Journal of Material Cycles and Waste Management (2021) 23:1015–1025
https://doi.org/10.1007/s10163-021-01187-7

ORIGINAL ARTICLE

Quantification of solid waste management system efficiency using input–output indices

Damien Bolingbroke[1] · Kelvin Tsun Wai Ng[1] · Hoang Lan Vu[1] · Amy Richter[1]

Received: 22 August 2020 / Accepted: 3 February 2021 / Published online: 22 February 2021

Abstract

The assessment of solid waste management systems is vital for continued improvement in the efficiency of waste management systems (WMSs). Many studies have aimed to develop metrics that examine policy and system effectiveness, but there appears to be a lack of simple and comparable metrics to evaluate the WMS efficiency. This study introduces a set of novel waste diversion indicators, including a jurisdictionally comparable index known as diversion size indicator (DSI), and employs them to analyze WMSs in Canada. DSI increased in only a single province Nova Scotia during the 14-year study period. The DSI variability was largest for all Prairie Provinces, indicating that large efficiency changes in these province's WMSs over the study period. Combining all proposed metrics into a single rank showed that Saskatchewan outperformed all other Canadian jurisdictions, balancing diversion rate goals well with cost efficiency. Findings indicate that Alberta and Ontario rank very low in diversion efficiency and tonnage hauled efficiency. Also, Nova Scotia, the DSI leader, ranks lowest in terms of costs per tonne handled. Data availability remains a large barrier to a complete evaluation of WMSs. Nonetheless, the proposed original metrics create a framework for creating comparable and easy to use metrics for waste management efficiency.

Keywords Efficient waste management system · Municipal solid waste · Diversion efficiency · Cost-effectiveness · Diversion size indicator · Materials handled efficiency indicators

Abbreviations

Jurisdictional abbreviations

CA	Canada
NL	Newfoundland and Labrador
PE	Prince Edward Island
NS	Nova Scotia
NB	New Brunswick
QC	Quebec
ON	Ontario
MB	Manitoba
SK	Saskatchewan
AB	Alberta
BC	British Columbia
YT, NT, NU	Yukon, Northwest Territories, and Nunavut

Other abbreviations

CuPT	Current spending per tonne handled
CV	Coefficient of variation
DGDP	Diversion gross domestic product ratio
GPT	Gross domestic product Sector 562 spending per tonne handled
DR	Diversion rate
DSI	Diversion size indicator
NAICS	North American Industrial Classification System
Ppl.	People or person
WMOI	Waste Management Output Index
WMS	Waste management system

Introduction

Due to its sheer quantity and biodegradable and toxic nature, solid waste poses a significant risk to ecosystems and human health if not properly managed. According to a United Nations Environment Programme report [1], estimated 11.2 billion tonnes of solid waste were collected worldwide in 2010, and 5% of global greenhouse gas

✉ Kelvin Tsun Wai Ng
kelvin.ng@uregina.ca

1 Environmental Systems Engineering, Faculty of Engineering and Applied Science, University of Regina, 3737 Wascana Parkway, Regina, SK S4S 0A2, Canada

emissions originated from waste decomposition. Environmental and health issues associated with solid waste management are increasingly common as various areas of the world experience rapid population growth and urbanization. Planning, operating, and upkeeping an effective waste management system (WMS) require constant critical review and periodic reassessment of current practices.

Waste studies examining policy effectiveness and system efficiency are common across the globe due to the practical significance of waste management service. Lombrano [2] studied how the management of urban solid waste in Italy affects cost efficiency, finding a connection between management techniques and financial/environmental performance. According to the study [2], industrial and integrated systems including a recovery plant had the highest performance. Simoes and Marques [3] reviewed the Portuguese solid waste sector, and found that regulation and distance to waste treatment decreased the performance of urban waste systems. They also found benefits in performance using incineration and privatized waste systems [3]. Simoes et al. [4] further looked at the productivity of different types of waste collection and treatment utilities. They found that private sector participation tended to increase efficiency in the retail market in Portugal, but not as much in the wholesale market, since the retail market often used short-term contracts, stimulating competition [4].

Simoes and Marques [5] conducted a meta-analysis on the economic performance of the waste sector using over 100 papers published since 1965. They found 62 papers from 2000 to 2011 that looked at the economic performance of the waste sector, which far exceeds the 16 from 1990 to 1999 [5]. Simoes and Marques's work [5] highlighted the increasing demand of theoretical background required to develop an efficient WMS.

Jacobson et al. [6] used 12 sets of Belgian waste efficiency data to compare private and public waste collection, and found that, in all cases, there were efficiency gains through the use of private services. Greco et al. [7] analyzed the possible factors related to collection costs and found that different Italian regions have different collection efficiency and productivity. Perez-Lopez et al. [8] looked at waste systems of varying sizes in Spain and found that intermunicipal cooperation worked best in areas with fewer than 20,000 citizens, but contracting services to private groups was more efficient in larger municipalities. Di Foggia and Beccarello [9] looked at the Italian case and tried to estimate the productive efficiency under a current regulation and the benefits of uptaking new regulatory ideas.

Greene and Tonjes [10] explicitly examined the common municipal waste system performance indicators and reported inconsistencies among indicators in ten municipalities in the New York state. Recently in 2020, Fellner and Lederer [11] explored relevant metrics for meaningful circular economy evaluation.

From the literature, it appears there is a lack of a simple method to evaluate and compare WMSs. Although indicators and indices have been proposed and adopted to measure WMS characteristics and quantify its effectiveness, these indicators and indices often fail to fully capture the practical aspect of WMSs, particularly with respect to financial and managerial efficiencies of waste diversion programs. In this paper, efficiencies will be defined as the ability to get higher outputs from the same inputs to a WMS. Many of the indicators and indices are also jurisdictionally incompatible, making assessment of different WMSs difficult. For example, Cervantes et al. [12] conducted a comprehensive review and identified 377 different indicators on performance of WMSs. They reported that many of the indicators suffer from a lack of standardization and comparability between jurisdictions [12].

One key to the choice of parameter type to study is that it must be comparable across many jurisdictions. One jurisdictionally comparable indicator is waste diversion rate (DR); defined as the ratio of waste diverted to total waste managed. A higher DR can be considered as desirable as it minimizes potential negative environmental impacts of landfill disposal, such as greenhouse gas generation [13, 14] and groundwater contamination by leachate [15, 16]. In Canada, waste diversion rate has been widely used to assess the environmental friendliness and sustainability of a WMS, and has been extensively reported in the literature [17–22]. Jurisdictions with higher diversion rates are likely to have sophisticated recycling programs, and/or higher resident participation.

Diversion rate, however, is not an efficiency measure, as it does not fully encompass the efficiency of a WMS [23]. This is due to the diversion rate only including the materials diverted as a measure of output but ignoring any inputs to the system. The DR not only fails to account for the financial and economical inputs, but also fails to account for the other energy, land, and material inputs to a WMS. Although jurisdictionally comparable, the use of DR alone in waste studies could often be misleading when comparing the performance of multiple WMSs in different regions. For example, a jurisdiction can have a high diversion rate, but have extremely large inputs (i.e., monetary resources) to their WMS, rendering the system unfavorable from an economical perspective. Lakhan [24] specifically examined the cost and performance of recycling programs in rural and northern Canada, and found that eliminating recycling programs in high-cost regions could decrease system costs with minimal impact to overall diversion rates. The behavioral implications of Lakhan's study [24] is controversial and intriguing; however, it also highlights the limitations of the use DR alone as an indicator in WMS evaluation and a cost or input parameter is needed along with the DR to better understand efficiency in a waste management system.

This necessitates the development of a set of new metrics that are able to be compared and used across jurisdictions to fully understand the efficiency of WMS, specifically regarding waste recycling and minimization. An input–output indicator is preferable to the conventional waste management indicators as it accounts for both the effectiveness and efficiency of a WMS. A previous study by Pan et al. [23] proposed Waste Management Output Index (WMOI), Diversion-GDP ratio (DGDP), and Diversion–Expenditure ratio to study system efficiency of Canadian WMSs in four neighboring provinces. This paper introduces an additional input–output indicator for WMSs and applies it to understand diversion efficiency in a province-wise comparison.

Historically, Canadians generated more solid waste per capita than most industrialized nations and sent the majority of this waste to landfills for permanent disposal [21, 23]. Stringent environmental regulations, however, make new landfill sites increasingly difficult to locate [25, 26]. The objectives of this study are therefore to (1) introduce an original waste diversion indicator to better quantify efficiency in waste diversion activities, and (2) apply the diversion size indicator (DSI), current expenditure per tonne handled (CuPT), and NAICS GDP Sector 562 per tonne handled (GPT) to analyze WMSs in Canada. These easily computable input–output indicators evaluate both the effectiveness and efficiency of a diversion program and allow for a direct comparison between jurisdictions. It is believed that these indicators can help in the widespread adoption of efficient waste management practices, and yield affordable and effective WMSs, especially for remote regions where input resources are scarcer.

To the best of the authors' knowledge, this is one of the first studies that explicitly use input–output indices to evaluate the effectiveness and efficiency of waste management systems. The use of such indicators can assist citizens, their representatives, and WMS workers to better understand the trade-offs inherent in the WMSs they demand, create, and operate.

Methodology

An input–output framework is adopted in the present work to identify input–output variables that can be used to create simple efficiency indicators. There are three key indicators considered in this work, including the Diversion Size Indicator (DSI), the current spending per tonne handled (CuPT), and the GDP Sector 562 per tonne handled (GPT). An inter-jurisdictional comparison will be conducted using both temporal (1998–2014) and cross-sectional (2014) approaches.

A study period of 16 years is used to investigate the trends in Canadian WMS efficiency temporally. The cross-sectional study of 2014 data will be used to rank jurisdictions within Canada to investigate their recycling behaviors. Also, specific focus will be placed on jurisdictions having higher variability as stated by these efficiency indicators. Statistic Canada is a federal government agency providing statistical information and analyses on Canada's economic and social structure. Waste data for this study were gathered from the biennial Statistics Canada Waste Management Industry Survey: Business and Government Sectors reports. The overall response rates of the national surveys were at least 70%. Only non-hazardous waste is considered in the Statistical Canada national surveys, and the reference period of the survey reports was from the beginning of April to the end of March of the following year. Data uncertainties and discrepancies in the survey reports due to the inconsistencies in methodologies and waste definitions are examined and discussed previously [19]. Economic indicators such as Gross Domestic Product (GDP), GDP of North American Industrial Classification System (NAICS) sector 562, and GDP of all NAICS industries in Canada were all collected from the same agency [27–36] for consistency purposes. Some jurisdictions' data (including 'NL', 'PE', and 'YT, NT, NU') have been suppressed in certain reporting years for confidentiality under the Statistics Act [33]. As such, only 8 of the 11 jurisdictions are reported. Unless otherwise stated, national averages are calculated using all available jurisdictional data.

Waste diversion is the process of diverting materials from municipal waste landfills. Diversion rate is a ratio of the total materials diverted divided by the total materials generated, shown in Eq. (1):

$$\mathrm{DR} = \frac{\text{Materials diverted (tonne)}}{\text{Materials generated (tonne)}} \times 100\%. \quad (1)$$

The WMOI, as first introduced by Pan et al. [23], utilizes the NAICS to show the proportional size of a waste management system as compared to all other industries in the NAICS. NAICS is widely adopted in North America, making comparisons between Canadian and American WMSs easier. It is presented in Eq. (2). WMOI, a dimensionless parameter, shows the relative economic output of a waste management system in a given jurisdiction. The GDP NAICS Sector 562 and the GDP NAICS All Sectors organizational chart can be seen in Fig. 1:

$$\mathrm{WMOI} = \frac{\text{GDP NAICS Sector 562 (\$2012 chained)}}{\text{GDP NAICS all Sectors (\$2012 chained)}}. \quad (2)$$

'All Sectors' is shown at the top of Fig. 1. It is the value of all goods and services produced in all NAICS categories

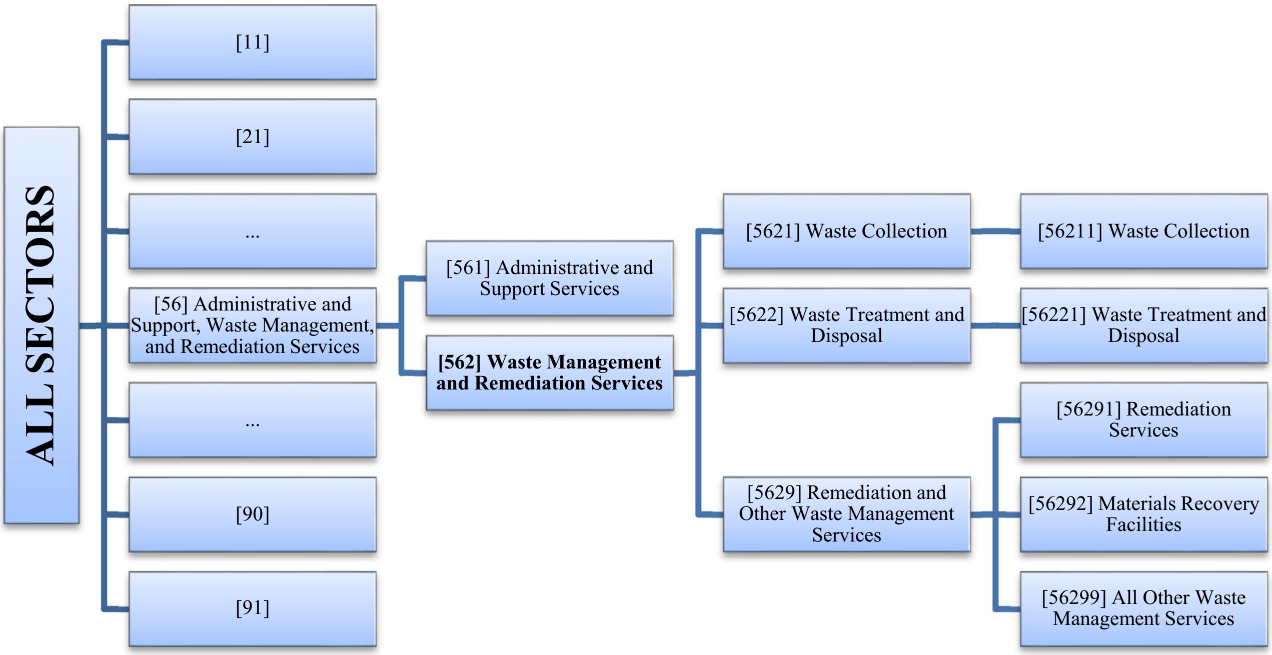


Fig. 1 Sector 562 of the North American Industrial Classification System (NAICS)

from 11 to 91 within a year, in a given jurisdiction [37]. Sector 56 is one of the 11–91 categories and includes both 'Administrative and Support Services' (Class 561) as well as the 'Waste Management and Remediation Services' (Class 562). Waste Management and Remediation Services includes Waste Collection, Waste Treatment and Disposal, as well as Remediation and Waste Management Services. Remediation is a constituent of this category, and includes a wider range of waste services outside of non-hazardous waste management including the cleanup of contaminated buildings, soil, groundwater, and mine sites as well as septic pumping and other waste services [37]. In other words, data presented include all these sectors of remediation and this larger definition of waste management sector must be used when discussing the WMOI. For a given jurisdiction, WMOI is generally much less than 1. A WMOI of zero represents a waste management sector which does not contribute to the GDP, whereas a WMOI of unity represents the unlikely scenario that the entire GDP of a region only depends on the output from the waste management sector [23].

The diversion size indicator (DSI) is a new indicator designed to measure a jurisdiction's diversion rate with respect to the relative economic impact of its waste management industry (Eq. 3):

$$\mathrm{DSI} = \frac{\mathrm{DR}}{\mathrm{WMOI}}. \tag{3}$$

DR is described by Eq. 1, and WMOI is described by Eq. 2. The DSI can be seen as an input–output indicator. An attribute of an efficient system is the ability to reduce the inputs and raise the outputs or quality. A higher DSI identifies a more efficient waste diversion program within a WMS. The DR and WMOI in Eq. 3 are both expressed as a decimal, making DSI dimensionless. As GDPs and DRs are standardized parameters and are easily available online, we believe that DSI is a simple and versatile metric to compare waste diversion efficiency across jurisdictions in Canada and the United States.

CuPT is the current expenditure per tonne of waste handled and GPT is the GDP Sector 562 per tonne of waste handled, as shown in Eqs. 4 and 5, respectively. In this study, the amount of waste handled (the denominator of Eqs. 4 and 5) is the total waste managed (sum of disposed and diverted materials). CuPT and GPT are used to quantify the amount of resource input to manage a given tonne of waste materials in a jurisdiction:

$$\text{Current spending per tonne handled (CuPT)} = \frac{\text{Current expenditure (\$2012 indexed)}}{\text{Tonnes of waste handled}}, \tag{4}$$

$$\text{GDP Sector 562 per tonne handled (GPT)} = \frac{\text{NAICS GDP Sector 562 (\$2012 chained)}}{\text{Tonnes of waste handled}}. \quad (5)$$

Results and discussion

Diversion size indicator

Figure 2 shows the temporal changes of DSI for Canadian jurisdictions from 1998 to 2014. Three jurisdictions' data have been suppressed for confidentiality by Statistics Canada, and only 8 of the 11 jurisdictions are shown. An obvious decreasing trend is observed in the national data (labeled 'CA' in Fig. 2), from 190.21 in 1998 to about 82.26 in 2014, representing less than half of the 1998 value. Both DR and WMOI were increasing in Canada during the study period. WMOI, however, increased at a more rapid pace. For example, the WMOI was 0.0012 in 1998, and increased over 2.5 times to 0.0033 in 2014. Although the waste management industry has grown considerably, the declining DSI trend suggests that Canadian waste diversion programs were lagging behind when compared to the growth of the waste industry. A closer look at the national data reveals that Canadian diversion programs are continuously improving while the system efficiencies are worsening. DSI has been decreased with time, leveling off at about 80. Results suggested that the resources that have been allocated to waste diversion initiatives have not provided a correspondingly similar level of increase in waste diversion.

With the exception of Nova Scotia (NS), a national leader in diversion rate, all jurisdictions in 2014 had a lower DSI than they did in 1998 (Fig. 2). NS started out at 139.86 in 1998 and then rose to 163.16 in 2014, representing a 16.7% increase. Every other jurisdiction has decreased DSI

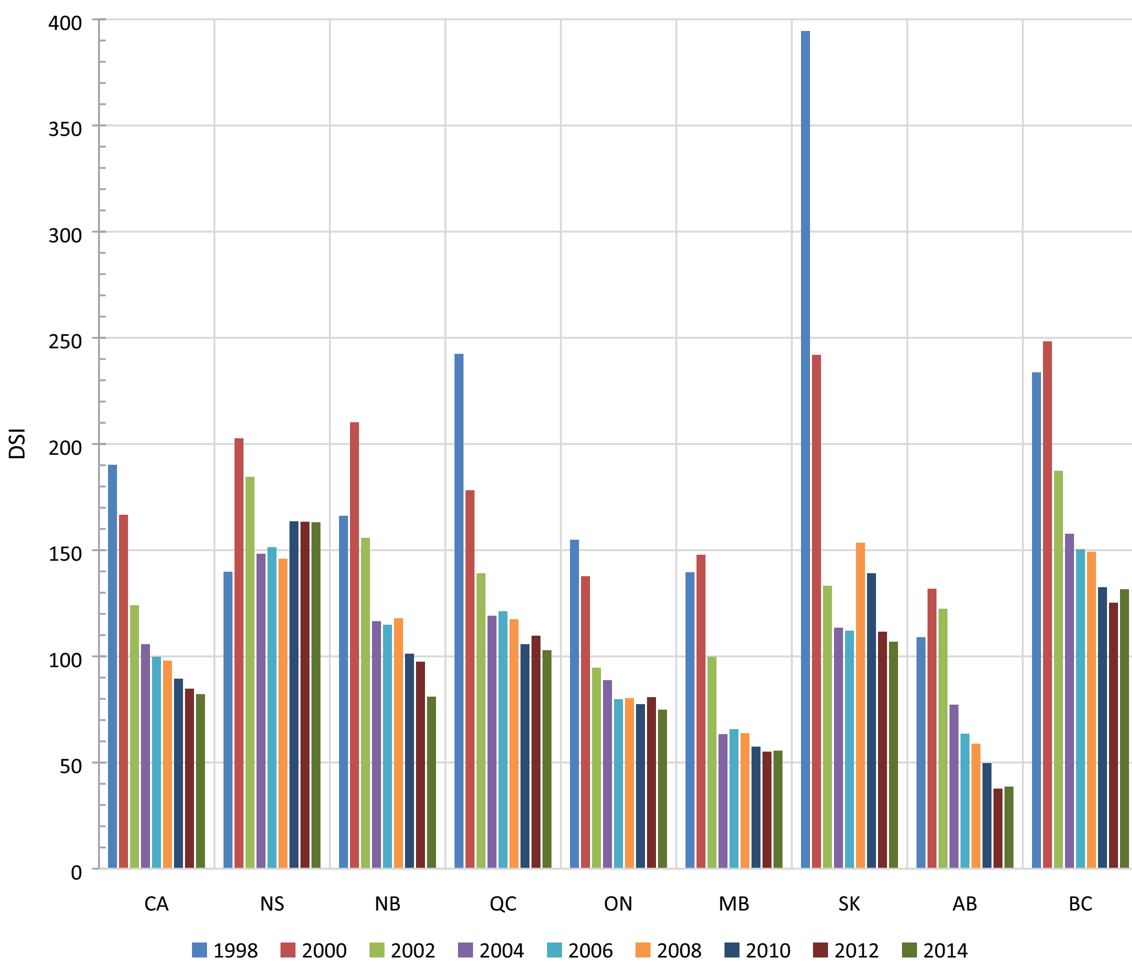


Fig. 2 Temporal changes of DSI across Canadian jurisdictions

between 44 and 73% from 1998 to 2014. NS also shows that DSI of over 150 can be consistently achieved (Fig. 2). Although more and more resources have been invested in Canadian WMS, it is believed that most of them are for remediation services (Sector 52691, Fig. 1) and therefore do not directly contribute to waste diversion. The government may assist the waste sector to establish more waste businesses helping to improve diversion services by setting up a simple and consistent regulatory framework to allow investors certainty and clarity for their large capital investment. Richter et al. [21] examined the success of NS diversion model and found that NS has considerably more waste management businesses per capita compared to its peers. Specifically, Richter et al. [21] found that there were nearly twice as many waste management businesses per capita in NS (6.35 business/cap) compared to ON (3.65 business/cap).

DSI varies widely among provinces. BC, located on the west coast, also has a higher DSI compared to the national data. NS and BC are top achievers in waste diversion. In Ontario (ON), the most populous province, the DSI is relatively constant from 2006 to 2014, suggesting a mature and established diversion industry. The lowest of all was AB in 2012, with a DSI of 37.72, or about 44.6% of the national average in the same year. The highest DSI was observed in SK in 1998, over two times higher than the national average. It is interesting to note that MB and SK are neighboring provinces located in the Canadian Prairies; however, DSIs of SK were noticeably higher than MB. WMSs of MB and SK are further discussed in Sect. "Materials handled efficiency indicators".

Figure 3 shows the province's DSI coefficient of variation (CV = standard deviation divided by mean) during the 16-year study period. Given the highest CV was 0.57, three groupings were used to create three equal-interval groupings: low variation over the period (CV < 0.2), moderate variation over the period (0.2 < CV < 0.4), and a high variation over the period (CV > 0.4). Using these equal-interval groupings, one can see where large changes have taken place over the study period. The low variation group only contains NS (CV = 0.12), the moderate variation group contains four jurisdictions (BC, ON, NB, and QC,) and the national average (CA), and the high variation group contains three provinces (MB, SK, and AB). Consistent DSI in NS suggests that its waste diversion industry is more developed and mature than its peers. Similar findings are reported by Richter et al. [21]. Richter et al. [21] studied the WMS characteristics in Canada from 1996 to 2010, and found that the province-wide landfill ban on organic waste, a higher population density, a higher budget allocation for waste technologies, and a more established waste business sector are some of the key factors to the success of NS diversion models.

On the other hand, the high variation group, consisting of all Prairie Provinces, has seen DSI decreases of over 60% from 1998 to 2014. These large decreases and large variation in the DSI show inefficiency becoming a larger problem in these waste systems. The diversion rates of the Prairie

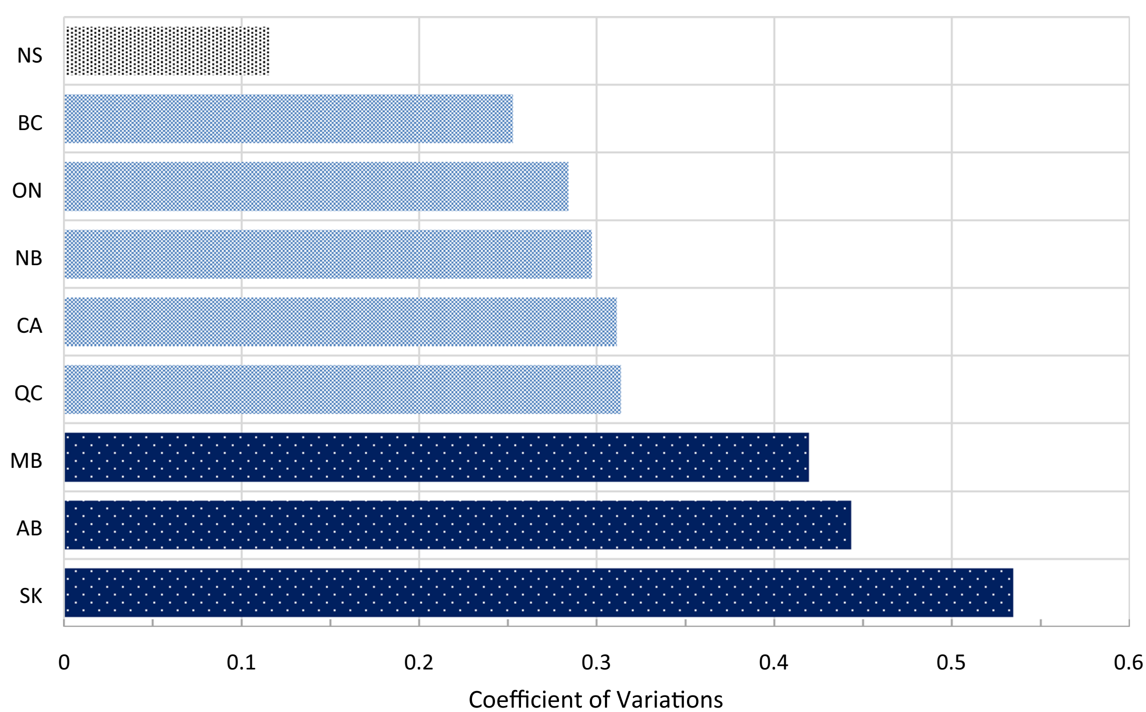


Fig. 3 Variability of DSI between 1998 and 2014 for Canadian jurisdictions

Provinces were lowest among other provinces [18, 19]. It appears that both the magnitude and the consistency of DSIs are required for a thriving waste diversion sector, at least in Canada from 1998 to 2014.

Materials handled efficiency indicators

Materials handled efficiency indicators such as Current Spending per Tonne Handled (CuPT) and GDP of Sector 562 per Tonne Handled (GPT) directly measure economic input of a WMS. CuPT and GPT focus on the entire WMS rather than just diversion activities. Unlike dimensionless DSI (Eq. 3), these two indicators both depend on the wet weight of materials and are easily affected by waste composition and origin (i.e., density, moisture content, compacting characteristics, etc.). As such, caution must be used when interpreting results between jurisdictions.

SK and MB are similar with respect to waste policy, level of economic activities, climatic condition, spatial footprint, and populations, and have similar waste generation characteristics and recycling behaviors [19]. Figure 4a, b illustrates SK's and MB's temporal changes of CuPT and GPT, respectively. NS (a perceived top performer) and CA (the national average) are added for comparison purposes.

With exception in 2004, SK generally spent \$1.4–\$33.5/tonne less than MB (Fig. 4a). However, the diversion rates in SK and MB were similar, probably due to a more efficient diversion sector (Fig. 2). Compared to the national average, these two Prairie Provinces spent at least \$50/tonne less for waste management services during the study period, and less

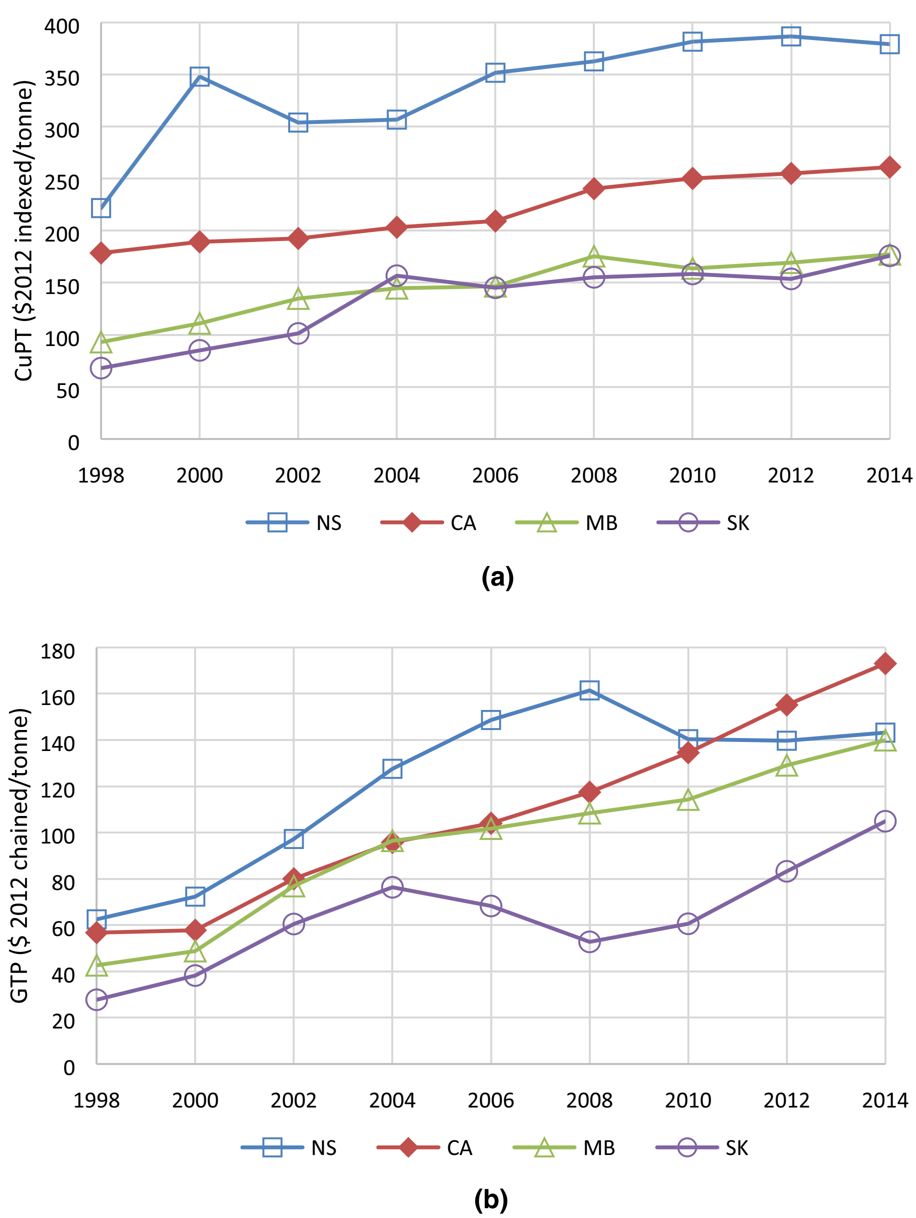


Fig. 4 **a** Current Spending per Tonne Handled in select jurisdictions. **b** GDP of Sector 562 per Tonne Handled in select jurisdictions

than half of what NS spent. Surprisingly, similar increasing trends are observed in all jurisdictions, suggesting a coordinated decrease in efficiency within WMSs nationally. The benefit of CuPT is that it shows an input measure (the current expenditure) without any remediation (of which the GPT encompasses). Therefore, this may be a more truthful reflection of the resources allocated to the non-hazardous waste management sector. However, it does lack the capital spending, which is captured by the GPT.

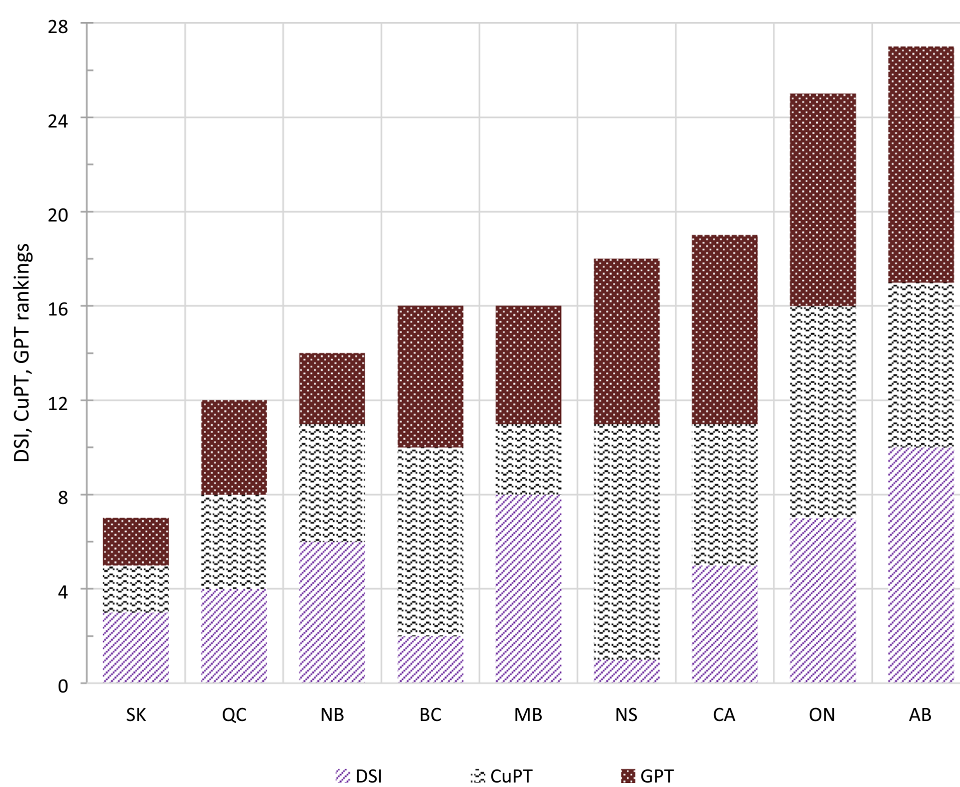
Instead of the current expenditure, the GDP of Sector 562 per tonne handled is used to show a broader measure than just current expenditure, as shown in Fig. 4b. However, like the DGDP measure proposed by Pan et al. [23], it suffers from the fact that it encapsulates remediation (Fig. 1). This means that by comparing Fig. 4a, b, one can understand what role capital and remediation plays in skewing these indicators. As shown in Fig. 4b, considerably more economic resources were needed to handle a tonne of waste in MB than SK, especially after 2004. Comparing Fig. 4a, b, it follows that SK spent less resources on capital and remediation services. MB, on the other hand, was quite comparable to the national average. It also appears that SK has put more effort in its diversion services. On a national level, the GTP curve in Fig. 4b was steeper than the CuPT curve in Fig. 4a, suggesting greater costs for capital and remediation services. A sharp decrease in GTP is observed in NS after 2008 (Fig. 4b), but similar drop is not observed in the CuPT curve in Fig. 4a. From 2010 to 2014, the GTP curve of NS is mostly below the national average. This suggests that NS has started to reduce its high spending on remediation and capital spending per tonne, but no similar efficiency improvement was seen in their high levels of current expenditure per tonne.

Provincial-wise comparison and ranking of the jurisdictions

The most recent available data (2014) are used to rank jurisdictions to investigate the diversion sector and recycling behaviors. Figure 5 combines multiple rankings to visualize the relative performance of the jurisdictions. Although the rankings are derived from different datasets, all of them are used in this study to interpret the efficiency and effectiveness of a WMS. The combined rankings shown in Fig. 5 are intended to be qualitative rather than quantitative, and cautions should be used when interpretating numerical results.

A lower rank generally represents a more efficient WMS. The national average (CA) is also treated as an independent jurisdiction in Fig. 5. SK is the best among Canada in 2014, with a total combined ranking of seven. MB has good ranking for CuPT and GPT, but lags in its DSI ranking due to its lower diversion rate. On the other hand, NS has the best DSI, and the worst CuPT, suggesting that while having a great diversion rate is achievable per WMOI, it does tend to cost more per tonne of material handled. AB and ON drag

Fig. 5 Combined rankings of proposed indicators in each jurisdiction in 2014



down the Canadian average and should further improve the efficiency of their systems as they are the two lowest ranking jurisdictions. BC, MB, and NS have the most unbalanced ranking profiles in 2014. Jurisdictions with identified deficiencies can work to improve their value through the emulation of appropriate waste handling procedures and technology in the other jurisdictions. One of the most important implications of all these indicators, and especially with the addition of the DSI, is the ability of jurisdictions to adequately measure and compare their overall macro-WMS. This allows for insights, such as the focus in NS, which having a great DSI, but a less desirable CuPT, means that policy makers, managers, waste laborers, and citizens can more easily see the implications of their waste system choices. With the system they have, there is definitely advantages regarding diversion rates, but this comes at a greater cost per tonne. Citizens who wish not to pay this extra cost can better articulate why they see diversion rate increases as harmful to their economic security, and citizens who wish to have higher diversion rates can better understand the trade-offs in terms of cost to their increased diversion rate activities. These indicators, when used together, provide a wider and more nuanced picture of WMS for the public and policy makers to have better informed discussions regarding sustainable solid waste management.

Limitations and future work

A single, easily computable indicator can only approximate a jurisdiction's multidimensional WMS profile. Many other factors should be considered in combination to evaluate a WMS. Specifically, recycling generally has a higher priority than incineration in a sustainable solid waste management system. The use of the proposed indicators, however, does not differentiate the social and environmental impacts between the two and treats them both as diversion activities.

One of the key challenges associated with the development of a jurisdictionally comparable indicator is the selection of input–output parameters. Ideally, the selected parameters should be relevant to individual WMSs and standardized parameters be widely available. Data suppression in certain jurisdictions poses significant barriers to a country-wide comparison. If other data become available as the data pool in that jurisdiction becomes larger, this could provide a cloak of anonymity through larger sample size, and may lead to more comprehensive results.

Future studies could also employ different inputs and outputs to suit the goals of various waste entities. Inputs such as carbon dioxide equivalent, other environmental inputs, and breaking down the indicators by material type would all greatly expand the use of such indicators. Furthermore, using life cycle assessment indicators could help to develop a universal system to quantify the efficiency of WMSs. However, getting data and detailed data verification could prove difficult. Further analysis of the Prairie Provinces, reviewing changes from 1998 to 2014, would help to further the understanding of their large coefficient of variation. Geospatial analysis of waste management regions and waste facilities siting may be helpful to understand the operation efficiency of a WMS, as reported by a number of recent studies [25, 26, 38, 39].

These indicators can be of great use at regional level, as well. Since the DSI is jurisdictionally comparable, more research in applying the DSI to American jurisdictions would be of great practical interest to citizens, regulatory agencies, and WMS operators.

Conclusion

A review of the current literature suggests that there is a lack of a simple evaluation method to compare WMSs. This study introduces an original indicator, DSI, to evaluate WMS, specifically regarding waste recycling and minimization. It uses an input–output model and explicitly assesses both the effectiveness and efficiency of WMSs in each jurisdiction. An interjurisdictional comparison of the federation of Canada is conducted using both temporal and cross-sectional approaches.

An obvious decreasing DSI trend is observed in Canada. With the exception of Nova Scotia, all jurisdictions in 2014 had a lower DSI than they did in 1998. Unfortunately, at the same time that the Canadian waste management industry has grown considerably, the declining DSI trend suggests that the waste diversion programs have not yielded the same magnitude of results that this growth should have accompanied. The government, by setting up a simple and consistent regulatory framework, may assist the private waste sector in establishing a greater number of waste businesses, fostering competition, and generating more efficient diversion services.

The variability of DSI was also investigated to assess the maturity and business chrematistics of the waste diversion sector. A consistent DSI in NS suggests its waste diversion industry is well established. The high variation group consists of all Prairie Provinces (SK, MB, and AB). It appears that both the magnitude and the consistency of DSIs are required for a thriving waste diversion sector in Canada.

Similar rates of increasing CuPT trends are observed in most jurisdictions, suggesting a coordinated approach investing WMS nationally. It appears that SK has prioritized its diversion services over capital and remediation services. NS, a perceived national leader on waste diversion, is seen as having a very expensive WMS when looking at the cost per tonne of waste managed compared to the national average or that of SK or MB.

Combined rankings of the indicators suggest that SK in 2014 is far above the best province. On the other hand, NS, which has the best DSI, has the lowest CuPT, suggesting that while having a great diversion rate is achievable per WMOI, it does tend to cost more per tonne of material handled. Jurisdictions with identified deficiencies, such as AB and ON, can work to improve their value through the emulation of appropriate waste handling procedures and technology in the other jurisdictions.

It is believed that proposed indicators are of great practical significances when comparing WMS in different regions. However, many other factors should be considered in combination in evaluating a WMS and the proposed indicators can only approximate a jurisdiction's multidimensional WMS profile.

Acknowledgements The research reported in this paper was supported by a grant from the Natural Sciences and Engineering Research Council of Canada (RGPIN-2019-06154) to the corresponding author (K. T. W. Ng). The authors are grateful for their support. The views expressed herein are those of the writers and not necessarily those of our research and funding partners.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. UNEP (2011) Towards a Green Economy pathways to sustainable development and poverty eradication, PART II: investing in energy and resource efficiency, Waste. United Nations Environment Programme. http://hdl.handle.net/20.500.11822/22012 . Accessed on 6 Jul 2020
2. Lombrano A (2009) Cost efficiency in the management of solid Urban waste. Resour Conserv Recycl 53:601–611
3. Simoes P, Marques RC (2011) How does the operational environment affect utility performance? A parametric study on the waste sector. Resour Conserv Recycl 55:695–702
4. Simoes P, Cruz NF, Marques RC (2012) The performance of private partners in the waste sector. J Clean Prod 29–30:214–221
5. Simoes P, Marques RC (2012) On the economic performance of the waste Sector. A literature review. J Environ Manage 106:40–47
6. Jacobsen R, Buysse J, Gellynck X (2013) Cost comparison between private and public collection of residual household waste: multiple case studies in the flemish region of Belgium. Waste Manage 33:3–11
7. Greco G, Allegrini M, Del Lungo C, Gori Savellini P, Gabellini L (2015) Drivers of solid waste collection costs. Empirical evidence from Italy. J Clean Prod 106:364–371
8. Perez-Lopez G, Prior D, Zafra-Gomez JL, Plata-Diaz AM (2016) Cost efficiency in municipal solid waste service delivery. alternative management forms in relation to local population size. Eur J Oper Res 255:583–592
9. Di Foggia G, Beccarello M (2018) Improving efficiency in the MSW collection and disposal service combining price cap and Yardstick regulation: the Italian case. Waste Manage 79:223–231. https://doi.org/10.1016/j.wasman.2018.07.040
10. Greene K, Tonjes D (2014) Quantitative assessments of municipal waste management systems: using different indicators to compare and rank programs in New York State. Waste Manage 34(4):825–836. https://doi.org/10.1016/j.wasman.2013.12.020
11. Fellner J, Lederer J (2020) Recycling rate—the only practical metric for a circular economy? Waste Manage 113:319–320. https://doi.org/10.1016/j.wasman.2020.06.013
12. Cervantes DET, Martinez AL, Hernandez MC, García L, de Cortázar A (2018) Using indicators as a tool to evaluate municipal solid waste management: a critical review. Waste Manage 80:51–63
13. Bruce N, Ng KTW, Richter A (2017) Alternative carbon dioxide modeling approaches accounting for high residual gases in LandGEM. Environ Sci Pollut Res 24(16):14322–14336. https://doi.org/10.1007/s11356-017-8990-9
14. Bruce N, Ng KTW, Vu HL (2018) Use of seasonal parameters and their effects on FOD landfill gas modeling. Environ Monit Assess 190:291. https://doi.org/10.1007/s10661-018-6663-x
15. Xu Y, Xue X, Dong L, Nai C, Liu Y, Huang Q (2018) Long-term dynamics of leachate production, leakage from hazardous waste landfill sites and the impact on groundwater quality and human health. Waste Manage 82:156–166. https://doi.org/10.1016/j.wasman.2018.10.009
16. Pan C, Ng KTW, Richter A (2019) An integrated multivariate statistical approach for the evaluation of spatial variations in groundwater quality near an unlined landfill. Environ Sci Pollut Res 26(6):5724–5737. https://doi.org/10.1007/s11356-018-3967-x
17. Assamoi B, Lawryshyn Y (2012) The environmental comparison of landfilling vs. incineration of MSW accounting for waste diversion. Waste Manag 32(5):1019–1030. https://doi.org/10.1016/j.wasman.2011.10.023
18. Bruce N, Asha A, Ng KTW (2016) Analysis of solid waste management systems in Alberta and British Columbia using provincial comparison. Can J Civ Eng 43(4):351–360. https://doi.org/10.1139/cjce-2015-0414
19. Wang Y, Ng KTW, Asha A (2016) Non-hazardous waste generation characteristics and recycling practices in Saskatchewan and Manitoba, Canada. J Mater Cycles Waste Manage 18(4):715–724
20. Chowdhury A, Vu HL, Ng KTW, Richter A, Bruce N (2017) An investigation on Ontario's non-hazardous municipal solid waste diversion using trend analysis. Can J Civ Eng 44(11):861–870. https://doi.org/10.1139/cjce-2017-0168
21. Richter A, Bruce N, Ng KTW, Chowdhury A, Vu HL (2017) Comparison between Canadian and Nova Scotian waste management and diversion models—a Canadian Case study. Sustain Cities Soc 30:139–149. https://doi.org/10.1016/j.scs.2017.01.013
22. Richter A, Ng KTW, Pan C (2018) Effects of percent operating expenditure on Canadian Non-Hazardous Waste Diversion. Sustain Cities Soc 38:420–428. https://doi.org/10.1016/j.scs.2018.01.026
23. Pan C, Bolingbroke D, Ng KTW, Richter A, Vu HL (2019) The use of waste diversion indices on the analysis of Canadian Waste Management models. J Mater Cycles Waste Manage 21(3):478–487. https://doi.org/10.1007/s10163-018-0809-3
24. Lakhan C (2015) North of the 46° parallel: obstacles and challenges to recycling in Ontario's rural and northern communities. Waste Manage 44:216–226. https://doi.org/10.1016/j.wasman.2015.06.044
25. Richter A, Ng KTW, Karimi N (2019) A data driven technique applying GIS, and remote sensing to rank locations for waste

disposal site expansion. Resour Conserv Recycl 149:352–362. https://doi.org/10.1016/j.resconrec.2019.06.013
26. Karimi N, Richter A, Ng KTW (2020) Siting and ranking municipal landfill sites in regional scale using nighttime satellite imagery. J Environ Manage 256:109942. https://doi.org/10.1016/j.jenvman.2019.109942
27. Statistics Canada (1998) Waste Management Industry Survey: Business and Government Sectors 1996. Ottawa: Statistics Canada 2000. Catalogue no.16F0023XIE. https://www150.statcan.gc.ca/n1/en/pub/16f0023x/16f0023x1998001-eng.pdf?st=AmTmk6Re. Accessed 1 Aug 2020
28. Statistics Canada (2000) Waste Management Industry Survey: Business and Government Sectors 1998. Ottawa: Statistics Canada 2003. Catalogue no. 16F0023XIE. https://www150.statcan.gc.ca/n1/en/pub/16f0023x/16f0023x2000001-eng.pdf?st=zdFlD1z5. Accessed 1 Aug 2020
29. Statistics Canada (2002) Waste Management Industry Survey: Business and Government Sectors 2002. Ottawa: Statistics Canada 2004. Catalogue no. 16F0023XIE. https://www150.statcan.gc.ca/n1/en/pub/16f0023x/16f0023x2002001-eng.pdf?st=9QInGKs9. Accessed 1 Aug 2020
30. Statistics Canada (2004) Waste Management Industry Survey: Business and Government Sectors 2004. Ottawa: Statistics Canada 2007. Catalogue no. 16F0023XIE. https://www150.statcan.gc.ca/n1/en/pub/16f0023x/16f0023x2004001-eng.pdf?st=s7l02Y0S. Accessed 1 Aug 2020
31. Statistics Canada (2006) Waste Management Industry Survey: Business and Government Sectors 2006. Ottawa: Statistics Canada 2008. Catalogue no. 16F0023X. https://www150.statcan.gc.ca/n1/en/pub/16f0023x/16f0023x2006001-eng.pdf?st=02XYjw69. Accessed 1 Aug 2020
32. Statistics Canada (2008) Waste Management Industry Survey: Business and Government Sectors 2008. Ottawa: Statistics Canada 2010. Catalogue no. 16F0023X. https://www150.statcan.gc.ca/n1/en/pub/16f0023x/16f0023x2010001-eng.pdf?st=xdm9m5us. Accessed 1 Aug 2020
33. Statistics Canada (2010) Waste Management Industry Survey: Business and Government Sectors 2010. Ottawa: Statistics Canada 2013. Catalogue no. 16F0023X. https://www150.statcan.gc.ca/n1/en/pub/16f0023x/16f0023x2013001-eng.pdf?st=On9LXaWJ. Accessed 1 Aug 2020
34. Statistics Canada (2019a) Table 36-10-0402-01. Gross Domestic Product (GDP) at Basic Prices, by Industry, Provinces and Territories (x 1,000,000)). https://doi.org/10.25318/3610040201-eng
35. Statistics Canada (2019b) Table 38-10-0032-01. Disposal of Waste, by Source. https://doi.org/10.25318/3810003201-eng
36. Statistics Canada (2019c) Table 38-10-0034-01. Materials Diverted, by Type. https://doi.org/10.25318/3810003401-eng
37. Statistics Canada (2016) North American Industry Classification System (NAICS) Canada: 2017 Version 1.0. Ottawa: Statistics Canada 2017. Catalogue no. 12-501-X. https://www150.statcan.gc.ca/n1/en/pub/12-501-x/12-501-x2016001-eng.pdf?st=-bE4XrO3. Accessed 1 Aug 2020
38. Richter A, Ng KTW, Karimi N, Wu P, Kashani AH (2019) Optimization of waste management regions using recursive Thiessen polygons. J Clean Prod 234:85–96. https://doi.org/10.1016/j.jclepro.2019.06.178
39. Richter A, Ng KTW, Karimi N, Chang W (2020) Developing a novel proximity analysis approach for assessment of waste management cost efficiency in low population density regions. Sustain Cities Soc. https://doi.org/10.1016/j.scs.2020.102583