

LETTER • **OPEN ACCESS**

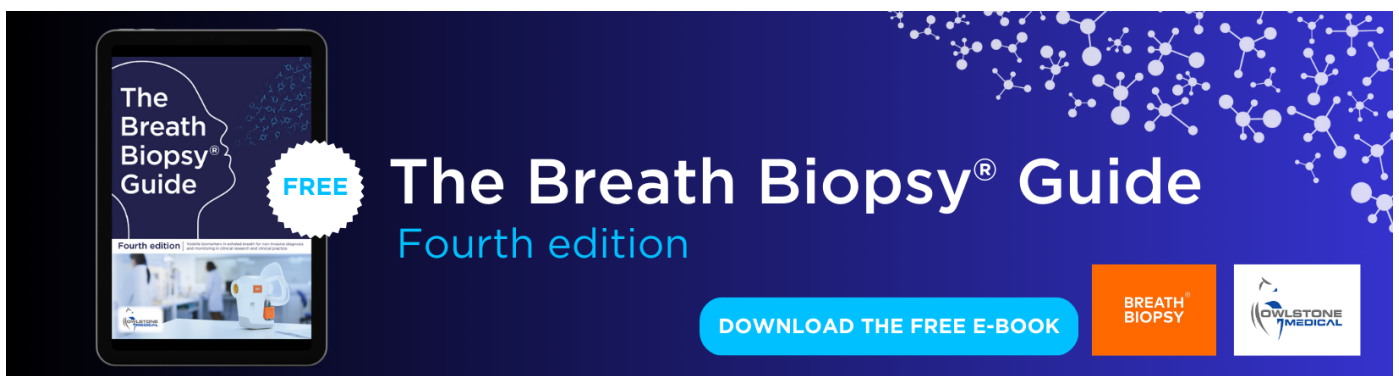
Geographic versus institutional drivers of nitrogen footprints: a comparison of two urban universities

To cite this article: Graham K MacDonald *et al* 2020 *Environ. Res. Lett.* **15** 045008

View the [article online](#) for updates and enhancements.

You may also like

- [Concealed nitrogen footprint in protein-free foods: an empirical example using oil palm products](#)
Kentaro Hayashi, Azusa Oita and Kazuya Nishina
- [Comparison of food supply system in China and Japan based on food nitrogen footprints estimated by a top-down method](#)
Junko Shindo, Azusa Oita, Kentaro Hayashi et al.
- [Nitrogen footprints: past, present and future](#)
James N Galloway, Wilfried Winiwarter, Adrian Leip et al.



The Breath Biopsy® Guide
Fourth edition

FREE

DOWNLOAD THE FREE E-BOOK

BREATH BIOPSY

OWLSTONE MEDICAL

Environmental Research Letters



LETTER

Geographic versus institutional drivers of nitrogen footprints: a comparison of two urban universities

OPEN ACCESS

RECEIVED

16 November 2019

REVISED

22 January 2020

ACCEPTED FOR PUBLICATION

28 January 2020

PUBLISHED

15 April 2020

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Graham K MacDonald^{1,5} , Julie Talbot^{2,5} , Tim R Moore¹ , Julien Arsenault² , Sibeal McCourt¹ , Aidan Goertzen¹ , Max Émile Kessler-Nadeau², Kevin Manaugh^{1,3} , Roxane Maranger⁴  and Brian E Robinson¹ 

¹ Department of Geography, McGill University, Canada

² Département de Géographie, Université de Montréal, Canada

³ McGill School of Environment, McGill University, Canada

⁴ Département des Sciences Biologiques, Université de Montréal, Canada

⁵ Authors to whom any correspondence should be addressed.

E-mail: graham.macdonald@mcgill.ca and j.talbot@umontreal.ca

Keywords: footprint, reactive nitrogen, sustainability, urban geography, food production, wastewater, higher education

Supplementary material for this article is available [online](#)

Abstract

Excess reactive nitrogen (N) is linked to a myriad of environmental problems that carry large social costs. Nitrogen footprint tools can help institutions understand how their direct and indirect activities are associated with N release to the environment through energy use, food, and transportation. However, little is known about how geographic context shapes the environmental footprints of institutions. Defining the system boundaries over which institutions are responsible and able to control individual drivers of N footprints is also a challenge. Here, we compare and contrast the *circa* 2017 N footprints for two research intensive universities located in Montréal, Canada, with a combined full-time equivalent campus population of ~83 000. Our estimate of McGill University's N footprint (121.2 t N yr⁻¹) is 48% greater than Université de Montréal's (74.1 t N yr⁻¹), which is also reflected on a per capita basis (3.3 and 1.6 kg N capita⁻¹ yr⁻¹, respectively). Key institutional factors that explain the differences include McGill's larger residential and international student populations, research farm, and characteristics of its on-campus fuel use. We use a series of counterfactual scenarios to test how shared urban geographic context factors lead to an effective reduction of the N footprints at both universities: the relatively small direct role of both institutions in food intake on campus (29%–68% reduction compared to a counterfactual scenario), energy from hydroelectricity (17%–21% reduction), and minimal car commuting by students (2%–3% reduction). In contrast, the near-zero N removal from the municipal wastewater system effectively increases the N footprints (11%–13% increase compared to a modest N removal and offset scenario). Our findings suggest that a shared geographic context of a dense city with plentiful off-campus housing, food options, and access to hydroelectricity shapes the absolute N footprints of Montréal's two main universities more than the divergent institutional characteristics that influence their relative N footprints.

1. Introduction

Human activity has dramatically accelerated the nitrogen (N) cycle primarily via the conversion of inert N₂ gas to reactive forms of N through synthetic fertilizer production, growth of N-fixing crops, and fossil fuel combustion (Gruber and Galloway 2008). While increased use of reactive N in agriculture has been

critical to increasing food production globally, it has contributed to a doubling of reactive N inputs to the environment toward levels that could have major consequences for global sustainability (Compton *et al* 2011, Fowler *et al* 2013, Steffen *et al* 2015). Reactive N can have many environmental and human health impacts depending on its form and location. For example, reactive N can contribute to eutrophication

of coastal and other surface waters, groundwater contamination, the formation of smog and other atmospheric pollutants that negatively impact air quality (primarily as nitrogen oxides, NO_x), as well as acting as a potent greenhouse gas, nitrous oxide (N_2O), that contributes to global climate change (Galloway *et al* 2003). Therefore, efforts to sustainably manage reactive N use and to mitigate N release to the environment have implications for meeting sustainability objectives ranging from the local scale (e.g. municipal or institutional net-zero emissions targets) to achieving the United Nations' sustainable development goals (SDGs) (Vanham *et al* 2019).

Nitrogen footprints estimate the release of reactive N to the environment as a result of individual or collective consumption activities (Galloway *et al* 2014). For example, the consumer-oriented N-Calculator model by Leach *et al* (2012) estimates the reactive N released to the environment on a per capita basis related to food production and consumption, household utilities, transportation, and the purchase of goods and services. National per capita N footprints have been calculated for more than 10 countries and vary between 15 and 47 kg N $\text{capita}^{-1} \text{yr}^{-1}$ (Pierer *et al* 2014, Shibata *et al* 2014, Stevens *et al* 2014, Liang *et al* 2016, Shibata *et al* 2017, Guo *et al* 2017, Elrys *et al* 2019). Typically, these studies have emphasized the role of food production (e.g. excess fertilizer N use in agriculture and other N losses during food processing) and to a lesser extent, food consumption (N excretion by humans and wastewater treatment), as key aspects of national N footprints (Galloway *et al* 2014). Given the large variation in the N losses associated with producing different foods (e.g. animal > vegetal products), N footprints are strongly influenced by diet (Leach *et al* 2012, Leip *et al* 2014).

Nitrogen footprints can play an important role in raising consumer awareness about the impacts of reactive N and in understanding how our activities affect the N cycle (Galloway *et al* 2014, Shibata *et al* 2017, Einarsson and Cederberg 2019). However, defining system boundaries and the scope of activities to include in footprint assessments is a challenge. Past N footprint studies have had variable system boundaries that may lead to different conclusions about potential impacts of reactive N on the environment (Einarsson and Cederberg 2019). Such impacts include economic damage costs to society through the effects of reactive N on the environment and human health, which have been calculated at institutional (Compton *et al* 2017), state (Keeler *et al* 2016), and national scales (Sobota *et al* 2015).

As centers of knowledge creation and learning, higher-education institutions have an important role in catalyzing local sustainability efforts and by empowering sustainability solutions in communities (e.g., Colding and Barthel 2017, Withycombe Keeler *et al* 2018). As a complement to consumer-focused and national scale N footprint assessments, Leach *et al* (2013)

adapted the N-Calculator model to the institutional scale (the 'Nitrogen Footprint Tool', NFT) and calculated the University of Virginia's N footprint. Many colleges and universities have subsequently applied the NFT approach to calculate their institutional N footprints. A comparison of the N footprints of seven US colleges and universities highlighted a wide range in institutional N footprints (from 7 to 27 kg N $\text{capita}^{-1} \text{yr}^{-1}$), and showed that the magnitude of animal products in food services and the reliance on fossil fuels in purchased electricity are key factors affecting the absolute and relative magnitudes of the N footprints (Castner *et al* 2017). Higher-education institutions therefore also make an impact directly through their operations and their efforts to address sustainability reporting around targets that might influence N footprints, such as the Association for the Advancement of Sustainability in Higher Education (AASHE) Sustainability Tracking, Assessment, & Rating System (STARS) (Fonseca *et al* 2011, Amaral *et al* 2015).

While N footprint magnitudes vary considerably across higher-education institutions (Castner *et al* 2017), less is known about the specific factors that shape this variation across different institutional and geographic contexts. For example, does a shared urban context outweigh the effects of university-specific differences on the overall N footprints for two schools of comparable size? We aim to compare and contrast the N footprints of two large, research intensive universities in Montréal, Québec, Canada, that have a shared urban setting but considerable variations in operations, governance, and student demographics. Greater Montréal has a high density of post-secondary schools, with 11 universities and a total of 155 000 students in 2015 (Board of Trade of Metropolitan Montréal, 2016). McGill University and Université de Montréal (UdeM) represent two of the four large universities in central Montréal and are located at the heart of the dense metropolitan region. Our specific objectives are to: (1) Calculate and compare the N footprint for these two universities; (2) Identify the institutional factors that affect the N footprints; and (3) Assess how shared geographic factors relating to the urban and provincial settings of these universities may either reduce or increase the N footprints based on counterfactual scenarios representing other geographic contexts. We further assess how operational boundaries affect estimates of N release to the environment associated with an institution, emphasizing food production linked to university-run food services and different scenarios of wastewater production and treatment. This research can help to inform the role of higher-education institutions in mitigating N release to the environment (i.e. academic researchers as well as university sustainability offices) but may also be relevant to other types of organizations seeking to incorporate new sustainability metrics to assess the environmental impacts of their operations.

2. Methods

We define ‘geographic context’ as the urban and jurisdictional setting of a university that shapes shared factors such as off-campus housing availability, public transportation, and electricity sourcing. University-specific factors related to the campus operations and activities as well as student demographics are defined as ‘institutional context’.

2.1. Study area and geographic context of Montréal

Montréal (45°30' N; -73°33' W) is Canada's second largest city with ~1.9 million and ~4 million people in the urban and metropolitan areas, respectively, and with a high population density of almost 4,000 people km⁻² on the Island of Montréal (Statistics Canada 2017). It has a comprehensive public transit system and more than 875 km of bike lanes (Vélo Québec 2016). Electricity is provided by the state-owned utility, Hydro-Québec, and renewable sources (typically >95% hydroelectricity) comprised 209 million MWh of the 212 million MWh produced in Québec in 2017 (Statistics Canada 2019). Montréal has a cool continental climate (average July/January temperatures of 21.2 °C and -9.7 °C, respectively; Government of Canada 2019a) and about 54% of household energy consumption is used for heating or air conditioning (Hydro-Québec 2019).

McGill and the UdeM are the oldest of the four large universities in Montréal and are similar in size and budget when excluding affiliated institutes (table S1 is available online at stacks.iop.org/ERL/15/045008/mmedia). They are located centrally in the city, 2.5 km away from each other on either side of Mount Royal, a large hill located north of Montréal's central business district (figure 1). They are easily accessible by public transportation, including several bus lines, Montréal's subway (metro), and commuter rail; major bike paths also intersect both of the main campuses. Both universities are research-oriented institutions that comprise a medical school and both have a large international student population, although McGill's international student population is proportionally higher (27% of the full-time equivalent (FTE) student population at McGill versus 13% for UdeM).

2.2. Overview of SIMAP and system boundaries for institutional footprints

Most of our N footprint calculations were conducted with the Sustainability Indicator Management and Analysis Platform (SIMAP, <https://unhsimap.org>), an online tool developed by the University of New Hampshire's Sustainability Institute. The focal year of our calculation is 2017, but some data sources were obtained from earlier years. The institutional N footprint calculation is based on the Nitrogen Footprint Tool (NFT) methodology described by Leach et al (2013). SIMAP considers all N released to the environment in dissolved, solid, or gaseous

forms resulting from university activities: fuel used by university-operated vehicles or boilers, the use of fertilizers on campus, and farm/research animal-related emissions. Utilities consumption by the university, the emissions generated by commuting as well as by academic and student mobility, and the N from the production and consumption of food sold on campus are also included (figure 2). Any N losses from off-campus housing and non-university administered food purchases, such as when students and staff bring lunches to the university or purchase food at independent or sub-contracted food vendors, are excluded here.

Different components of the institutional N footprint are divided into ‘scopes’ based on the operational boundaries of the institution (GHG Protocol 2004). This allows categorization of the potential N pollution contribution by level of institutional control over emission sources (figure 2). A critical aspect of N footprint calculation is therefore how institutional boundaries are set. We used a control approach for both universities (GHG Protocol 2004), where we included emissions from operations over which the university has some level of control, whether owned or not by the university (e.g. it may include leased facilities). Because the structures of the universities differ, including in terms of official data availability, campus boundaries for each university have some particularities. We excluded affiliated entities that are independently administered to ensure that the main operational teaching and research aspects of the universities were of comparable size. For example, UdeM has large affiliated schools (engineering and business schools) and both universities are affiliated with large teaching hospitals and health care centers, which are excluded from our analyses.

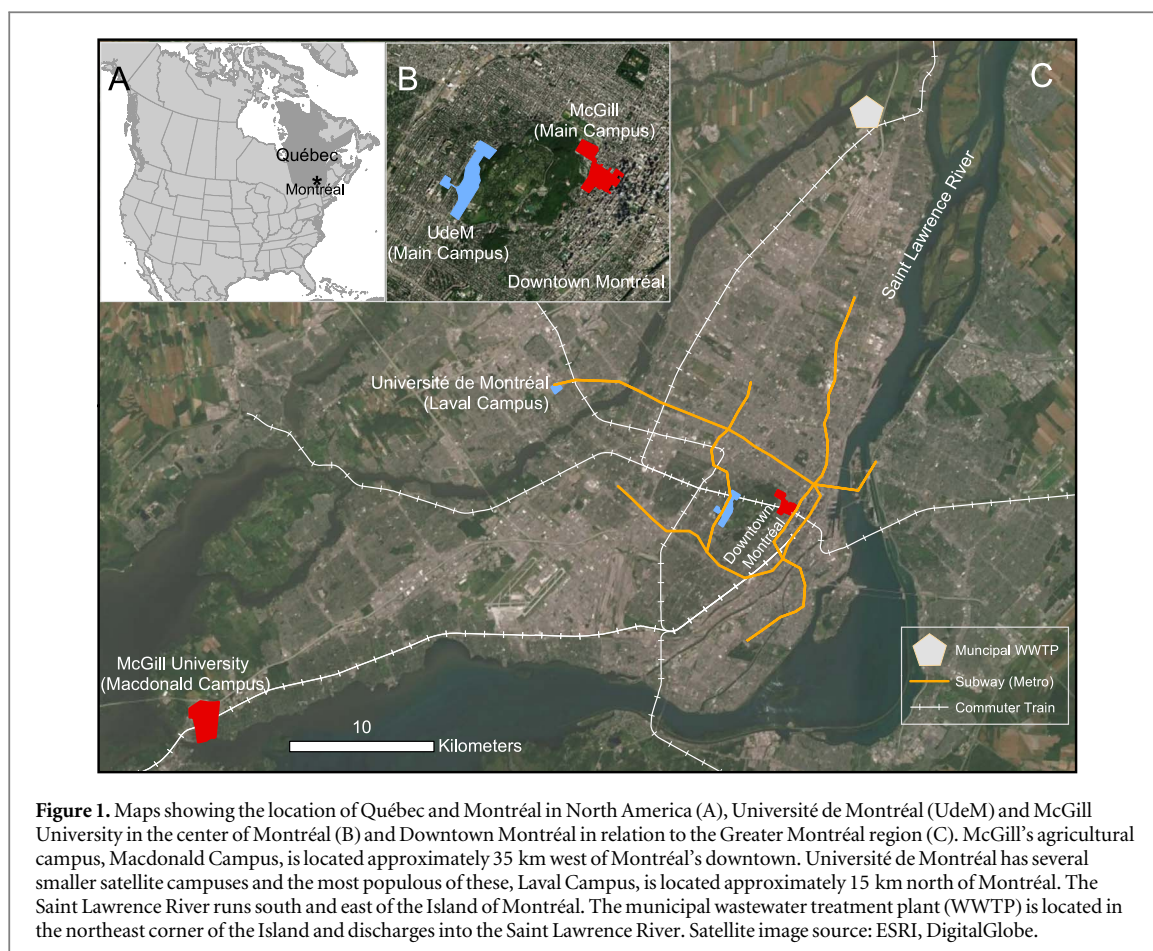
2.3. Details on N footprint calculations by component

2.3.1. On-campus fuel use

Detailed inventories of stationary fuels (e.g. propane, natural gas, and diesel) as well as transport fuels for university vehicle fleets were provided by McGill's Greenhouse Gas Inventory report (Rivers and Conraud 2018). For UdeM, stationary fuels data were obtained from Québec's Ministry of Education and transport fuels data were provided by the University.

2.3.2. Fertilizers, research animals, and livestock

Neither university used nitrogenous fertilizers on grounds for landscaping in 2017. The quantity of fertilizers used on McGill's farm was directly available, with an average N content of 33%. Research and farm animals standing stocks were available for both universities. McGill has a research farm that contains poultry, swine, and dairy production, and also supplies campus food services with a considerable amount of food. We estimated the direct waste-related N footprint for animals by using the NFT methodology



(Leach *et al* 2013). Our estimates of N losses for animals includes waste and incineration but omits the N use embodied in the production of animal feeds, which was unavailable for either university and to avoid double-counting of N with food production at McGill.

2.3.3. Purchased electricity and utilities

N₂O and NO_x emissions associated with purchased electricity and chilled water were calculated in SIMAP using emission factors (EF) specific to Québec, 0.0001 g N₂O kWh⁻¹ and 0.025 g NO_x kWh⁻¹ (Government of Canada 2019b and Statistics Canada 2019) based on university reporting of purchased electricity. This is likely a conservative estimate that integrates the province's entire fuel mix, as the reported NO_x EF for hydroelectricity is roughly one-third of the province-wide estimate (Hydro-Québec 2018). Default EFs in SIMAP were applied for purchased steam. Transmission and distribution (T&D) losses were ~0.1 t N yr⁻¹ at each university based on SIMAP defaults for this region.

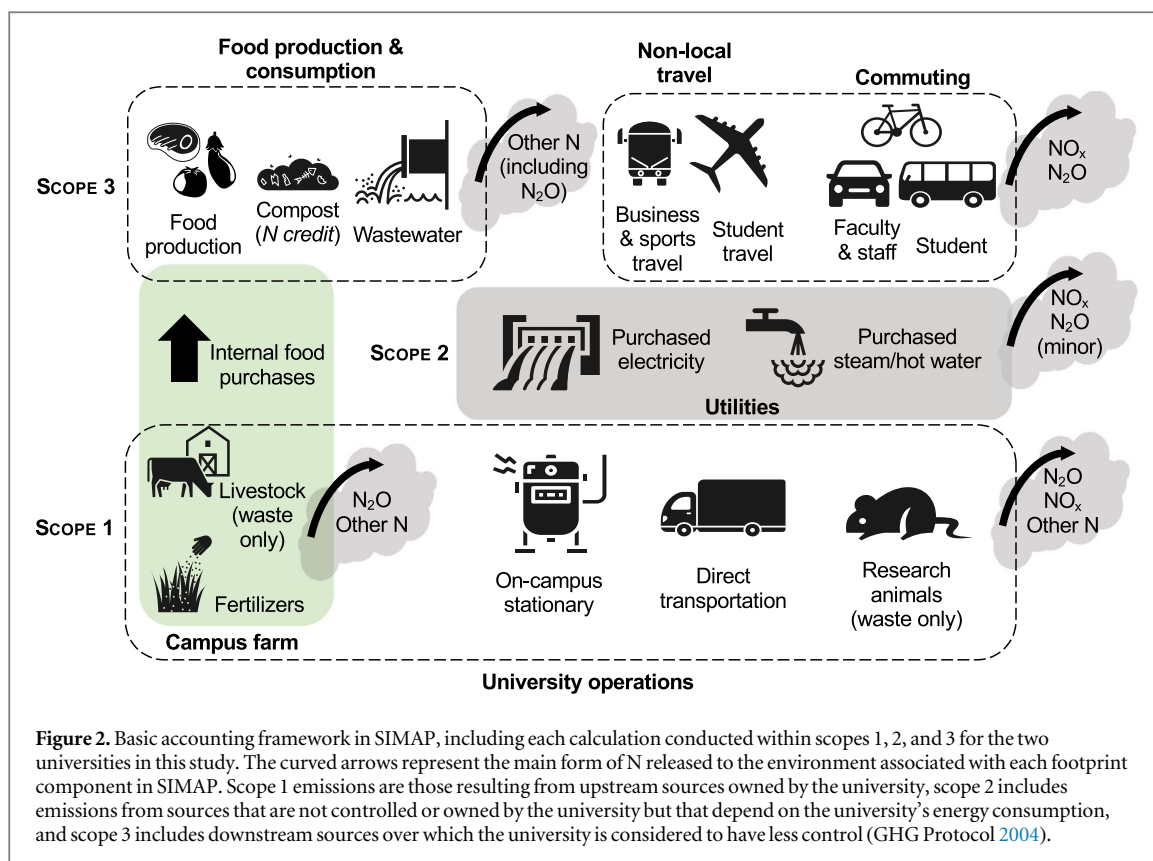
2.3.4. Commuting emissions

Local travel-related emissions for all students, staff, and faculty were estimated based on student and staff

mode shares derived from survey data at McGill (Shaw *et al* 2013) and UdeM (Université de Montréal, HEC Montréal and Polytechnique Montréal 2013). Commuting weeks per year and trips per week (10 one-way trips) were held constant between the two universities (faculty: 47 wks⁻¹ yr⁻¹; staff 46 wks⁻¹ yr⁻¹; full-time students 35 wks⁻¹ yr⁻¹). We applied an EF for public buses (0.0055 g N₂O passenger km⁻¹) used by Montréal's public transit authority (Environment and Climate Change Canada 2019). The metro (light rail subway) in Montréal is powered by hydroelectricity and assumed to have negligible NO_x/N₂O emissions (see supplementary information, SI, text for rationale).

2.3.5. Directly financed travel-related emissions

Statistics on directly financed air travel, and ground travel for sports teams, were available from McGill's Greenhouse Gas Inventory report (Rivers and Conraud 2018). However, no official data were available for other directly financed ground transportation for McGill, which is omitted here. Data for long-distance academic travel were unavailable for UdeM, so the annual passenger kilometers travelled by students, staff, and faculty was estimated based on an online



survey, while data on sports team travel was provided by the university (Arsenault *et al* 2019).

2.3.6. Student non-local travel-related emissions

Official statistics on international students by home country and out-of-province Canadian students by home province were used to estimate total passenger kilometers travelled by mode (air or ground transport) to and from each university following the approach of Arsenault *et al* (2019). Students are assumed to take one round-trip per year from capital cities of their home countries or provinces (or the national population centroid for US students). We applied a similar approach to estimate study-abroad travel and field trips, based on counts of students by destination country in 2017–2018. Information on home locations of Québec students was unavailable and is therefore omitted.

2.3.7. Food production

We estimated N losses embodied in production of the food that was served at university-run or university-affiliated eateries by using detailed inventories of food purchases and default virtual N factors (VNFs) in SIMAP. Virtual N factors represent the N released to the environment per unit of food (Leach *et al* 2012), which includes excess N from fertilizer and manure management in agriculture as well as transportation-related NO_x emissions and N losses from food waste

sent to landfills. Separate VNFs for Canada and Québec are not currently available so we use default US national average values in SIMAP; we expect that this may slightly overestimate N release for food production given the typically lower recommended N fertilizer application rates for key food crops in Québec compared to the US national average (as much as 62% lower on average in Québec for soybean, wheat, apples, tomatoes, lettuce, potatoes, and onion) despite typically lower crop yields (15% lower on average in Québec) (CRAAQ 2010, Leach *et al* 2012, ISQ 2019).

Detailed annual food purchases for McGill's five dining halls were available from the two main food suppliers for the 2015–2016 period, including the University's own farm. For UdeM, food purchase inventories from the university dining halls (annual basis for the main supplier and for a three-month period for others) and weekly purchases for 16 of the 20 student run cafés were available. These detailed inventories were subsequently scaled to represent food purchases during a full year across all food service locations (following Leach *et al* 2013). Further details are provided in the SI text on the food calculations, including estimates of the shares of local and organic food in overall sales.

2.3.8. Wastewater

Montréal has a combined sewage overflow system that drains to the Jean-R. Marcotte treatment plant, which is a chemically enhanced primary treatment (CEPT)

system and the second largest wastewater treatment plant in the world (Canadian Water Network 2018). However, as with many wastewater treatment plants in eastern Canada, the plant is primarily designed to remove phosphorus (Oleszkiewicz and Barnard 2006). Primary treatment with coagulants to remove organic waste results in an incidental removal of about 20%–25% of total Kjeldahl nitrogen (TKN), which includes removal of ammonia and organic N, but excludes nitrates/nitrites (personal communication, Tony Di Fruscia, August 2019). However, because most sewage sludge is subsequently incinerated, we assumed that there was effectively zero net-removal of reactive N in our total N footprint calculation. We use three alternative approaches to estimate lower-, middle-, and upper-bound scenarios of wastewater in the total N footprint. These scenarios follow the ‘food consumption’ approach of Leach *et al* (2013), per capita N intake for the approximate total number of meals consumed annually on campus with the recommended daily allowance (RDA) for protein, and per capita wastewater discharge estimates for education institutions in Québec (detailed in the SI text). Since almost all N intake by adults is excreted, we assume in the ‘food consumption’ and RDA scenarios that N intake in food is excreted to wastewater (Liang *et al* 2018). We apply the upper-bound per capita wastewater discharge scenario except where specified.

2.4. Counterfactual scenarios

We use a series of counterfactual scenarios for food production, purchased electricity, commuting, and wastewater to examine how shared geographic context affects the total N footprint value of each university. When comparing these scenarios to the actual (baseline) *circa* 2017 N footprints, we estimate the magnitude by which each university’s footprint is reduced or increased relative to an alternative situation, such as: low availability of off-campus housing and dining options; fossil fuel reliance in purchased electricity; lower walkability and public transit access; and municipal primary sewage treatment without incineration. We test scenarios that emulate the effect of alternative geographic contexts and use these to make inferences about the effects of shared city and provincial factors in our analysis:

- (1) *A larger direct role of the university in food intake on campus:* in this scenario, we assume that all food sales on campus are controlled directly by the university and that UdeM has a similar university food service configuration to McGill (i.e. more residential student dining halls).
- (2) *A lower share of renewables in purchased electricity:* assumes average US eGrid emission factors instead of the current energy mix in Québec (i.e. emission factors per kWh for NO_x 79 times higher and N₂O 119 times higher than the baseline).

- (3) *A larger share of car commuting for students:* assumes that student commuting mode share is equivalent to faculty mode share at each university, resulting in more car commuting and less active or public transportation (i.e. ~30% personal car travel for student commuters instead of ~8% in the baseline).
- (4) *Beneficial reuse of sewage sludge:* the 20%–25% of the N influent to Montréal’s wastewater treatment plant that is removed is mostly transferred to the atmosphere due to sludge incineration. In this scenario, we therefore assume that 25% of N influent is captured and beneficially reused thereby offsetting the N footprint as a credit (*sensu* Leach *et al* 2013).

3. Results and discussion

McGill’s institutional N footprint is ~48% larger than UdeM’s and is consistently larger based on standardizations per capita, university budget, and built area bases. However, the N footprint estimates at both universities are highly sensitive to assumptions about food and wastewater. We therefore present scopes 1 and 2 separately and provide multiple estimates of the total institutional N footprint with scope 3 according to different system boundaries for wastewater (table 1). While several institutional factors affect the relative N footprint magnitudes (table 2), shared geographic context factors often have a relatively stronger role and effectively reduce or increase each of the university’s footprint relative to institutions in other settings (table 3).

3.1. Breakdowns of McGill and UdeM N footprints

The total N footprint of McGill University with wastewater is ~121.2 t N yr⁻¹, or 3.3 kg N per capita FTE, while UdeM’s is ~74.1 t N yr⁻¹, or 1.6 kg N per capita FTE (figure 3). McGill’s agricultural research farm contributes the largest share of scope 1 N release (11.4 t N yr⁻¹, mostly as N₂O from N fertilizer use and other N from animal waste), followed by on-campus stationary fuels (6.4 t N yr⁻¹), and research animals (3.8 t N yr⁻¹). McGill’s scope 2 emissions total ~3.0 t N yr⁻¹, with roughly half coming from minor NO_x and N₂O emissions from hydroelectricity or associated with the small share of fossil fuels in Québec’s electricity grid, and roughly another half coming from purchased steam and hot water from natural gas burners from a nearby hospital site. In contrast, the largest share of the UdeM’s scope 1 and 2 emissions are from on-campus stationary fuels (4.4 t N yr⁻¹, including natural gas burners) and purchased electricity from the hydroelectricity-dominated grid (1.0 t N yr⁻¹). Waste from and disposal of research animals contribute the next largest share at 2.4 t N yr⁻¹, while livestock animals at the

Table 1. Comparison of total N footprint estimates at each university with and without Scope 3, including N release linked to food production and consumption (wastewater). All values are metric tonnes N yr⁻¹.

N footprint components	McGill University	Université de Montréal (UdeM)
Scopes 1 and 2 only	25.2	8.0
Scope 1, 2, and 3		
Total N footprint including transportation but excluding food and wastewater	47.1	31.2
Total N footprint with food production	74.2	39.6
Total N footprint with food production and wastewater scenarios, assuming that all wastewater N is ultimately released to the environment (to atmosphere via sludge incineration or dissolved forms to Saint Lawrence River)		
+ lower-bound: direct food consumption N footprint (estimated N release in wastewater directly linked to protein N intake at campus food services)	76.0	40.8
+ middle-bound: per capita wastewater estimate based on recommended daily allowance (RDA) protein intake by population (estimated wastewater N for protein in >8 million meals served and average protein N content of 16%)	93.1	62.9
+ upper-bound: per capita wastewater estimate based on discharge factors (liters per person varied by residential students, non-residential students, and staff), assuming 50 mg N l ⁻¹ concentration	121.2	74.1

University's veterinary college contribute a small share (<0.1 t N yr⁻¹).

Given the small contributions of both universities to scope 1 and 2 emissions, the largest share of their N footprints is linked to scope 3 emissions (79% and 89% of the N footprint for McGill and UdeM, respectively). Wastewater is by far the largest single source at ~50.4 t N yr⁻¹ for McGill and ~35.2 t N yr⁻¹ for UdeM. Our alternative lower- and middle-bound estimates for wastewater range from 5.2 to 22.3 t N yr⁻¹ for McGill and from 2.0 to 24.0 t N yr⁻¹ for UdeM (see section 3.3 for details).

Nitrogen release associated with producing food for McGill's university-run cafeterias comprises ~27.1 t N yr⁻¹, of which about 7% (1.9 t N yr⁻¹) is linked to food produced at the University's own farm. A substantial share of N linked to food is composted at McGill, which contributes a 'credit' of -3.4 t N yr⁻¹ to the footprint. The UdeM's N release linked to food production for campus food services is about 8.4 t N yr⁻¹ with a credit of -0.7 t N from composting.

McGill's non-local travel comprises 12.5 t N yr⁻¹, most of which is international student air travel to/from home, while local commuting comprises 9.0 t N yr⁻¹ mostly from student commuting by bus and faculty/staff car travel. Non-local travel (11.3 t N yr⁻¹) and local commuting (11.9 t N yr⁻¹) contribute nearly equal contributions to UdeM's N footprint. Given uncertainty about the specific origin

city of students and their travel habits, we examined the influence of our two major assumptions around international student air travel at each university. We varied the number of trips from 1 to 3 trips per student per year and tested different points of origin (capital city, largest city, population centroid and busiest airport) in home countries. In both cases, the assumption about the number of trips taken per year had a greater effect on the total N footprint (up to 11% and 16% increases for UdeM and McGill, respectively; see SI text for details) rather than the location of departure within origin countries.

3.2. Institutional drivers of differences in the institutional N footprints

Although UdeM has a larger campus population in terms of both student and staff numbers and McGill has a larger built area as well as budget (table S1), we find that McGill's N footprint is consistently greater than UdeM's (from 1.4 to 2.0 times larger) according to different standardizations per unit population, dollar, and area (figure 4). For both McGill and UdeM, the standardized footprints are highly sensitive to assumptions about N release linked to wastewater, which results in intra-university variability that is of a comparable magnitude to the inter-university differences (1.7- and 1.9-times greater N release when including wastewater for McGill and UdeM, respectively).

Table 2. Effects of university-specific factors (institutional context) as drivers of the differences in the N footprint results. The effect of each driver is estimated in the third column, sorted from highest to lowest magnitude.

Difference in N footprints	Institutional context driver	Likely magnitude of the effect on each university's N footprint
<i>Large difference in food production N (McGill > UdeM)</i>	McGill has more food services on-campus due partly to mandatory meal-plans for residential students (Scope 3). McGill also has a different food composition (e.g. more full meals and meat served), which increases the food production N footprint.	Food production is ~ 18.7 t N yr ⁻¹ higher for McGill than UdeM, ~ 4 times greater per student FTE.
<i>Large difference in wastewater N (McGill > UdeM)</i>	McGill has a larger residential student population, therefore more water discharge per capita (Scope 3).	Wastewater discharge is ~ 12.6 t N yr ⁻¹ greater at McGill than UdeM; UdeM has slightly higher wastewater N based on a per capita (RDA) scenario (~ 1.7 t N).
<i>Presence of N emissions from agricultural research farm (McGill)</i>	Only McGill has a research farm (Scope 1).	Increases McGill's N footprint by at least 11.3 t N yr ⁻¹ relative to UdeM.
<i>Moderate difference in international student travel (McGill > UdeM)</i>	$\sim 27\%$ of McGill's student population is international compared to $\sim 13\%$ at UdeM (Scope 3).	McGill's student-travel related N footprint is ~ 4.4 t N yr ⁻¹ greater than UdeM's.
<i>Small difference in commuting (UdeM > McGill)</i>	Slightly more car commuting at UdeM, with location outside of central business district and a higher number of available parking spaces (Scope 3).	UdeM's commuting N footprint is ~ 2.6 t N yr ⁻¹ greater than McGill's; however, they are nearly equivalent on per student basis (0.29–0.30 kg N per FTE student).
<i>Small difference in on-campus transportation and stationary fuels (McGill > UdeM)</i>	McGill has relatively larger diesel fleet (66% of fuel consumption at McGill versus 3% of fuel consumption at UdeM) and greater consumption of natural gas (Scope 1).	McGill's campus fuel-related emissions are ~ 2.5 t N yr ⁻¹ greater than UdeM's.
<i>Small difference in purchased utilities (McGill > UdeM)</i>	McGill has access to purchased steam and hot water from nearby large former hospital site (Scope 2).	Adds ~ 1.6 t N yr ⁻¹ to McGill's footprint.
<i>Discrepancy in directly financed travel (UdeM > McGill)</i>	UdeM appears to have more directly financed travel-related N emissions (Scope 3).	No official data for McGill.

Since urban geographic context is similar between the two universities, we systematically compared each of the N footprint components by scope to examine how institutional factors determine the disparities in the total N footprints. The share of McGill's N footprint from scopes 1 and 2 is roughly double that of UdeM's, mainly due to McGill's use of purchased steam, more oil consumption on campus, and the presence of a research farm. McGill's research farm considerably elevates its footprint relative to UdeM (by 11.3 t N yr⁻¹), which does not have a farm but has a small livestock animal population at its veterinary college (< 0.1 t N t N yr⁻¹). If N release linked to livestock feed production were considered, McGill's total N footprint would be at least 33% higher (an additional ~ 48.5 t N yr⁻¹ release linked to animal feed production, based on the approximate weight of animal production in 2015 and the virtual N factor approach of Leach *et al* 2013).

The largest factors that affect the relative N footprints relate to scope 3, including differences in the magnitude of on-campus food services and residential student populations among the two universities (table 2). The types of foods served at the universities differ considerably, with more full meals represented in McGill's data for residential dining halls; McGill also has a much larger share of animal products (dairy,

eggs, and meat) in its food purchases ($\sim 35\%$) compared to UdeM ($\sim 16\%$) on a mass-basis, which contributes proportionally to its larger food production N footprint. McGill's larger overall role in campus food services and different types of foods served therefore results in a per capita N release for food production ~ 4 times that of UdeM (0.86 kg N versus 0.22 kg N student⁻¹ yr⁻¹, respectively). Since our 'per capita discharge' method for estimating wastewater N is determined by whether students live on- or off-campus, McGill's larger residential student population also considerably elevates the total N footprint (by 12.6 t N). However, when using a 'per capita daily protein intake' method, UdeM's larger population results in a slightly higher wastewater estimate (by 1.7 t N yr⁻¹).

Other institutional characteristics that increase McGill's N footprint include its larger share of international students than UdeM (27% versus 13%, respectively), which mainly elevates NO_x emissions related to international air travel. McGill is primarily an English language institution that draws a considerable student population from other Canadian provinces and countries; in contrast, UdeM is primarily a French language institution where the student base is primarily from Québec. These factors in turn influence student housing, air travel, and commuting. UdeM has slightly more car commuting, elevating its

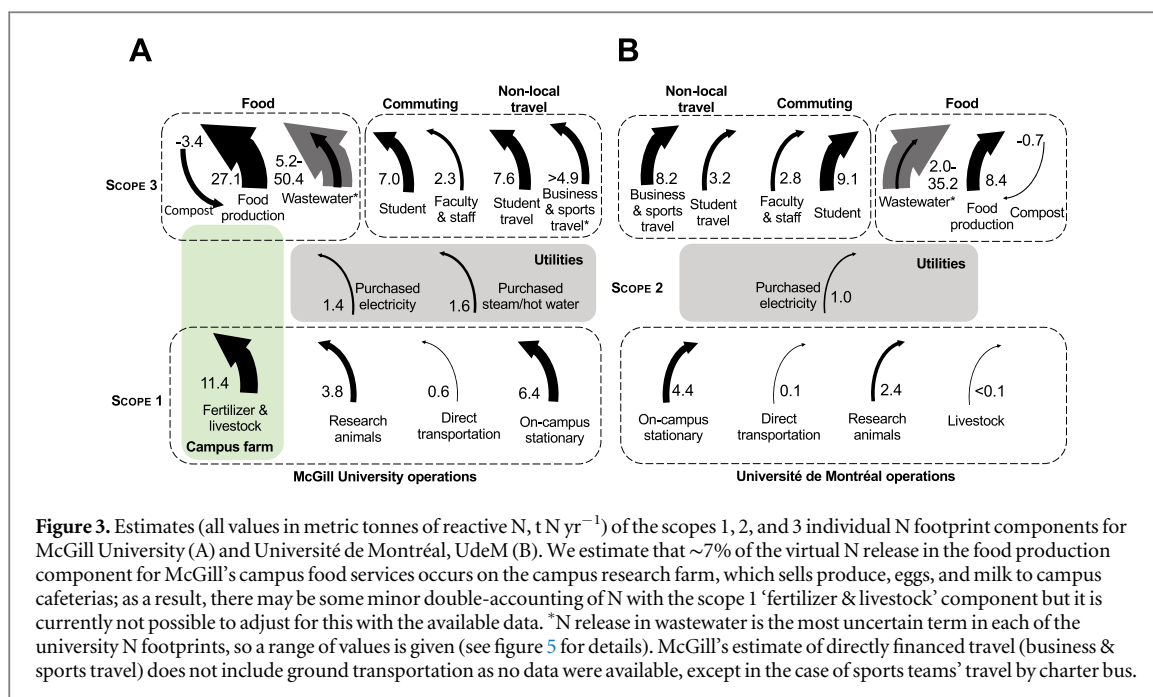


Figure 3. Estimates (all values in metric tonnes of reactive N, t N yr⁻¹) of the scopes 1, 2, and 3 individual N footprint components for McGill University (A) and Université de Montréal, UdeM (B). We estimate that ~7% of the virtual N release in the food production component for McGill’s campus food services occurs on the campus research farm, which sells produce, eggs, and milk to campus cafeterias; as a result, there may be some minor double-accounting of N with the scope 1 ‘fertilizer & livestock’ component but it is currently not possible to adjust for this with the available data. *N release in wastewater is the most uncertain term in each of the university N footprints, so a range of values is given (see figure 5 for details). McGill’s estimate of directly financed travel (business & sports travel) does not include ground transportation as no data were available, except in the case of sports teams’ travel by charter bus.

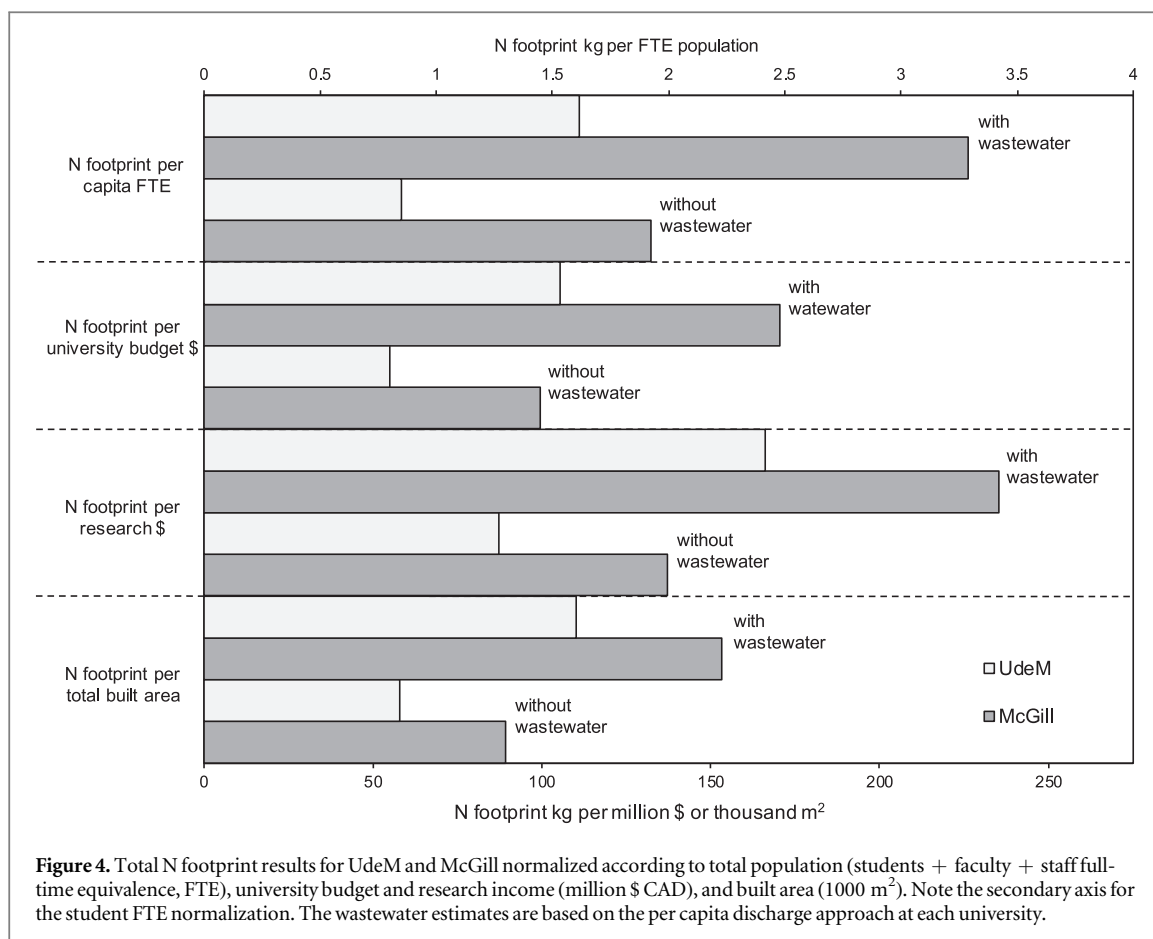
Table 3. Effects of shared geographic context drivers on the N footprints of both universities, including whether there was an effective reducing (–) or increasing (+) effect of the driver. For each geographic context driver, a counterfactual scenario is used to estimate the magnitude of the effect on each institution’s N footprint (shown in the fourth column), sorted from highest to lowest magnitude.

Shared N footprint finding	Geographic context driver	Effect on N footprints	Magnitude of effect based on counterfactual scenarios
Relatively small role of food production (–)	Plentiful off-campus housing, food and dining options in Montreal.	Limited direct role of campus food services in total food intake by the university population reduces Scope 3.	Inferred reduction effect of between 29%–68% ^a assuming a more widespread direct role in food consumed on campus.
Small role of purchased electricity (–)	Reliance on renewables in Quebec’s electrical grid.	Hydroelectricity reduces Scope 2 emissions.	Inferred reduction effect of 17%–21% assuming average US eGrid emission factors instead of the current energy mix in Quebec.
Relatively small role of commuting (–)	Dense urban setting, walkability and plentiful public transit options, often powered by hydroelectricity or biodiesel.	Large % mode share of walking/biking/transit and low % of car travel reduces Scope 3 emissions for students.	Inferred reduction effect of 2%–3% assuming ~30% car commuting by students.
Large role of wastewater (+)	Municipal combined overflow sewage system with primary treatment and incineration of sludge.	Effective lack of N removal by central treatment system increases Scope 3 emissions.	Inferred increasing effect of 11%–13% assuming 25% N removal with beneficial reuse of sewage sludge instead of incineration.

^a A multiplication factor of ~2.5 times the current food production N footprint is used for McGill, which results in a per capita food production N footprint of 1.8 kg N capita FTE⁻¹ yr⁻¹. This assumes that the current food mix is held constant (i.e. no change in the types of foods being sold) but that there is an increase in the volume of food services controlled directly by the university (see SI text for details). For UdeM, we apply the same per capita food production footprint as in McGill’s scenario (above) to UdeM’s population to mimic a situation with more residential student dining halls, more full meals (and animal products), as well as a larger share of food services controlled directly by the university.

contribution primarily to local NO_x emissions compared to McGill by about 2.6 t N yr⁻¹, possibly due to its location outside of the central business district and larger local student population. McGill also has parking policies that restrict permits for those living in close proximity to the University (personal communication, Jo-Anna Sciampone, McGill Parking

Manager). Limited data for McGill’s directly financed ground transportation also results in a considerable discrepancy; assuming that McGill has a similar proportion of N release for directly financed ground transportation in total directly financed travel as that of UdeM (i.e. 50% ground, 50% air), it’s footprint would be about 1.6 t N yr⁻¹ higher.



3.3. Urban geographic context drivers of institutional footprints

Both Montréal universities have much lower per capita N footprints than US universities with published N footprint values (from 7 to >25 kg N per full time student; Castner *et al* 2017). This is largely due to the very small scope 2 emissions with hydroelectricity and the limited role of food services, which we attribute to geographic context with university locations in a dense city with plentiful off-campus food options and modest campus residential student populations. In table 4, we compare the two Montréal university N footprints in this study to three universities with comparable overall populations. Of these, two are in much smaller cities (Charlottesville and Fort Collins, USA) that have a large share of coal in their fuel mix, which considerably elevates their total and per capita N footprints compared to the Montréal universities, despite having much higher rates of N removal in wastewater treatment. The University of Melbourne, Australia, is located in a city of similar size to Montréal, with a total and per capita N footprint similar to that of the Montréal universities (i.e. 139 t N yr⁻¹ and 2.6 kg N per capita). Liang *et al's* (2018) assessment of the University of Melbourne N footprint found that electricity generation represented 29% of the total given use of fossil fuels (e.g. brown coal) compared to just 3% for the food consumption component due to secondary wastewater treatment; however, their study

omitted non-local student travel despite a student population that is 36% international (University of Melbourne 2018).

Our N footprint comparison illustrates how geographic and institutional context interact with system boundaries of the analysis in complex ways to affect institutional N footprints. Both of the Montréal universities considerably lower N footprints than would be likely if located in a different geographic context, such as in a rural or suburban area with higher residential student populations, or in a region with a lower share of renewables in the electrical grid. We examine these effects based on the counterfactual scenarios described next (table 3).

3.3.1. Campus food services

Based on a simple counterfactual scenario where each university is assumed to have a more widespread direct role in the total food intake on campus, the N footprint of McGill would be 40.7 t N yr⁻¹ greater and UdeM's would be 70.6 t N yr⁻¹ greater. We therefore interpret that the current campus food service arrangements reduce the theoretical potential institutional N footprints for McGill and UdeM by 29% and 68%, respectively. Of the seven initial US colleges and universities with N footprint calculations using NFT methodology, all have much higher shares of food production in their totals (Castner *et al* 2017) likely given a greater role of the institutions in food services

and higher proportions of students living in campus residence.

3.3.2. Utilities

Assuming a counterfactual scenario where the electricity purchased by McGill and UdeM is sourced with the US average energy mix, McGill's N footprint would be 22.4 t N yr⁻¹ greater and UdeM's 17.6 t N yr⁻¹ greater—meaning that the reliance on renewables in purchased electricity reduces McGill's and UdeM's footprint by 17% and 21%, respectively. Therefore, access to hydroelectricity effectively reduces the Montréal university N footprints relative to contexts with lower shares of renewables in the electricity grid.

3.3.3. Commuting

A large share of students at both Montréal universities commute via active transportation (walking or cycling) or via subway, powered by hydroelectricity. We expected that this would reduce the footprints of both universities relative to a setting where there is more car commuting. For example, in their comparison of the N footprint for seven US universities and colleges, Castner *et al* (2017) found per capita commuting values around 1 kg N per FTE student for institutions in less dense urban or suburban settings compared to our estimates of 0.22–0.23 kg N per FTE student at McGill and UdeM. In our counterfactual scenario for commuting, we therefore assume that students commute with the same mode share as faculty (e.g. ~30% car mode share instead of the actual ~8% car mode share for students, with lower active transport mode shares). Contrary to our expectations, in this scenario reflecting a context where students have less access to public and active transit options, the Montréal university N footprints would be only ~2%–3% greater (~3.1 t N yr⁻¹ for McGill and ~1.4 t N yr⁻¹ for UdeM). The effect of urban context on N footprints due to commuting is likely relatively small as long as car mode share is held at a moderate level.

3.3.4. Wastewater treatment

Our final counterfactual scenario addresses the effect of beneficial recycling of N from wastewater. If ~25% of N were captured in the wastewater treatment plant and recycled to, for example, agricultural lands instead of lost to the atmosphere via incinerated sewage sludge, it would offset McGill's N footprint by ~12.6 t N yr⁻¹ and UdeM's by ~8.8 t N yr⁻¹. We therefore infer that wastewater increases our institutional N footprints by 11%–13% relative to a municipal context with basic aerobic wastewater treatment focused on reducing reactive N losses to the environment. However, this is not an ambitious scenario, as municipal wastewater treatment plants with tertiary treatment remove as much as 90% of reactive N and involve complete denitrification to inert N₂ gas (Oleszkiewicz *et al* 2015).

3.4. Complexities of institutional system boundaries for N footprints

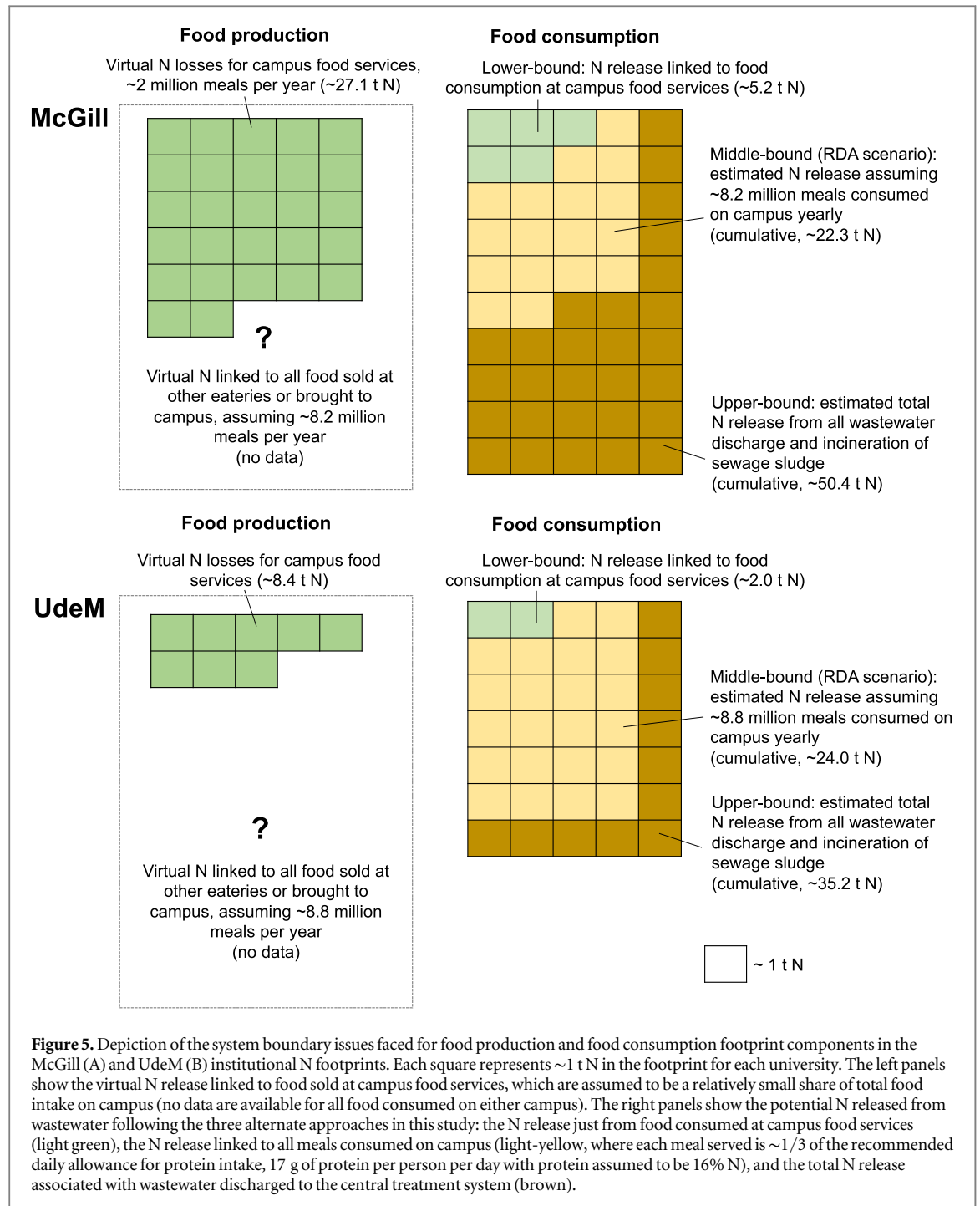
Food and wastewater are the single largest fluxes in McGill's N footprint, but our counterfactual scenario for food production indicates that the food component is likely heavily reduced since the university controls only a fraction of food consumed on campus. While wastewater is also the largest flux for UdeM, the university oversees an even smaller fraction of all food theoretically consumed on-campus. Therefore, N discharged in wastewater at both universities likely results in large part from food that was sourced from off-campus or from food services not controlled by the institutions. Figure 5 illustrates the mismatch between the food production and wastewater system boundaries. Comparison of our three wastewater N scenarios shows the strong effect of McGill's residential student population in the per capita discharge scenario (~50.4 t N yr⁻¹) compared to limiting wastewater N to excretion from food consumed at university-run food services (~5.2 t N yr⁻¹); at UdeM, its larger overall campus population drives a much larger value (~24.0 t N yr⁻¹) in the protein intake (RDA) scenario compared to food consumed at university-affiliated food services (~2.0 t N yr⁻¹).

Institutional N footprints were developed for US universities and colleges that often have a large proportion of students living in residence. While both Montréal universities have students in residence, UdeM's >1000 residential students mostly prepare their own food while McGill's >3000 residential students have mandated meal plans (table S1). The use of scope 3 scenarios that estimate all food consumed on campus by the university population regardless of the direct institutional involvement may therefore ensure fairer comparisons with universities in diverse contexts. While the Montréal universities source purchased electricity from renewable sources historically subsidized by the provincial government that reduce NO_x and N₂O emissions, the absence of effective N removal in wastewater treatment by the municipal government results in tradeoffs in terms of N release to the environment that influence potential damage costs (i.e. riverine N inputs and atmospheric N₂O emissions).

To assess the potential to mitigate N losses linked to activities at McGill and UdeM, we categorized each of the components according to the degree of institutional control versus the potential for additional change in N footprints (figure 6). Scope 3 components have the greatest potential to reduce the N footprints of these Montréal universities, since emissions related to purchased utilities are already small in Québec. UdeM has considerable opportunity to increase composting, with a moderate mitigation potential, while both universities could further address academic travel (e.g. through tele-conferencing or shifting short-haul flights to rail). Both universities are currently undertaking new initiatives that could affect their

Table 4. Comparison of N footprints for a set of universities with populations >30 000 (full-time students and staff). The fraction of students in residence was estimated based on publicly available statistics for each university.

University	City	kg N per capita yr ⁻¹ (FTE population)	Main driver of N footprint	Fraction of students in residence	Utilities	Wastewater	Boundary issues potentially affecting the comparison
<i>Université de Montréal (UdeM)</i> (this study)	Montréal, Canada	1.6	Wastewater (48%), commuting (16%), non-local travel (15%), and food (11%)	Small	>95% hydroelectricity	Zero net-removal (~20%–25% N removal from initial primary treatment followed by sludge incineration)	Hospitals and professional schools excluded.
<i>McGill University</i> (this study)		3.3	Wastewater (42%), food production (22%) and agriculture (9%)	Moderate			Hospitals and field centers excluded; some student apartments excluded; animal feed-related N release omitted.
<i>University of Melbourne</i> (Liang <i>et al</i> 2018)	Melbourne, Australia	2.6	Food production (37%), utilities (32%), and business travel (27%)	Small	Fuel mix includes brown coal, natural gas, oil, and renewables	~73% N removal (second- ary treatment)	Does not include non-local student travel.
<i>Colorado State University</i> (Kimiecik <i>et al</i> 2017, Castner <i>et al</i> 2017)	Fort Collins, USA	9.1	Agriculture (49%), food production (11%), utilities (10%)	Moderate to large	Fuel mix mostly coal, small share of natural gas	~92% N removal (tertiary treatment)	Does not include non-local student travel. More detailed treatment of livestock emissions than in McGill's footprint.
<i>University of Virginia</i> (Leach <i>et al</i> 2013, Castner <i>et al</i> 2017)	Charlottesville, USA	12.4	Utilities (52%) and food production (34%)	Large	Fuel mix contains a large share of coal	~42% N removal	Hospital included. Does not include non-local student travel.

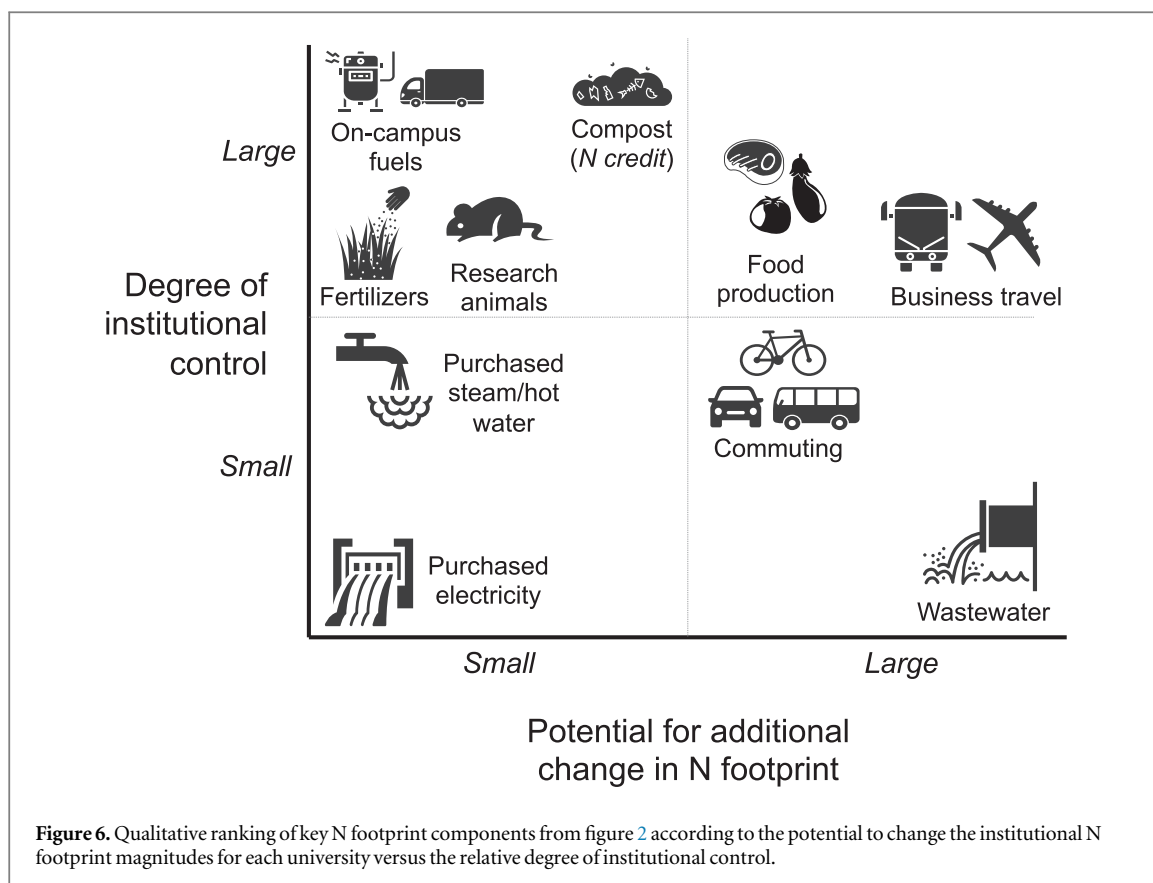


absolute and relative N footprints: for example, in 2019 UdeM opened a new LEED-certified campus (the MIL Campus) and McGill is currently redeveloping a former hospital site into a new sustainability research hub (the New Vic). McGill has also committed to becoming carbon-neutral by 2040 (McGill Office of Sustainability 2017) and UdeM by 2050, which could have synergies for reducing N_2O and NO_x emissions. Future research on the effects of institutional context should explore how university structure and governance affect N footprints and mitigation potential, including via sustainability commitments under frameworks such as the AASHE STARS system, which also differ among UdeM and McGill. A detailed

consideration of how these universities can learn from each other and partner to make an impact on each other's N footprints warrants more systematic consideration, particularly as each school continues to adopt new sustainability strategies.

4. Conclusions

We identified institutional and geographic factors that affect the relative and absolute N footprints of the two major Montréal universities. McGill's larger N footprint is mainly due to its greater share of residential and international students compared to UdeM



(affecting the number of meals served at campus cafeterias, wastewater discharge, and air travel, respectively) as well as the presence of a research farm. While these university-specific factors shape many N losses under the university's control, geographic factors typically beyond the university's control have an overarching influence by either reducing or increasing the N footprints. Our findings therefore highlight that while N footprints are useful campus sustainability benchmarks, inter-university comparison is challenging due to the strong effect of geographical setting and system boundaries on scope 2 and 3 emissions.

Higher-education institutions can play an important role in sustainability efforts, for which the N footprint represents one example. Estimating how much of an individual consumer's per capita N footprint (Leach *et al* 2012) is accounted for within an institution's N footprint could allow for investigation of the mitigating potential of alternative scenarios (e.g. the effects of students living on-campus versus off-campus). When comparing institutional N footprints, consideration of the role of universities in food consumption on campus, residential student population, wastewater treatment, and the degree of renewables in utilities should be considered. Our analysis also stresses how a university's international ties that may represent a strength academically can also increase its N footprint—in particular, the share of international students and degree of international research travel

that drive NO_x emissions for air travel. With a community equal to roughly 5% of the City of Montréal's population, our case study of these urban universities can also inform efforts that institutions can make toward reducing city-level N footprints.

Acknowledgments

We thank the many individuals at McGill and Université de Montréal who provided information or resources necessary for the N footprint calculations, including: Stéphane Béranger, Lama Boustani, Julie Chevette, Jerome Conraud, Thierry Gras-Chouteau, Kalyna Kruczowyj, John Lindsay, Ali Rivers, Suzanne Smith, Luc Surprenant, and Oliver de Volpi. Allison Leach and Tony Di Fruscia provided helpful guidance on specific calculations. Funding was provided by the Trotter Institute for Science and Public Policy (TISPP), the McGill Sustainability Systems Initiative (MSSI), the *Unité du Développement Durable* (sustainable development unit) at Université de Montréal, and the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grants program.

Data availability statement

Any data that support the findings of this study are included within the article.

ORCID iDs

Graham K MacDonald  <https://orcid.org/0000-0002-7120-1366>

Julie Talbot  <https://orcid.org/0000-0002-1417-2327>

Tim R Moore  <https://orcid.org/0000-0001-7472-7569>

Julien Arsenault  <https://orcid.org/0000-0002-7840-1838>

Sibeal McCourt  <https://orcid.org/0000-0003-1850-9932>

Aidan Goertzen  <https://orcid.org/0000-0003-1520-3735>

Kevin Manaugh  <https://orcid.org/0000-0003-2975-030X>

Roxane Maranger  <https://orcid.org/0000-0002-2509-4678>

Brian E Robinson  <https://orcid.org/0000-0002-8972-8318>

References

- Amaral LP, Martins N and Gouveia JB 2015 Quest for a sustainable university: a review *Int. J. Sustain. Higher Educ.* **16** 155–72
- Arsenault J, Talbot J, Boustani L, Gonzales R and Manaugh K 2019 The environmental footprint of academic and student mobility in a large research-oriented university *Environ. Res. Lett.* **14** 095001
- Board of Trade of Metropolitan Montréal 2016 The Contribution of Greater Montréal Universities to the Québec Economy *Report* Chamber of Commerce of Metropolitan Montréal/Montréal International pp 68
- Canadian Water Network 2018 Canada's Challenges and Opportunities to Address Contaminants in Wastewater *National Export Panel Report* Canadian Water Network pp 76
- Castner E A *et al* 2017 The nitrogen footprint tool network: a multi-institution program to reduce nitrogen pollution *Sustain.: J. Rec.* **10** 79–88
- Colding J and Barthel S 2017 The role of university campuses in reconnecting humans to the biosphere *Sustainability* **9** 2349
- Compton JE, Harrison JA, Dennis RL, Greaver TL, Hill BH, Jordan SJ, Walker H and Campbell HV 2011 Ecosystem services altered by human changes in the nitrogen cycle: a new perspective for US decision making *Ecol. Lett.* **14** 804–15
- Compton JE, Leach A M, Castner E A and Galloway J N 2017 Assessing the social and environmental costs of institution nitrogen footprints *Sustain.: J. Rec.* **10** 114–22
- Centre de référence en agriculture et agroalimentaire du Québec (CRAAQ) 2010 *Guide de référence en fertilisation* 2nd edn, ed L-E Parent and G Gagné (Québec QC: Centre de référence en agriculture et agroalimentaire du Québec) pp 473
- Einarsson R and Cederberg C 2019 Is the nitrogen footprint fit for purpose? An assessment of models and proposed uses *J. Environ. Manage.* **240** 198–208
- Elrys A S, Raza S, Abdo A I, Liu Z, Chen Z and Zhou J 2019 Budgeting nitrogen flows and the food nitrogen footprint of Egypt during the past half century: Challenges and opportunities *Environ. Int.* **130** 104895
- Environment and Climate Change Canada 2019 *National Inventory Report 1990–2017: Greenhouse Gas Sources and Sinks in Canada*. (Gatineau, QC: Environment and Climate Change Canada)
- Fonseca A, Macdonald A, Dandy E and Valenti P 2011 The state of sustainability reporting at Canadian universities *Int. J. Sustain. Higher Educ.* **12** 22–40
- Fowler D *et al* 2013 The global nitrogen cycle in the twenty-first century *Phil. Trans. R. Soc. B* **368** 20130164
- Galloway J N, Aber J D, Erisman J W, Seitzinger S P, Howarth R W, Cowling E B and Cosby B J 2003 The nitrogen cascade *Bioscience* **53** 341–56
- Galloway J N, Winiwarter W, Leip A, Leach A M, Bleeker A and Erisman J W 2014 Nitrogen footprints: past, present and future *Environ. Res. Lett.* **9** 115003
- GHG Protocol 2004 *The Greenhouse Gas Protocol: a Corporate Accounting and Reporting Standard* (Washington, DC: World Resources Institute and World Business Council for Sustainable Development)
- Government of Canada 2019a Canadian Climate Normals. (https://climate.weather.gc.ca/climate_normals/index_e.html)
- Government of Canada 2019b Air Pollutants Emissions Inventory online search. (<https://pollution-waste.canada.ca/air-emission-inventory/>)
- Gruber N and Galloway J N 2008 An Earth-system perspective of the global nitrogen cycle *Nature* **451** 293
- Guo M, Chen X, Bai Z, Jiang R, Galloway J N, Leach A M, Cattaneo L R, Oenema O, Ma L and Zhang F 2017 How China's nitrogen footprint of food has changed from 1961 to 2010 *Environ. Res. Lett.* **12** 104006
- Hydro-Québec 2018 Hydro-Québec's Electricity Facts: Electricity Supply and Air Emissions *Report* Hydro-Québec, Montréal QC pp 2
- Hydro-Québec 2019 Breakdown of a household's electricity use. (<http://hydroquebec.com/residential/customer-space/electricity-use/electricity-consumption-by-use.html>)
- Institut de la statistique du Québec (ISQ) 2019 Superficie des grandes cultures, rendement à l'hectare et production, par regroupement de régions administratives, Québec, 2007–2019. (stat.gouv.qc.ca/statistiques/agriculture/grandes-cultures/grandes-cultures-2007-2019.html#tri_cult=10)
- Keeler B L, Gourevitch J D, Polasky S, Isbell F, Tessum C W, Hill J D and Marshall J D 2016 The social costs of nitrogen *Sci. Adv.* **2** e1600219
- Kimiecik J, Baron J S, Weinmann T and Taylor E 2017 Adding a nitrogen footprint to Colorado State University's sustainability plan *Sustain.: J. Rec.* **10** 89–95
- Leach A M, Galloway J N, Bleeker A, Erisman J W, Kohn R and Kitzes J 2012 A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment *Environ. Dev.* **1** 40–66
- Leach A M *et al* 2013 Toward institutional sustainability: a nitrogen footprint model for a university *Sustain.: J. Rec.* **6** 211–9
- Leip A, Weiss F, Lesschen J P and Westhoek H 2014 The nitrogen footprint of food products in the European Union *J. Agric. Sci.* **152** 20–33
- Liang X, Leach A M, Galloway J N, Gu B, Lam S K and Chen D 2016 Beef and coal are key drivers of Australia's high nitrogen footprint *Sci. Rep.* **6** 39644
- Liang X, Ng E L, Lam S K, Castner E A, Leach A M, Gu B, Healey G, Galloway J N and Chen D 2018 The nitrogen footprint for an Australian university: institutional change for corporate sustainability *J. Clean. Prod.* **197** 534–41
- McGill Office of Sustainability 2017 *Vision 2020 Climate & Sustainability Action Plan* (Montréal QC: McGill University) pp 29
- Oleszkiewicz J A and Barnard J L 2006 Nutrient removal technology in North America and the European Union: a review *Water Qual. Res. J.* **41** 449–62
- Oleszkiewicz J, Kruk D and Devlin T 2015 Options for improved nutrient removal and recovery from municipal wastewater in the Canadian context *Report* Canadian Water Network (<http://cwn-rce.ca/project/options-for-improved-nutrient-removal-and-recovery-from-municipal-wastewater-in-the-canadian-context/>) pp 563
- Pierer M, Winiwarter W, Leach A M and Galloway J N 2014 The nitrogen footprint of food products and general consumption patterns in Austria *Food Policy* **49** 128–36
- Rivers A and Conraud J 2018 *McGill Greenhouse Gas Inventory: Reporting year 2017*. (Montréal, QC: McGill University) pp 48

- Shaw E, St-Louis E, Manaugh K, van Lierop D, Stewart C and El-Geneidy A 2013 *Findings from the 2013 McGill commuter survey* (Montréal QC: Transport Research at McGill, TRAM) pp 136
- Shibata H, Cattaneo L R, Leach A M and Galloway J N 2014 First approach to the Japanese nitrogen footprint model to predict the loss of nitrogen to the environment *Environ. Res. Lett.* **9** 115013
- Shibata H *et al* 2017 Nitrogen footprints: Regional realities and options to reduce nitrogen loss to the environment *Ambio* **46** 129–42
- Sobota D J, Compton J E, McCrackin M L and Singh S 2015 Cost of reactive nitrogen release from human activities to the environment in the United States *Environ. Res. Lett.* **10** 025006
- Statistics Canada 2017 *Profiles of a community or region: 98-316-X2016001. Census Profile, 2016. Census Montréal, Territoire équivalent [Census division], Quebec* (Statistics Canada, Ottawa ON)
- Statistics Canada 2019 Table 25–10–0020–01 Electric power, annual generation by class of producer (<https://doi.org/10.25318/2510002001-eng>)
- Steffen W 2015 Planetary boundaries: Guiding human development on a changing planet. *Science* **347** 6223
- Stevens C J, Leach A M, Dale S and Galloway J N 2014 Personal nitrogen footprint tool for the United Kingdom *Environ. Sci.: Process. Impacts* **16** 1563–9
- Université de Montréal, HEC Montréal & Polytechnique Montréal 2013 *Diagnostic de mobilité durable: Campus de l'Université de Montréal*. (Montréal, QC: HEC Montréal, Polytechnique Montréal, Université de Montréal) pp 137
- University of Melbourne 2018 *The University of Melbourne 2017 Annual Report* (Melbourne, The University of Melbourne) pp 81
- Vanham D *et al* 2019 Environmental footprint family to address local to planetary sustainability and deliver on the SDGs *Sci. Total Environ.* **693** 133642
- Vélo Québec 2016 *L'état du vélo à Montréal en 2015* (Montréal QC: Vélo Québec) pp 16
- Withycombe Keeler L, Beaudoin F, Lerner A, John B, Beecroft R, Tamm K, Wiek A and Lang D 2018 Transferring sustainability solutions across contexts through city–university partnerships *Sustainability* **10** 2966