Spatial, temporal and socioeconomic patterns of illicit drug use in New Zealand assessed using wastewater-based epidemiology timed to coincide with the census

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ABSTRACT

AIMS: A discrete experiment in wastewater-based epidemiology (WBE) timed to coincide with the census was used to investigate the spatial, temporal and socioeconomic patterns of illicit drug consumption in Auckland, Bay of Plenty and Canterbury.

METHODS: For seven consecutive days over census week (6 March 2018), wastewater was sampled from seven wastewater treatment plants and analysed for methamphetamine, cocaine (as benzoylecgonine) and 3,4-methylenedioxymethamphetamine (MDMA). Detailed sewer catchment maps were developed and, together with the data, were used to analyse drug consumption.

RESULTS: Methamphetamine (mean 22.9 ± 9.9 doses/day/1000 people) was the most consumed drug, followed by MDMA (mean 1.7 ± 1.5 doses/day/1000 people) and cocaine (mean 0.5 ± 0.3 doses/day/1000 people). Methamphetamine consumption (and to a lesser extent MDMA) was high compared to that reported for Western nations, while cocaine consumption was extremely low. Cocaine and MDMA consumption were higher in cities compared to towns. In contrast, methamphetamine was typically higher in towns. Cocaine and MDMA were consumed more at weekends. Methamphetamine use was more consistent throughout the week. MDMA and cocaine were correlated with socioeconomic advantage, whereas methamphetamine was correlated with disadvantage.

CONCLUSIONS: This paper contextualises illicit drug use in three New Zealand regions containing 18.3% of the national population and confirms the pervasiveness of methamphetamine consumption in New Zealand towns. This work demonstrates how WBE can be used to explore the socioeconomic dimensions of drug use when duly combined with other data sources like censuses.

Accurate and timely information about drug consumption is important for informing health and enforcement policy. Such information is often obtained from population surveys, drug seizures and hospital and drug treatment admissions, which have important limitations.[1] Surveys can suffer from self-report biases (due to social stigma and concerns about legal repercussions) and can underrepresent certain demographics (eg, homeless, young, rural).[2,3] Drug seizures are often linked to police priorities and may reflect increased enforcement, resources or chance encounters rather than drug availability.[4] Hospital and treatment centre admissions can fail to capture recreational drug use and can under-represent those

users that do not seek help or experience medical problems.

Wastewater-based epidemiology (WBE) is an established complementary approach to assess drug use that can support these other sources of information. Through the chemical analysis of drugs excreted into reticulated sewage systems, WBE provides quantitative measures of community-scale drug consumption that are not subject to self-report biases and aggregates from all dwellings connected to the sewer network. This mitigates some of the issues of under-reporting common to population surveys.[1] WBE can be conducted frequently, which enables assessments of short-term fluctuations in drug use.

WBE has been used to assess spatio-temporal patterns in drug consumption at international, national and regional scales.[5–8] In Europe, cocaine and MDMA consumption is reportedly higher in cities compared to smaller towns, whereas methamphetamine consumption tends to be similar in both.[5,8] In Australia, drug use is generally higher in regional communities than cities, except for cocaine.[9] However, these urban–rural patterns vary across regions,[9] a reminder of the need to sample across a range of communities.

To better explain and understand these spatial patterns of drug use, attention has recently turned to examine correlations between WBE and socioeconomic information. For example, significantly higher methamphetamine use was observed in areas characterised by socioeconomic disadvantage.[10] A few studies have timed WBE to coincide with the census to better estimate drug consumption and relate such patterns to demographics.[10–13]

New Zealand has several drug monitoring systems in place, including the New Zealand Health Survey.[14] Previous drug-monitoring studies, like the Arrestee Drug Use Monitoring study (NZ-ADUM) and the Illicit Drug Monitoring System (IDMS), conducted physical interviews of frequent drug users in New Zealand's main cities, unintentionally creating the impression that drug use is an urban phenomenon.[15,16] This is perhaps unsurprising given the relative difficulty of recruiting drug-using populations for physical interviewing in more isolated, rural communities.[2] Anecdotal evidence, however, suggests that methamphetamine use is proliferating in towns and rural communities,[17–19] and this is corroborated by data on the location of clandestine laboratories[20] and drug availability.[21] WBE is gaining traction in New Zealand,[22–24] and the recently commissioned National Wastewater Testing Programme (NWTP) has expanded national understandings of illicit drug use by reporting findings at the regional level.[25] To complement this work, we present data from WBE that was specifically timed to coincide with the census and report on the spatial, temporal (within-week) and socioeconomic patterns of illicit drug use in three regions of New Zealand.

Methods

Sites and catchment mapping

Wastewater samples were collected at seven wastewater treatment plants (WWTP) across three regions of New Zealand (Table 1; Figure 1). The WWTPs were selected to cover a range of population sizes and land uses (ie, cities and towns) and enable both inter- and intra-regional comparisons to be drawn. Site selection was also pragmatic, based on our contacts in the wastewater industry. Collectively, these sites service 18.3% of the New Zealand population. Catchment maps were developed by superimposing geo-referenced sewer pipe information onto census statistical area 1 geographies[26] and trimmed to remove properties not connected to the wastewater assets. Populations for each site were calculated as the sum of the 2018 census night (*de facto*) population for these trimmed areas. The census-night dataset accounts for all individuals physically present and therefore includes domestic and international tourists.

There are well-documented issues with the 2018 census, including a lower than anticipated response rate.[27] This was not ideal, but through sampling across census we were able to capture the most accurate and representative picture of the people present in our study sites at the time of sewer monitoring. This is an improvement on much of the published WBE literature that typically relies on population estimates derived from the design capacity of the WWTP and/or a previous census, both of which may be years out of date.

Wastewater sampling and chemical analysis

Wastewater was sampled daily at each WWTP for seven consecutive days coinciding with the New Zealand census on 6 March 2018. Samples were 24-hour composites collected using time-proportional sampling of 100 mL of raw, screened influent every 15 minutes starting 6 am daily. At the end of each 24-hour period, samples were mixed and reduced to a 1-litre volume. Mechanical failure of the autosampler at site C1 was compensated for by collecting three 1-litre grab samples every eight hours (at 8 am, 4 pm and 12 am). At the end of each 24-hour period, samples were frozen, and at the end of the week they were transported on ice to the University of Auckland laboratory. During transit, two samples leaked (A3 Saturday and B1 Wednesday) and were not analysed. Within two days of arriving at the lab, samples were defrosted, filtered through a 0.2 micrometre cellulose filter and acidified to pH 2 with 2 M hydrochloric acid. The processed samples were refrozen at -80 °C and transported on ice to the University of Queensland where they were stored frozen and analysed within two months.

Sample analysis followed a validated direct injection analytical method.[28,29] Samples were defrosted and spiked with deuterium-labelled chemical standards to correct for instrument variability and matrix effects during analysis. Drug concentrations were measured by direct injection using liquid chromatography-tandem mass spectrometry (LC-MS/MS). Concentrations of each drug/metabolite were quantified using a calibration curve of the ratio between the signal response for the unlabelled authentic drug standard and deuterated analogue. Samples were analysed for methamphetamine, cocaine (as benzoylecgonine) and 3,4-methylenedioxymethamphetamine (MDMA). Benzoylecgonine was selected as the target residue rather than cocaine because benzoylecgonine is solely an excretory by-product of cocaine consumption (unlike the parent drug), and concentrations therefore will be unaffected by the flushing of cocaine.[1] The limit of detection (LOD) for all metabolites was 33 ng/L.

Calculation of per capita consumption

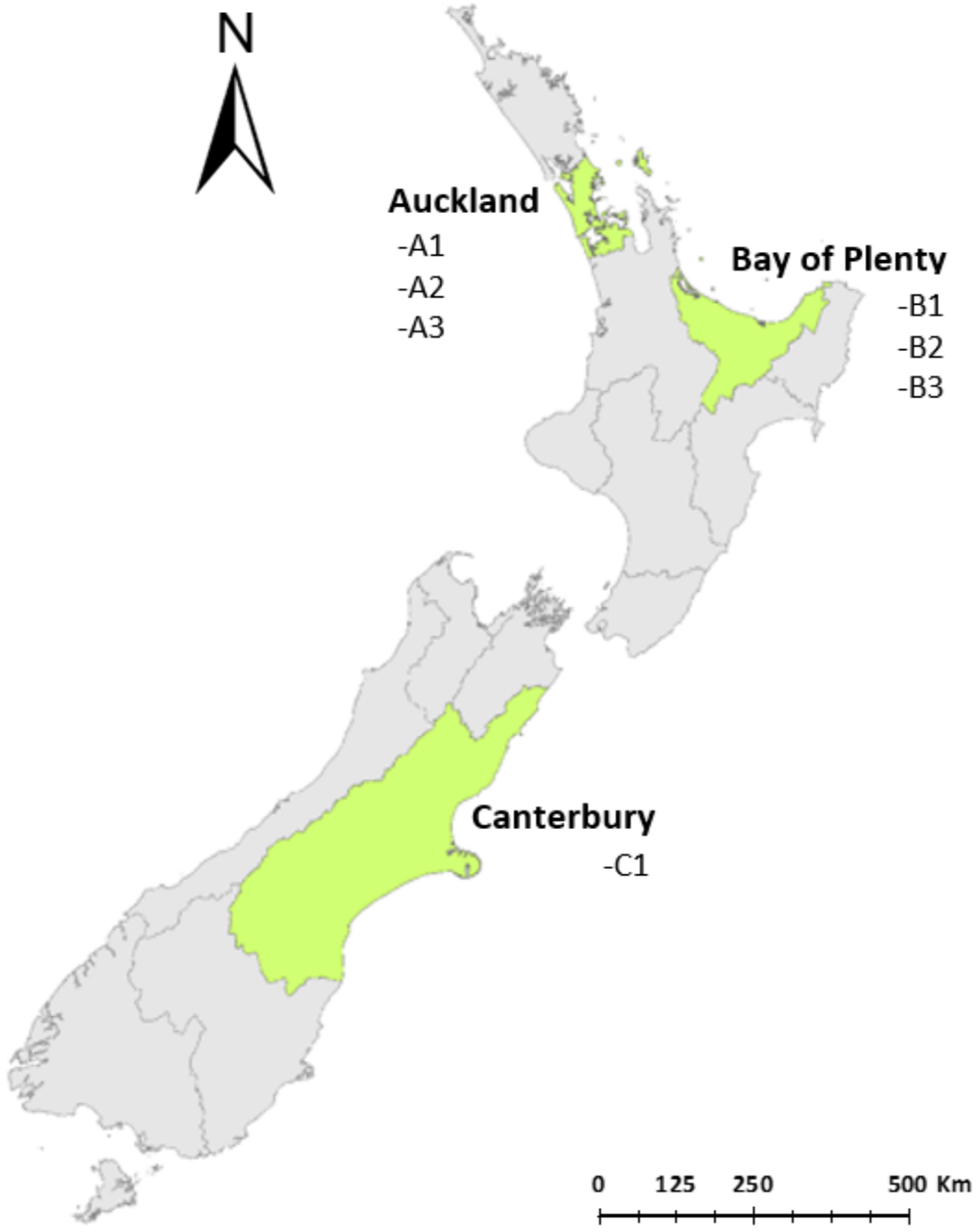
Consumption was estimated using an established back-calculation formula.[30] Briefly, mass loads (mg/day) were estimated by multiplying concentrations (mg/mL) by daily wastewater volumes (mL). Mass loads were multiplied by a correction factor that accounts for the metabolite's average excretion rate and molecular weight ratio between the metabolite and parent drug: 2.56, 3.00 and 4.44 for methamphetamine, cocaine and MDMA, respectively.[28,30,31] These back-calculation factors are based on an average excretion rate. Although people metabolise drugs at different rates, these differences will likely average-out at the population level. It is not our intention to discuss the uncertainties of excretion rates, as this has been done elsewhere.[1,32,33] However, very briefly, the back-calculation formula does

Table 1: Study site information.

Site	Region	Population Size	Community Type
A1	Auckland	4,841	Town
A2	Auckland	54,547	City with rural areas
A3	Auckland	239,522	City
B1	Bay of Plenty	48,513	City
B2	Bay of Plenty	87,298	Town
B3	Bay of Plenty	66,856	City with rural areas
C1	Canterbury	374,364	City with rural areas

Although B2 has a large population, this site has a large wastewater catchment comprising of primarily suburban and rural landcovers and hence was classified as a town.

Figure 1: Regional study site locations: Auckland, Bay of Plenty and Canterbury.



not account for sewage leakage from pipes or stormwater infiltration. We therefore checked and confirmed that there were no wastewater overflow events. Additionally, stormwater infiltration and subsequent dilution was likely negligible given the low rainfall recorded in the three regions for the duration of the study. Consumption was normalised by population and converted to doses/day/1000 people by dividing by a mean standard dose: 30, 100 and 100 mg for methamphetamine, cocaine and MDMA, respectively.[30] Please keep in mind that the exact quantity of drugs consumed (in mg) in a single dose will vary based upon variations in local drug purity and individual consumer preferences.[1] Dosages simply facilitate comparisons across countries and between individual drugs. Weekends were grouped as Saturday and Sunday, except for MDMA, which included Monday as it has a relatively long excretion time.[34]

Socioeconomic dataset

The 2018 New Zealand Index of Multiple Deprivation (IMD) provided a descriptor of relative socioeconomic status.[35] The IMD aggregates 29 indicators of socioeconomic deprivation under seven broad domains (employment, income, crime, housing, health, education and access to services) for the 2018 period across 6181 data zones that together cover all of New Zealand. Each data zone has a single rank score (from one to 6181), with higher scores representing higher levels of disadvantage. Where data zones intersected mapped catchments, data-zone rank scores were population-weighted and averaged.

Statistics

The Shapiro–Wilk test was used to assess the normality of data groups. Kruskal–Wallis followed by Dunn–Bonferroni post-hoc testing was used to compare drug consumption between sites. To assess relationships between drug use and socioeconomic disadvantage, daily drug consumption values were correlated with IMD rank scores using Spearman's correlation.

Results

Methamphetamine

Methamphetamine was detected in 100% of samples, with a mean consumption of 22.9 ± 9.9 doses/day/1000 people. Methamphetamine consumption was significantly higher in B1 and B3 than both A3 and C1 (Table 2; Appendix Table 1). Methamphetamine consumption was also significantly higher in A1 than C1. Temporal patterns of methamphetamine use were different between sites. For C1 and all Auckland sites, methamphetamine consumption was relatively consistent throughout the week, with mean weekday (Monday–Friday) and weekend (Saturday–Sunday) differences ranging from 15 to 21% (Figure 2). In contrast, methamphetamine consumption was higher on weekends for the Bay of Plenty sites, particularly B1 (32% higher) and B2 (69% higher). Methamphetamine use was significantly positively correlated with socioeconomic disadvantage: r = .402, 95% CI [.118, .616], p = .005 (Figure 3).

Cocaine

Cocaine was only detected in 21% of samples, with a mean consumption of 0.5 ± 0.3 doses/day/1000 people. The highest average cocaine consumption was observed for A3, followed by A2, B1 and B2 (Table 2). Cocaine was not detected at the other sites. Cocaine was detected infrequently throughout the week, with use restricted to weekends and discrete weekdays. Cocaine exhibited a moderate, albeit insignificant negative correlation with socioeconomic disadvantage: r = -.562, 95% CI [-.966, .192], p = .091 (Figure 3).

MDMA

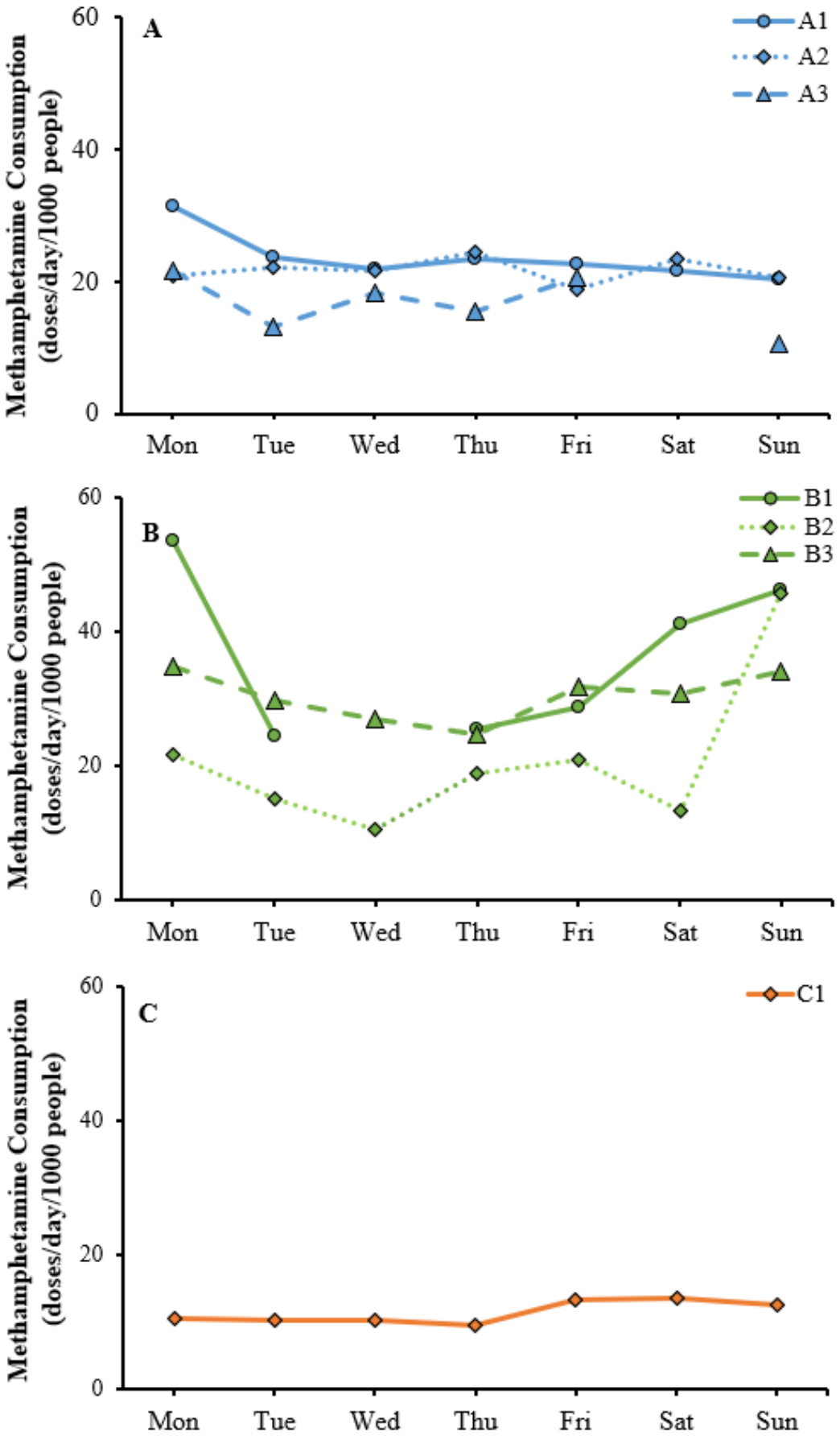
MDMA was observed in 74% of samples, with a mean consumption of 1.7 ± 1.5 doses/day/1000 people. MDMA consumption was significantly higher in A3 and C3 than B3 (Table 2; Appendix Table 1). For all sites, MDMA consumption was higher on weekends compared to weekdays. Notably, for A2, B1, B2 and B3, mean MDMA consumption was between 71 and 247% higher on weekends (Saturday–Monday) than weekdays (Tuesday–Friday). MDMA was significantly negatively correlated with socioeconomic disadvantage: r = -.614, 95% CI [-.796, -.327], p < .001 (Figure 3).

Discussion

Overview of consumption

Methamphetamine was the most widely consumed illicit drug for which we tested, followed by MDMA and cocaine, which corroborates other work in New

Figure 2: Observed weekly methamphetamine consumption (doses/day/1000 people) for all sites in Auckland (A), Bay of Plenty (B) and Canterbury (C). Saturday and Wednesday are missing for A3 and B1, respectively.



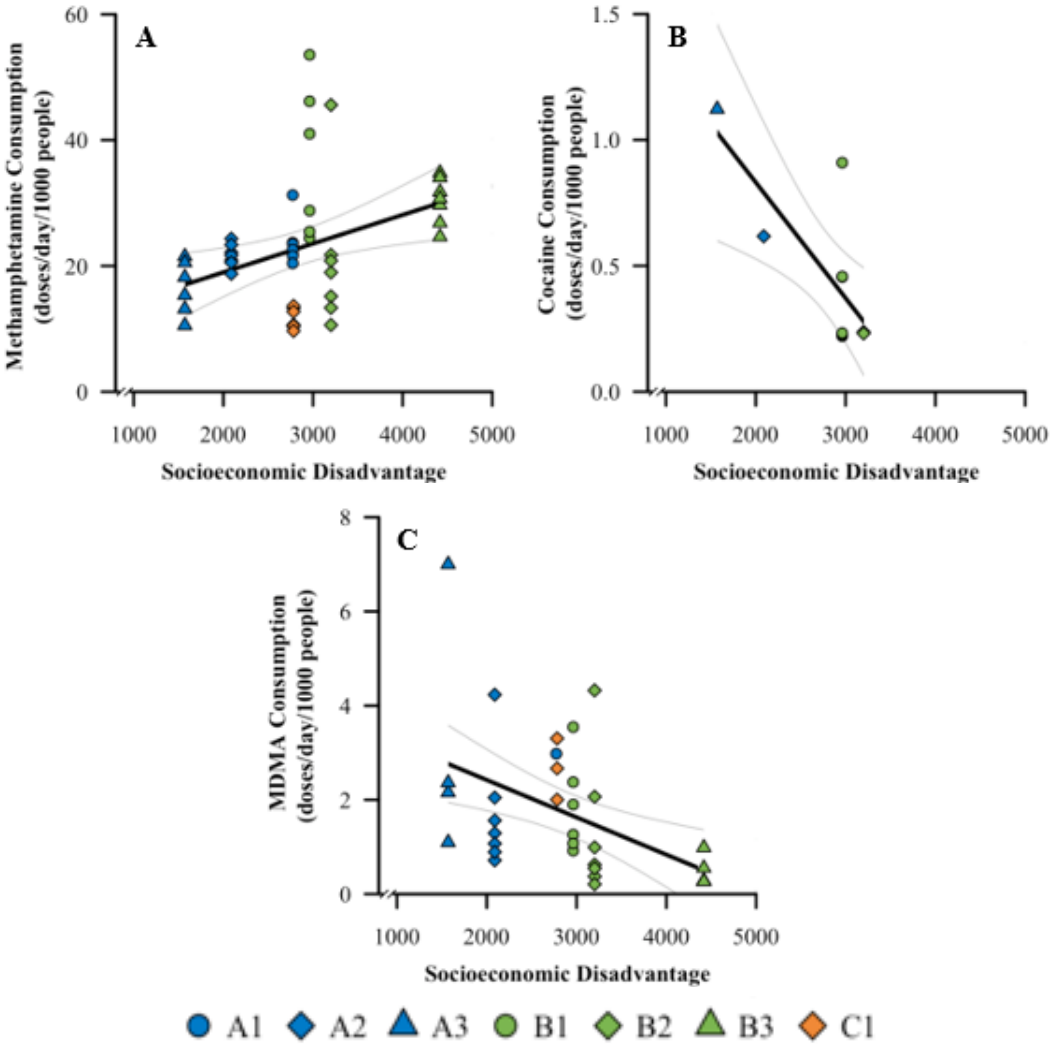
NZMJ 25 June 2021, Vol 134 No 1537
ISSN 1175-8716
www.nzma.org.nz/journal

Table 2: Observed drug consumption rates (doses/day/1000 people) for methamphetamine, cocaine and MDMA for each site.

Site	Methamphetamine		Cocaine		MDMA	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
A1	23.6 (3.6)	20.4–31.3	<LOD	<LOD	3.0 (–)	<LOD–3.0
A2	21.7 (1.9)	18.8–24.3	0.6	<LOD–6.2	1.7 (1.2)	0.7–4.2
A3	16.6 (4.3)	10.6–21.5	1.1	<LOD–1.2	3.2 (2.6)	<LOD–7.0
B1	36.6 (12.1)	24.4–53.6	0.4 (0.3)	0.2–0.9	1.8 (1.0)	0.9–3.5
B2	20.9 (11.6)	10.6–45.6	0.2 (0.0)	<LOD–0.2	1.3 (1.5)	0.2–4.3
B3	30.4 (3.7)	24.6–34.8	<LOD	<LOD	0.4 (.3)	0.3–1.0
C1	11.5(1.6)	9.7–13.6	<LOD	<LOD	2.7 (0.7)	<LOD–3.3

Standard deviation could not be estimated for A1 given that MDMA was only detected once at this site. <LOD = below limit of detection.

Figure 3: Relationship between deprivation rank scores and observed methamphetamine (A) (n = 47), cocaine (B) (n = 10) and MDMA (C) (n = 35) consumption (doses/day/1000 people) across all sites. Grey lines represent 95% confidence intervals.



NZMJ 25 June 2021, Vol 134 No 1537
ISSN 1175-8716
www.nzma.org.nz/journal

Zealand.[15,23,24] The data highlight the pervasiveness of methamphetamine in New Zealand and supports its prioritisation in public health and enforcement policy. Unlike methamphetamine (which is both imported and domestically manufactured in New Zealand), MDMA and cocaine are almost entirely imported.[16] They have low availability and low observed use, especially cocaine, likely due to New Zealand's geographic isolation, tight border controls and relatively small market. New Zealand Police and Customs are reportedly concerned about moves from international gangs to establish a larger cocaine market in New Zealand.[36,37] This makes sense given cocaine's high street price; however, it appears that this has yet to come into fruition in these regions, as evidenced in the WBE data.

Global comparison of methamphetamine, cocaine and MDMA consumption

Mean methamphetamine consumption was considerably higher in New Zealand than reported in Europe (Figure 4), which likely reflects the European preference for amphetamine sulphate over methamphetamine and the wider availability of other illicit drugs.[38] Methamphetamine consumption was lower than reported in the United States, Canada and Australia. These countries provide much larger markets than New Zealand. It has been estimated that over 90% of methamphetamine trafficked to Oceania is destined for Australia.[39] In contrast, mean cocaine consumption in New Zealand ranked well below that of the United States, Australia and Europe (Figure 4). This reflects the low volume and high price of cocaine in New Zealand (€221 per gram) compared to, say, the United States (56 € per gram) and European countries like Belgium (€50 per gram) and Italy (€80 per gram).[40] Mean MDMA consumption was relatively high in New Zealand compared to many parts of Europe and North America (Figure 4). Given the paucity of cocaine, it is likely that MDMA is the substitute New Zealand party drug.[3]

Spatial patterns

The regional pattern of relatively high methamphetamine consumption in the Bay of Plenty, and MDMA (and cocaine) in Auckland and Canterbury, is consistent with observations from recent wastewater studies.[22,25] The high methamphetamine consumption observed in the Bay of Plenty also supports the high availability reported for this region.[21] The relatively high use of MDMA in Canterbury, and both MDMA and cocaine in Auckland, may simply reflect the presence of nightclubs in cities.[41] Cities have larger populations too, which can sustain larger and more diverse drug markets.[42] Cocaine and MDMA is almost entirely imported to New Zealand,[15,21] so it makes sense that their consumption was higher in the sites with ports (A3 and C1) than in site B3, which is landlocked and without an international airport.

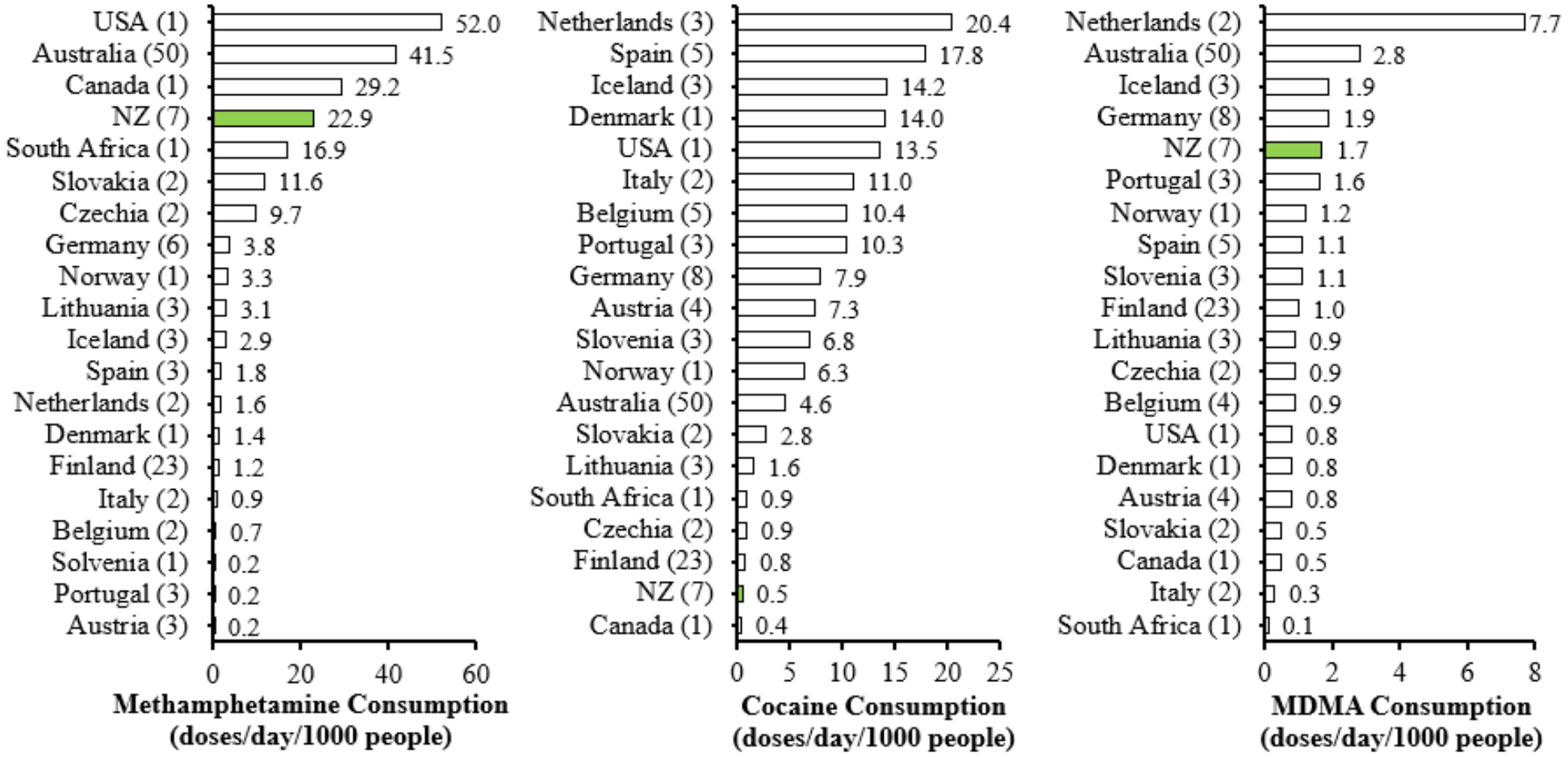
The spatial patterns of methamphetamine paint a contrasting picture. Corroborating a recent study,[21] the data show that methamphetamine consumption is greater in towns compared to cities. Methamphetamine laboratories are often located in more isolated areas to avoid detection.[20] Gangs have reportedly sought to expand methamphetamine markets in towns.[21] Local production, socioeconomic decline, fewer police personnel and a lack of market choice likely contribute to this pattern.[19,21] Wastewater studies in Australia and the United States have also observed high methamphetamine use in more rural communities.[7,9,43]

However, our data show that methamphetamine is not only used in towns. There was high consumption observed at the city site B1, which is adjacent to New Zealand's busiest port. Perhaps this area is an entry point for internationally supplied methamphetamine and/or pseudoephedrine (a chemical precursor for methamphetamine) and, therefore, a subsequent hotspot for domestic methamphetamine manufacture. This is consistent with the large number of clandestine laboratories seized in the region.[20] It is important to understand site-specific supply and demand dynamics for drug policy, and clearly WBE adds knowledge to support these efforts.

Within-week patterns

MDMA consumption was higher on weekends compared to weekdays across all sites. This weekend spike in MDMA accounts for the large standard deviation across all sites. Cocaine had a similar pattern, with consumption largely restricted to weekends

Figure 4: Methamphetamine, cocaine and MDMA consumption rates (doses/day/1000 people) estimated for New Zealand (this study) and other countries. Number in brackets is the number of WWTPs. European and North American data are from SCORE, which is presented in the National Wastewater Drug Monitoring Program Report 7 alongside Australian data.[9] All consumption rates were converted using the same excretion factors and dosages used in this study. European and North American data were collected in March 2018. Australian data were collected in December 2018.



and the odd discrete weekday. MDMA has a low dependence liability.[44] Coupled to the relatively high street prices of MDMA and cocaine, the data suggest that habitual use (ie, daily) of these drugs is uncommon.

Within-week patterns of methamphetamine use were variable. For C1 and all Auckland sites, methamphetamine was consumed relatively consistently throughout the week, supporting previous data for these regions.[22–24] Methamphetamine is highly addictive, so frequent and consistent user consumption is common.[15] Interestingly, methamphetamine consumption was higher on weekends for the Bay of Plenty sites, particularly B1 and B2. This perhaps reflects the high number of bars and nightclubs in B1. Other studies have found city populations to have more pronounced weekend drug use compared to towns.[6] B1 is also a popular tourist destination, and the high weekend consumption may be attributable, in part, to tourists.

It was surprising that different patterns of methamphetamine use were observed at sites B1, A3 and C1, given that these are all city sites (with bars and nightclubs). MDMA consumption rates were higher in A3 and C1 compared to B1 (Table 2). It may be that MDMA is more available and thus preferred as a recreational weekend drug in these sites. This would suggest that the low availability of MDMA and/or high availability of methamphetamine may facilitate recreational methamphetamine consumption. This is concerning from a public health perspective given methamphetamine's relatively high dependence liability.[16] As only a single week of samples were collected, longer-term sampling is being undertaken to confirm these findings.

Socioeconomic patterns

To better explore these spatial patterns, drug use was compared with socioeconomic disadvantage. MDMA was significantly negatively correlated with disadvantage. Cocaine was similar but not significant, being influenced by the small number of detections. Conversely, methamphetamine was positively correlated with disadvantage, which is consistent with local survey data.[16] Due to methamphetamine's relatively low street price (compared to more expensive drugs like cocaine), methamphetamine may be more accessible to lower-income individuals.[16] Additionally, clandestine methamphetamine laboratories are often more concentrated in disadvantaged communities,[20] likely making it more widely available in such areas. However, the correlation was not strong (r = .402), so the data highlight that methamphetamine is consumed by people in advantaged communities too.

These trends are different to the 2007/2008 New Zealand Alcohol and Drug Use Survey (NZADUS), which found no relationship between neighbourhood socioeconomic status and the use of methamphetamine, cocaine or MDMA.[45] It could be that the NZADUS simply did not capture heavy user groups.[2] Perhaps people were reluctant to participate in the survey for fear of stigmatisation or legal repercussions. Another contributing factor is that drug surveys may not representatively capture rural populations.[3] Regardless of the reason, our data highlight the complementary nature of WBE to other measures of drug use. The next challenge is to best align the datasets as a step towards transdisciplinary public health policy and drug intervention.

Conclusion

Wastewater-based epidemiology was timed to coincide with the 2018 New Zealand census. The data confirm the pervasiveness of methamphetamine in New Zealand and supports its ongoing prioritisation in public health and enforcement policy. There were inter- and intra-regional differences in drug consumption. Cocaine and MDMA consumption were higher in cities, whereas methamphetamine was generally higher in towns. Notably, high methamphetamine consumption was observed at Bay of Plenty's urban site, highlighting the importance of site-specific supply dynamics and local consumer preferences. Cocaine and MDMA were consumed infrequently throughout the week, with consumption largely restricted to weekends. Methamphetamine was consumed more consistently throughout the week in Canterbury and all Auckland sites. In contrast, methamphetamine consumption was higher on

weekends in the Bay of Plenty. The data show that methamphetamine is consumed both habitually and recreationally. Such patterns, however, cannot be accounted for by differences in urbanisation or population size alone. Expectedly, MDMA (and cocaine) consumption was negatively correlated with socioeconomic disadvantage, whereas methamphetamine was positively correlated. The research shows that WBE provides valuable data on the spatial, temporal and socio-economic patterns of drug use, and with complementary information can be used to help guide the development of nested local, regional and national-scale drug policy in response.

ISSN 1175-8716

Appendix

Appendix Table 1: Dunn–Bonferroni comparisons of methamphetamine consumption rates (doses/day/1000 people) between sites. Bolded values are significant.

Site comparison	Mean rank difference	Std. error	Adjusted *p*-value
C1–A3	7.6	7.6	0.999
C1–B2	13.4	7.3	0.999
C1A2	18.3	7.3	0.265
C1–A1	**22.3**	**7.3**	**0.05**
C1–B3	**33.4**	**7.3**	**< .001**
C1–B1	**34.8**	**7.6**	**< .001**
A3–B2	-5.8	7.6	0.999
A3–A2	10.7	7.6	0.999
A3–A1	14.7	7.6	0.308
A3–B3	**-25.8**	**7.6**	**0.015**
A3–B1	**-27.2**	**7.9**	**0.013**
B2–A2	4.9	7.3	0.999
B2–A1	8.9	7.3	0.999
B2–B3	-20	7.3	0.133
B2–B1	21.3	7.6	0.108
A2–A1	4.0	7.3	0.999
A2–B3	-15.1	7.3	0.815
A2–B1	-16.5	7.6	0.646
A1–B3	-11.1	7.3	0.999
A1–B1	-12.5	7.6	0.999
B3–B1	1.3	7.6	0.999

Appendix Table 2: Dunn-Bonferroni comparisons of MDMA consumption rates (doses/day/1000 people) between sites. Bolded values are significant.

Site comparison	Mean rank difference	Std. error	Adjusted *p*-value
B3–B2	8.0	5.3	0.999
B3–A2	13.3	5.3	0.188
B3–B1	15.5	5.5	0.076
B3–A3	**20.1**	**6.2**	**0.019**
B3–C1	**-21.2**	**6.9**	**0.031**
B2–A2	5.3	5.3	0.999
B2–B1	7.5	5.5	0.999
B2–A3	12.1	6.2	0.786
B2–C1	-13.2	6.9	0.824
A2–B1	-2.2	5.5	0.999
A2–A3	-6.8	6.2	0.999
A2–C1	-7.9	6.9	0.999
B1–A3	4.6	6.4	0.999
B1–C1	-5.7	7.0	0.999
A3–C1	-1.1	7.6	0.999

Competing interests:
Nil.

Acknowledgements:
We would like to thank Watercare Services Limited, Christchurch City Council, Ngāi Te Rangi and Tauranga City Council Safe Communities for their assistance with the sample collection and the facilitation of the research. We thank Arnuad Besse-Ciller for his help visualising the data. We are also grateful to the two anonymous reviewers and the section editor for their time to read and comment on the paper.

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www.nzma.org.nz/journal-articles/spatial-temporal-and-socioeconomic-patterns-of-illicit-drug-use-in-new-zealand-assessed-using-wastewater-based-epidemiology-timed-to-coincide-with-the-census-2

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