its own primary metabolite; the cocaine metabolite is benzoylecgonine; wastewater morphine indicates consumption of morphine, codeine, heroin, and a few other less-common opioids; codeine is its own primary metabolite. The methamphetamine June measurement was identified as an outlier and removed. Load per capita y-axis values are in grams per week per 1 million people. The absolute levels of the metabolites in the wastewater should not be compared across drugs because drugs have different typical doses and also different excretion rates, resulting in very different quantities of metabolites in the wastewater per dose.

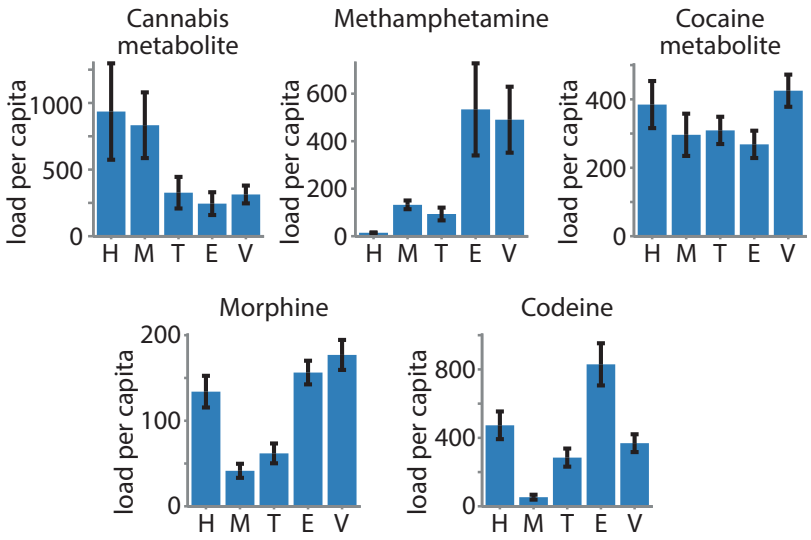

Figure 5: Geographic patterns of drug consumption. The drug metabolites varied across the five cities, and each drug had its own pattern. The cannabis metabolite (THC-COOH) was much higher in Halifax and Montreal than in Toronto, Edmonton, and Vancouver, after normalizing by the sampled populations. However, methamphetamine showed nearly the opposite pattern, where it was much higher in Vancouver and Edmonton than Toronto and Montreal, with Halifax having very little methamphetamine. Cocaine had no significant differences between the five cities. Morphine was higher in Halifax, Edmonton, and Vancouver than it was in Toronto and Montreal. Codeine was high in Edmonton and low in Montreal, but the other three cities were similar. H: Halifax; M: Montreal; T: Toronto; E: Edmonton; V: Vancouver. Error bars represent ±1 standard error of the mean of the 12 monthly measurements. Load per capita y-axis values are in grams per week per 1 million people.

	Halifax	Montreal	Toronto	Edmonton	Vancouver
Cannabis metabolite	2.1	1.9	0.7	0.5	0.7
Methamphetamine	0.1	0.5	0.3	2.0	1.8
Cocaine metabolite	1.1	0.9	0.9	0.8	1.3
Morphine	1.3	0.4	0.6	1.5	1.7
Codeine	1.5	0.2	0.9	2.6	1.1

Figure 6: Summary of geographic patterns. The values in each cell are the load per capita compared to the average for that metabolite across the five pilot cities. Reading across the rows gives the same patterns as Figure 5. Reading down the columns shows the drug profiles of each city. For example, Halifax has 2.1 times more cannabis metabolite but 10 times less methamphetamine per capita in the wastewater than the pilot-city average. The magenta and green hues indicate higher- and lower-than-average metabolite presence.