The Urban Metabolism of the Greater Toronto Area: A Study of Nitrogen and Phosphorus Fluxes across the Urban, Suburban, and Rural Continuum

by

Melani-Ivy Samson

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Author’s Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

I acknowledge Dr. Kimberly Van Meter and Dr. Nandita Basu as my co-authors who both contributed to this research and helped guide its vision. Dr. Kimberly Van Meter aided with the management and interpretation of data as well as the development of figures. Dr. Nandita Basu provided her insight with the writing of the thesis.

Abstract

It has been predicted that approximately 65% of the developing world and 85% of the developed world will be living in cities by 2050. Toronto, the largest city in Canada and the fourth largest in North America, is expected to double in population in the next 50 years. Although such rapid urbanization can lead to enormous social, economic, and environmental change, little is understood about how population growth in Toronto and the surrounding area will impact the ecological systems of Southern Ontario. In our study, we are particularly interested in the ways in which increasing population densities in the Greater Toronto Area (GTA) are impacting nutrient flows (nitrogen and phosphorus) across Southern Ontario's urban/rural continuum and how changing nutrient dynamics may lead to increasingly impaired water quality in Lake Ontario and beyond.

In this work, we utilize a mass balance and metabolism approach to quantify the flow of nutrients through urban, suburban, and agricultural areas of the GTA. A wide range of factors are considered, including human behaviour, domestic animals, stormwater management, and wastewater treatment processes. We found urban nutrient flows to be distinctly different from agricultural flows, with combined sewer overflows, pet waste and lawn fertilizers emerging as significant components. The present results suggest that any study of urban metabolism must take into account not only nutrient flows within urban boundaries, but must also identify externalities of urban development associated with a range of processes, from global trade to regional waste management.

The nutrient budgets were then used to identify ways in which nutrient movement within the GTA could be optimized to minimize environmental impacts. The results highlight that if the GTA implemented better composting and manure application combined with biosolid reuse, it is possible to eliminate all needs to import fertilizer. The population needs exceed agricultural production values in this region and this only further highlights the importance of safeguarding current agriculture lands through legislations such as those which led to the Greenbelt.

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1 Introduction

"In the twenty-first century, it is becoming increasingly apparent that whether we consciously address it or not, human cultures and societies are entangled with what was once called nature."

- Holm et al. (2016)

1.1 Background: Humans and the Environment

Humans play an important and influential role in the management of the Earth's resources and the preservation of the environment. In fact, the rapid increase in population calls for a higher demand for food and has induced stress on the environment, biodiversity, and ecosystems (The Economist 2011; Nellemann et al. 2009). In turn, it is estimated that the breakdown of the environment caused by factors such as extensive farming and the exacerbation of climate change, may cause our global food production to decrease by 25% (Nellemann et al. 2009). Indeed, we have entered the age of the anthropocene in which humans are the driving factor behind global changes, particularly to the environment (Holm et al. 2016). Since the 1750s, we have experienced a 40% increase in carbon dioxide emissions, over 20% loss in mean species abundance globally, and have entered into a high-risk position with the mismanagement of biogeochemical flows with respect to the natural environment ("The Anthropocene | Great Acceleration" 2012). In many cases, we have gone beyond the Earth's carrying capacity to properly sustain itself and the degree of our perturbation of natural conditions have drastically altered landscapes, biodiversity, as well as water and air quality (The Economist 2011).

An often disregarded aspect of environmental conditions is the mining and management of nutrients such as nitrogen (N) and phosphorus (P). Humans have accelerated the bioavailability of N and P, especially through the manufacture of synthetic fertilizer to provide for a growing population (Goyette et al. 2016; Roy, White, and Seibert 2014; Law, Band, and Grove 2004; Scholz et al. 2013). Anthropogenic disturbance has sped up the N cycle by 150% and has become one of the primary concerns to human well-being and safety (The Economist 2011; Sebilo et al. 2013; Galloway et al. 2008). Similarly, the management of P is seen as a "paradox"; due to a finite reserve of global P concentrated in a few countries, while increases in intensive agriculture and other demands have resulted in an excess of P in receiving water bodies (Roy, White, and Seibert 2014; G. S. Metson et al. 2012; Cordell, Drangert, and White 2009). In fact, approximately 90 % of globally mined P is designated for food production and 7% for detergents (Prud'Homme 2010; Liu et al. 2008; University of the West of England, Science Communication Unit 2013). The depleting sources of P poses great concern for future food availability and it is predicted that continued mining will yield lower quality phosphate rock at higher prices which would inevitably effect poorer farmers first (Cordell, Drangert, and White 2009; Scholz et al. 2013).

Mismanagement of nutrients has raised concern regarding increasing eutrophication to nearby waterbodies. Eutrophication is the results of the growth of harmful algae blooms in abundance driven by the presence of excess nutrients, N and P (Glibert and Burkholder 2011). This poses a threat to water quality which in turn negatively impacts biodiversity and human activities, such as fishing (Roy, White, and Seibert 2014; Glibert 2017). For freshwater lakes, it has long been surmised that P is the limiting nutrient driving eutrophication (Schindler 1977). There is increasing evidence that N and P must both be carefully managed to tackle the issue of eutrophication (Peñuelas et al. 2013; Paerl et al. 2016; Goyette et al. 2016; Glibert 2017).

1.2 Cities: The Construction of "Landscapes of Consumption"

"Cities are intricate and messy, moulded by countless influence."

- Robert E. Millward (1992)

The world is rapidly evolving and people are choosing to live closer together in cities (Hiller 2010). Urbanization is defined as a transformative process involving socioeconomic and land-use changes that alter the traditional concept of society to that of a more modern metropolitan one (Atta-ur-Rahman et al. 2016). There is an increasing trend towards urbanization and it is it is suspected that almost 70% of the global population will reside in urban areas by 2050 (Population Reference Bureau 2016; Templer et al. 2015). Globally, we have the emergence of "megacities" which is defined as a city populated with more than 10 million people (Zhao et al. 2017). An increasing number of cities are growing in population and earning this status, and so we start to view each city as a "landscape of consumption" (Hiller 2010). There is a stark difference between urban and rural areas in terms of factors such as population density, physical characteristics of the environment, and the contrast in production and consumption. It is of no surprise that these massive cities function differently than other landscapes.

Cities are a hub for a large influx of imported food from regional and international sources, with trade being the major facilitator for the flow of nutrients to cities (Sahely, Dudding, and Kennedy 2003; Lassaletta et al. 2014). Even though a small percentage of food consumed within a city may be grown locally, a much larger portion tends to be imported from distant sources (Hiller 2010). Beyond the physical nutrient flow, there are economic and social issues that stem from food production and consumption. For example, when food is grown in locations that are water or nutrient deficient, the nutrient or water footprint of these commodities can be quite high and unsustainable for certain nations (Grönman et al. 2016; Joensuu et al. 2019). However, this process is driven by factors such as the economy and consumer demand from nations that are affluent (Joensuu et al. 2019; Lassaletta et al. 2014). The influx of food from trade further emphasizes the disconnect between consumers and producers (Lassaletta et al. 2014). Consumers are primarily concentrated in cities and may not be fully aware of the origins of their imports nor their associated footprints, thus creating further ignorance to the issue of social and resource disparity.

Cities are characterized by a number of key features that give them a “distinct urban biogeochemistry” (Kaye et al. 2006) and their physical processes must be considered differently than rural or more pristine conditions (Carey et al. 2013). Firstly, the built-up areas in cities are primarily impervious and generate higher magnitudes of runoff that leads to the faster transport of nutrients such as fertilizer applied on residential lawns and pet waste (Pataki et al. 2011; Hobbie et al. 2017; Law, Band, and Grove 2004). Most urban areas have developed in an ad hoc manner over time, without an overarching plan or full consideration of the entire natural and manufactured system (Hiller 2010; Paul and Meyer 2001). For example, sewer systems and roads were historically constructed to handle water quantity and solid waste with little regard for water quality as these areas were designed to manage standard pooling and floods with the goal of clearing water quickly (Meakin 1993). Storm sewers act as a quick conveyance for water, nutrients, and other materials to outlets such as rivers, lakes, and wastewater treatment plants

(WWTPs). Bernhardt et al (2017) have identified storm sewers to be a “transport control point” in urban landscapes because they play an important role in rapidly moving critical biogeochemical elements or concealing fixed spots of high nutrient activity. Moreover, WWTPs are constructed to manage the waste for large and densely compacted populations, and the outlet of these facilities act as point sources for N and P (Kaye et al. 2006; G. S. Metson and Bennett 2015). The WWTPs act as its own separate subsystem with processors that vary in their ability to remove and reuse nutrients, as well as the quantity it releases. Their inefficiency is an important factor in establishing a city’s ability to manage nutrients.

Furthermore, creating a “landscape of consumption” sets cities up to manage a large amount of waste (Hiller 2010). Landfills are key urban features that are constructed to remove waste from main residential, commercial, and industrial areas (Forkes 2007). This could create a disconnect from the point of waste production to disposal in landfills and residents may be less mindful of the potential circularity of their waste. In fact, it was estimated by Lind et al. (2001) that recycling domestic waste has the potential to reduce commercial fertilizer by 35-45%. One could argue that urban systems, such as these storm sewers and landfills, were not constructed with nutrient management in mind, but rather for flood mitigation and the efficient handling of physical waste.

1.2.1 The Rural-Urban Collaboration

Most of today’s cities were constructed many years ago and often beside a large, connecting body of water. Cities were historically built beside waterways to facilitate trade and sustain agricultural development (G. Metson, Aggarwal, and Childers 2012; Millward 1992). With an more people moving to cities, these urban areas continue to grow and sprawl outwards. As a result of cities’ great influx of nutrients and their ability to act as conduit to waterways, location beside important and clean water sources is a major issue.

As the city has become more distinct, there is evidence of a relationship development between rural and urban areas. Urban areas tend to be less involved in food production, and instead engage in remote work that can be tightly compacted in buildings and offices; this is a response to a world that is becoming increasingly globalized and connected through rapidly improving technology (Hiller 2010). The migration from rural to urban areas has increased significantly in the last 50 years. In Canada, we see an increasing trend towards urbanization (**Figure 1**), rapidly accelerating after World War II (Statistics Canada 2015). This mass exodus did not forge a divide between the urban and rural areas, but instead created an interdependent relationship or a "rural-urban collaboration" (Hiller 2010). Hiller (2010) describes this phenomenon as when the rural areas provide for the urban areas and external markets, while the urban areas facilitate the trade between rural and outside areas. The emergence of the suburban area is another interesting component in a city's development. There are many different definitions to each of these terms, but generally speaking, the suburban area is characterized by lower density housing coupled with larger green spaces than that of the urban area (Forsyth 2012). In many city configurations, one may see a unique feature for which there is an urban core, surrounding suburbs, and rural, agricultural, and forested outskirts (G. Metson, Aggarwal, and Childers 2012; Sahely, Dudding, and Kennedy 2003). There can also be configurations that are more heterogeneous with multiple smaller urban centers sprouting across a region, which has been further facilitated by improvements in transportation (Forsyth 2012).

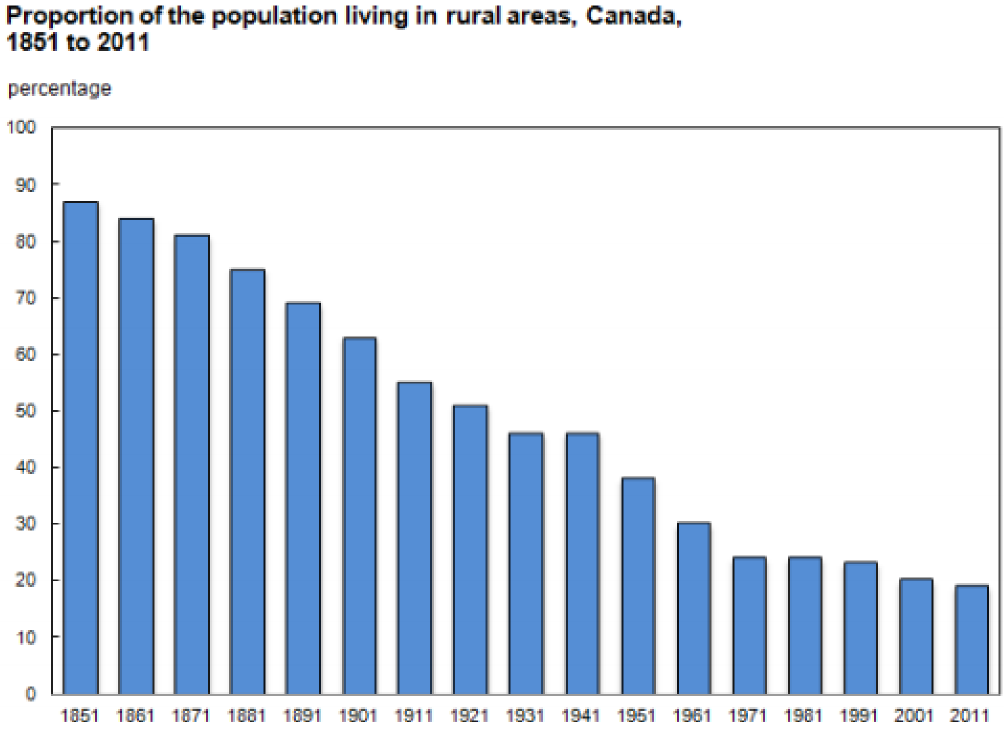

Figure 1: A chart of the proportion of the population living in rural areas in Canada from 1851 to 2011 (Statistics Canada 2015). Note: The data shown between 1851 to 1951 represent the definition of rural used during this time.

The abovementioned collaboration effect can be seen on a global platform. There are set trade agreements to safeguard the rural-urban relationship across international platforms. Furthermore, we see this collaboration echoed in the safeguard of green spaces in growing urban areas. For instance, in the Greater Toronto Area (GTA), the Greenbelt was established in 2005 to protect farmland and sensitive environmental areas from further urban development (Government of Ontario 2017). The Greenbelt has impeded further development and drastic land use changes in this designated area (Government of Ontario 2017). A similar initiative exists in New York City with the establishment of Central Park, one of the most visited urban parks in the United States. In 1876, the park opened as a response to the city's rapid urbanization, and New York is currently listed as the fourth biggest megacity in the world ("Central Park: Description, History, Attractions, & Facts" 2018; Zhao et al. 2017). The establishment of Central Park creates a rare contrast in the landscape of the city as it is a large greenspace surrounded by densely packed skyscrapers.

1.2.2 The Study of Urban Metabolism

Wolman (1965) first coined the term "urban metabolism" in the hopes of characterizing key flows and areas of concern within a city. A typical urban metabolism study encompasses the fluxes of water, material, energy, and wastes in and out of the system (Sahely, Dudding, and Kennedy 2003). It uses mass or material balances to improve understanding of the inputs, outputs, and internal processing of the applicable components to identify important system drivers (Zhang 2013; Sahely, Dudding, and Kennedy 2003). The number of urban metabolism studies has picked up in recent years, gaining popularity and recognition in the importance of its application (Beloin-Saint-Pierre et al. 2017; Kennedy, Pincetl, and Bunje 2011).

In the urban metabolism framework, the city is treated as an organism with its own metabolic processes for which materials are consumed and released by the city (Zhang 2013; Sahely, Dudding, and Kennedy 2003). The city itself contains various organisms (humans, animals, and their surrounding vegetation) as well as constructed subsystems (WWTPs and landfills) to manage its resources (Kennedy, Pincetl, and Bunje 2011; Beloin-Saint-Pierre et al. 2017). Cities display a relatively unsustainable management of energy and mass balance in comparison to natural systems that exhibit high efficiency of inputs (Kennedy, Pincetl, and Bunje 2011). As it stands, most cities function through a linear process with much of its input moving in one direction and headed to an irretrievable output (Wolman 1965; Zhang 2013). The movement of material and their recycling back into the system is described as a circular economy; cities typically demonstrate a low circular nutrient economy with much of the flows directed to landfill and waterbodies (Zhang 2013). Urban metabolism studies challenge this low degree of circularity and aim to suggest points of improvement in the city system.

1.3 Quantifying Nutrient Flows in Urban Landscapes

From a biogeochemical perspective, since cities should be treated differently than other landscapes, questions are raised on how nutrients should be quantified and how they are affecting neighbouring waterbodies. There have been many studies conducted globally that employ different methods other than urban metabolism to quantify nutrients such as mass balances, substance flow analysis (SFA), and net anthropogenic N or P input (NANI or NAPI; Baker et al. 2001; Brunner and Ma 2009; Hong et al. 2012). Even amongst these named methods, there are adaptations and inconsistencies in the manner in which they are carried out (Beloin-Saint-Pierre et al. 2017). The following section defines and describes the different types of nutrient studies that have been executed in the past.

Mass Balance Approaches

The mass balance approach is a popular method that quantifies and compares inputs and outputs to a closed system that can be as small as the human body or as large as whole continents (Organisation for Economic Co-operation and Development 2019; Boyer et al. 2002; Forkes 2007; Hobbie et al. 2017). Mass balance studies have been performed for many years and are typically conducted in rural and agricultural settings and watersheds (Cordell, Drangert, and White 2009; Hong, Swaney, and Howarth 2013; Peñuelas et al. 2013; Hale et al. 2015). This may leave a misrepresented understanding of nutrient flows because these patterns are not exactly reflected in urban areas. In fact, the first nutrient mass balance for a major urban city was conducted by Baker et al. (2001) for the Central Arizona-Phoenix ecosystem, and highlighted important human drivers of the N cycle. This study described the major influence humans have on their environment with 88% of the N inputs being a causal effect of both direct and indirect human actions.

Net Anthropogenic Nitrogen/Phosphorus Input

The NANI and NAPI methods extend from the mass balance study with distinct assumptions in the flow of N and P. The NANI methodology was first introduced by Howarth et al. (1996) to study areas draining into the North Atlantic Ocean at a relatively large scale. Other studies followed this procedure for other regions to understand the N storage/stocks and flows (Boyer et al. 2002; Hong, Swaney, and Howarth 2011), and NAPI became a popular addition following the same methodology (Hong, Swaney, and Howarth 2013; Goyette et al. 2016). The benefit of this approach is that it categorizes essential components such as human consumption and agriculture production that can be subsequently applied to diverse areas. However, one problematic and fixed assumption in the NANI/NAPI framework is that regional foods fulfill the needs of the local population before import or export. This assumption does not capture important trade dynamics in highly urbanized areas where a majority of foods are coming from outside the system.

Substance Flow Analysis

The SFA works in a similar fashion as mass balance studies, though it places more emphasis on the flow of substances through a system. The SFA is a subset of the more commonly known material flow analysis (MFA) which focuses on the movement of a specific chemical element or compound as opposed to materials that are tracked for economic purposes (Brunner 2012). The term MFA was first recorded by Santorio (1737) in his analysis of the human body (inputs, outputs, and stocks) and has since expanded to an urban context, especially with regard to waste management (Brunner and Ma 2009).

1.3.1 Themes of Nutrient Studies

"Only a doctor that knows the metabolism of a person is able to cure him."
- Santorio (1737), translated by (Brunner and Ma 2009)

Given the multitude of different nutrient studies conducted globally to assess the movement of N and P, we looked for commonalities between them. There is an overarching goal to better understand the dynamics of N and P, especially involving major urban cities, to help improve the condition of adjacent waterbodies and the natural environment. From those studies that are closely related to this work, we identified three main themes: (1) diminishing nutrient reserves call for higher circularity or recycling, (2) the importance of quantifying inputs and outputs to better inform decision makers with urban areas behaving very differently from their rural counterparts, and finally, (3) understanding the input, output, and flow changes over time and space for one location.

Theme 1: Diminishing reserves and higher circularity

As previously mentioned, as a result of the depletion of limited resources and the lack of circularity of those that are already mined, food security is expected to be of increasing concern (Cordell, Drangert, and White 2009). The motivation behind many nutrient studies was to identify potential points of circularity back into the system. There is particular concern surrounding an accelerated P deposit depletion that would increase the ratio of N and P in the environment thus creating biogeochemical imbalances (Peñuelas et al. 2013). Metson and Bennett (2015) stressed that understanding the stocks and movement of P (or nutrients in general) is key to managing it sustainably. The motivation of one particular study conducted by Álvarez et al. (2018) states that there is no phosphate rock in Spain and any fluctuation in the global availability of fertilizer would directly impact the country's agriculture and food security.

Theme 2: Urban cities require special analysis for better policy advising

There have been many nutrient studies that focus predominantly on agricultural areas, but it has become increasingly evident that the urban landscape should be studied and analyzed in a different manner. Nutrient studies are important in urban areas because they frequently have higher population densities across smaller given areas and thus act as "hot spots" or ecosystem control points for N and P (McClain et al. 2003; Bernhardt et al. 2017; G. Metson, Aggarwal, and Childers 2012; Kaushal and Belt 2012).

Urban cities have additional systems and "regulators", such as dams and WWTPs, that require different consideration (Hale et al. 2015). For example, many urban studies have identified waste disposal infrastructures as points of interests for better nutrient management. Food for humans and animals is the dominant component of N and P inputs within cities and therefore, an important flow path to monitor at start and end points (Forkes 2007; G. S. Metson et al. 2015).

Landfills act as a sink for nutrients and WWTPs process a large amount of nutrients from the residing population and industries. In cities, much of the resources move in a linear fashion to either lakes or landfills through WWTPs and waste management respectfully where they are not easily recoverable (Zhang 2013). Estimates of the nutrient masses going to landfills and WWTPs help to identify the quantities that have the potential to be reused for other purposes such as fertilizer (Treadwell, Clark, and Bennett 2018).

Urban areas are strictly managed by municipalities, and there is a need to both better inform policy makers and be proactive with the management of the city's environment. Goyette et al. (2016) highlighted the importance of identifying sources of high N and P input as a preventative measure to potentially better manage them before eutrophication and biodiversity issues arise. There is also potential to couple the urban and natural environment with mitigation strategies using bio-based solutions and to better regulate urban water pollution (Hobbie et al. 2017).

Theme 3: Changes in inputs, outputs, and flows across space and/or time

Most studies determine their areas of interest according to watershed or administrative boundaries. Watershed analyses are able to tie in the connection with riverine exports (Goyette et al. 2016). The studies completed based on administrative boundaries are typically those that examine major cities and were dominated by anthropogenic influences. There are few bodies of work that focus on nutrient flow from islands and these isolated land masses strongly establish the environmental boundaries when calculating the input and output of nutrients. A multitude of P studies were conducted in Montreal, Canada and an N and P study was completed in St. Eustatius located in the Caribbean that clearly defined the nutrient inputs and outputs coming out of these islands (G. S. Metson et al. 2015; Treadwell, Clark, and Bennett 2018; Firmansyah et al. 2017).

Some nutrient studies looked at changes of nutrient input, output, and interim processes across their areas of interest which varied in terms of time frame. Long term studies were able to capture distinct land use changes and the effect it has on nutrient movements (Goyette et al. 2016; Hale et al. 2015; G. Metson, Aggarwal, and Childers 2012). Even though many compared different time periods within the same space (Roy, White, and Seibert 2014), a few focused on a single annual analysis of N and/or P through their study sites and involved more of the intricacies of a major urban city (Álvarez et al. 2018; G. S. Metson et al. 2012).

1.4 The State of the Great Lakes: Canadian Perspective

The Great Lakes and its tributaries are vital freshwater sources for Canada and therefore important resources to protect (Environment and Climate Change Canada and the U. S. Environmental Protection Agency 2017). Eutrophication has been threatening the health of these waterbodies, specifically Lake Erie which is the shallowest and most southern amongst the five lakes (International Joint Commission and Lake Erie Ecosystem Priority 2014). In all five lakes, it was found that P was the limiting agent except for instances in Lake Ontario where overwhelming anthropogenic sources of P induce an N limitation during parts of the summer (Schindler 1977; Dove and Chapra 2015). The issue of harmful algal blooms has been on the radar for the last 50 years; in 1972, the binational Great Lakes Water Quality Agreement set out to combat P loads and it seemed conditions were improving (Environment and Climate Change Canada and the U. S. Environmental Protection Agency 2017). However, in 2011, Lake Erie had the largest algal bloom in its history and in response, the Lake Erie Ecosystem Priority project was formed to address problems of P enrichment that would only be further exacerbated by climate change and invasive species (International Joint Commission and Lake Erie Ecosystem Priority 2014).

There is now more attention than ever before on the effect of urban areas from a nutrient loading perspective. For Lake Ontario, there is evidence of a higher nutrient concentration in the lake adjacent to urban areas, perhaps due to the proximity of the WWTPs (Howell, Chomicki, and Kaltenecker 2012). In fact, the International Joint Commission designated Toronto as an area of concern to the Great Lakes in 1985 due its low water quality and impaired ecosystem functioning (Kidd 2016). Although remediation actions were set in place in 1994 and P input concentrations have decreased, this area is still listed as “impaired” in terms of eutrophication or undesirable algae (Kidd 2016). Moreover, it was noted that the Don Valley River, the largest tributary draining to Lake Ontario, was named the “most-messed-with” river in Canada as it runs right through the middle of Toronto, Canada’s biggest city (Bonnell 2014).

1.5 Objectives

The goal of this research is to identify key drivers and flows of N and P through a complete urban metabolism study of the GTA. We also analyzed the flow of N and P through the GTA's urban, suburban, and rural areas to understand the impact of both land use and population density on these nutrients. We suspect that the GTA's metabolism will reflect those of other major cities with heavy inputs stemming from food needs and evidence of little internal recycling. We hypothesize that the anthropogenic influence will dominate and drive the bulk of nutrient management through the system.

We attempt to answer the following questions:

1. Can we quantify the urban metabolism of the GTA? How are N and P processed in the urban, suburban, and rural subsystems of the GTA?
2. What is the GTA's footprint on soil, streams and lakes, and the external landscape surrounding it?
3. What are the opportunities for creating a more circular nutrient economy and reducing fluxes of nutrients to lakes and landfills in the GTA?

2 Methods

2.1 Study Site: The Greater Toronto Area

The Greater Toronto Area (GTA) is the biggest metropolitan region in Canada and is located along the shores of Lake Ontario, encompassing the City of Toronto as well as the suburban and the rural area surrounding it (**Figure 2**). It is over 7,000 km^2 in area and is comprised of five regions with 25 municipalities (**Table A1**) that is home to over 6 million people. Land use in the GTA comprises of approximately 29% urban and developed area, 20% forests, 19% croplands, and the remaining area is comprised of pastures, fallow or barren land, wetlands, and inland water (Agriculture and Agri-Food Canada [AAFC] 2011). The mean annual rainfall is 937 mm and the mean annual temperature is 9.2 degrees Celsius (Environment and Climate Change Canada 2019).

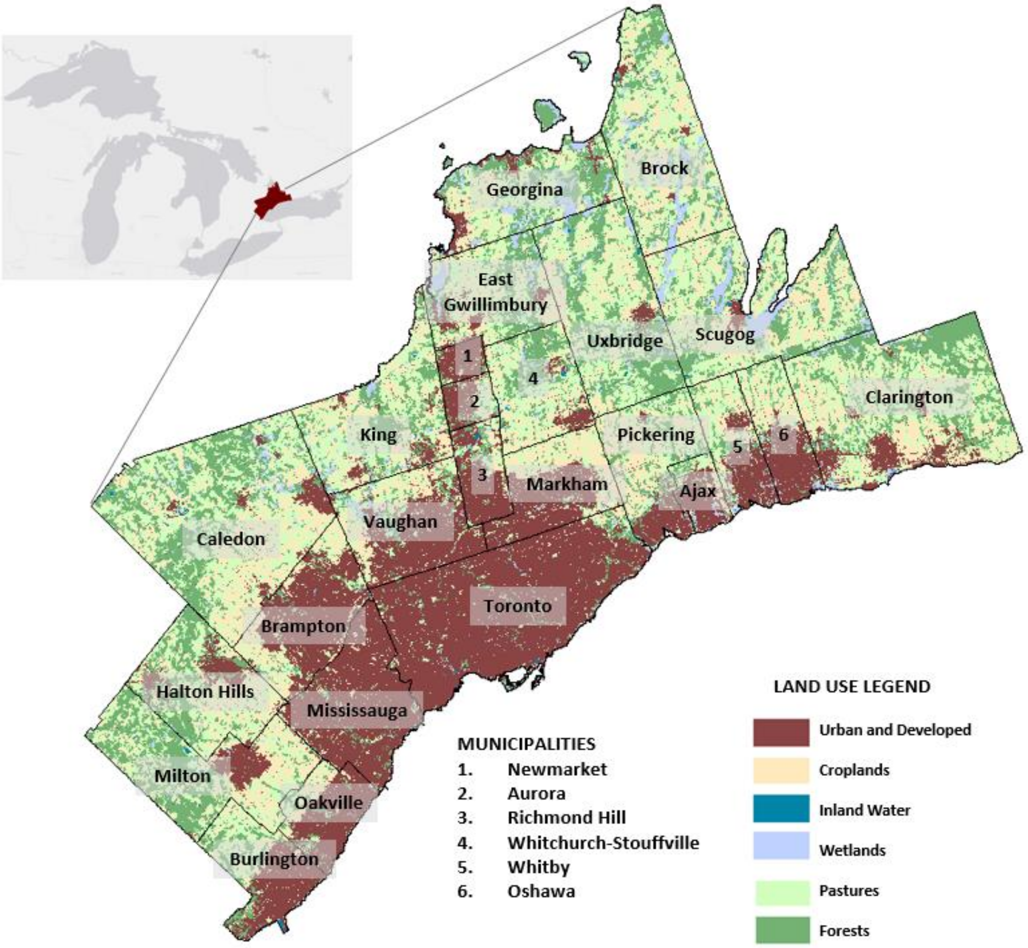

Figure 2: Map displaying the boundaries of the GTA, its 25 municipalities, and the various land-use types (AAFC 2011). The GTA is centered around the City of Toronto and is located along the shores of Lake Ontario.

The GTA experienced rapid urban sprawl starting in the 1960s and continues to grow with an expected population increase of over 41% by 2040 (Ministry of Finance 2018). Originally, the city was strategically built around a convenient trading route beside Lake Ontario and adjacent to prosperous agricultural land (Millward 1992). The history of its construction contributes greatly to the GTA's unique structure with its mega-urban center located near the harbour-front and more suburban housing and agriculture stemming outwards. In the current urban and developed areas, the population density is relatively high and so water and waste management is mostly centralized to accommodate this. The GTA is heavily reliant on adjacent river and lake water, especially Lake Ontario (Toronto and Region Conservation Authority 2012). The unique urban expansion of the GTA combined with the management style that has accommodated this population growth has increased waste disposal as far as Michigan, United States (Clapp and Princen 2003). This expansion has also contributed to urban runoff into the GTA's fresh water sources that has subsequently caused poor water quality in the lake shores (Kidd 2016).

Our analysis for this work is restricted to the administrative boundaries of the GTA and for the year 2011. To further understand nutrient fluxes across the GTA, we partitioned the area into three subsystems, namely urban, suburban, and rural (**Figure 3**) based on methods described by Forsyth (2012). Specifically, we used an aerial land-use map from Census Canada that defined the urban and developed areas, croplands, forests, pastures and wetlands (**Figure 2**) and overlaid this with a population density map using data (Computing in the Humanities and Social Sciences [CHASS] 2011) to distinguish between urban and suburban areas. The urban core was defined as an area with a population density of over 52 persons per hectare (Statistics Canada 2006), while the remaining portions were designated as suburban (**Figure 3**). All other land use types (such as croplands and forests) were designated as rural. Based on this categorization, we established that the GTA was 4% urban, 25% suburban, and 71% rural in 2011.

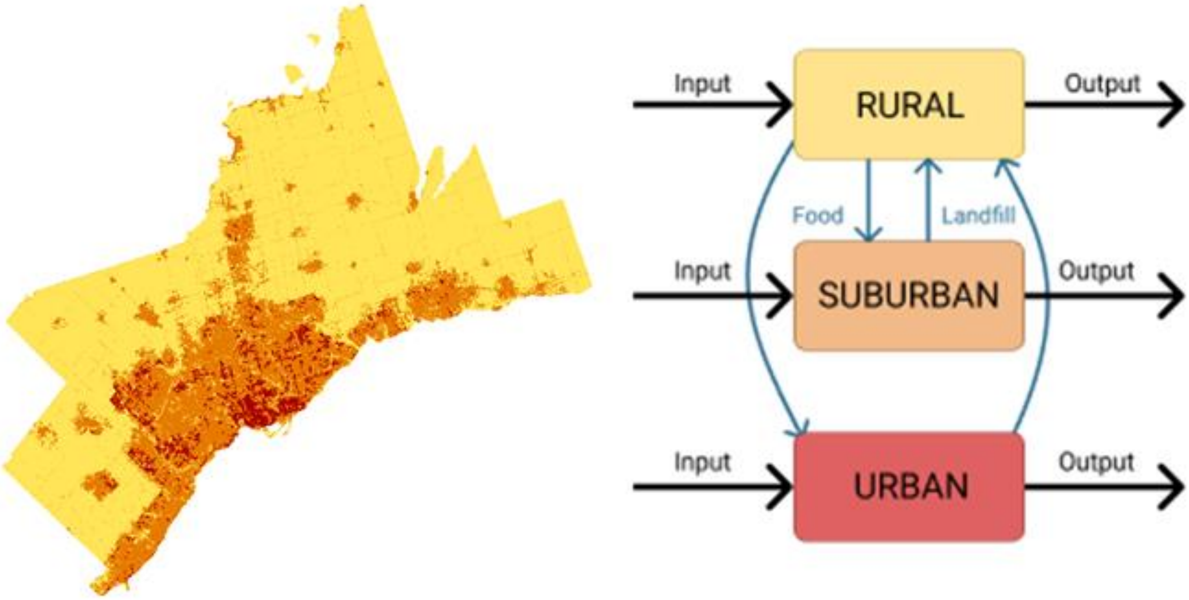

Figure 3: The GTA was divided into three main subsystems: urban (red), suburban (orange), and rural (yellow) areas. The built-up areas that were defined as "urban and developed" were extracted from the land-use map in Figure 1 and coupled with population density information to distinguish the urban (>52 people per hectare) from suburban (AAFC 2011; Statistics Canada 2006; CHASS 2011). Each of the subsystems has varying inputs and outputs as well as interactions between them with two examples displayed (food and landfill). The rural areas supply food to the urban and suburban areas, while the urban and suburban areas send portions of their wastes to landfills located in the rural areas.

2.2 Nutrient Fluxes through the GTA

The GTA can be conceptualized as an agricultural and an urban system that exchange nutrients through food and waste pathways. These subsystems also exchange food and waste across the GTA boundaries, marked as external inputs and outputs to and from the GTA (**Figure 4**). **Figure 4**, an adaptation of Roy, White, and Seibert 2014, described these various fluxes and stores, and the methods for quantifying these fluxes are outlined in **Section 2.3** and **Section 2.4**.

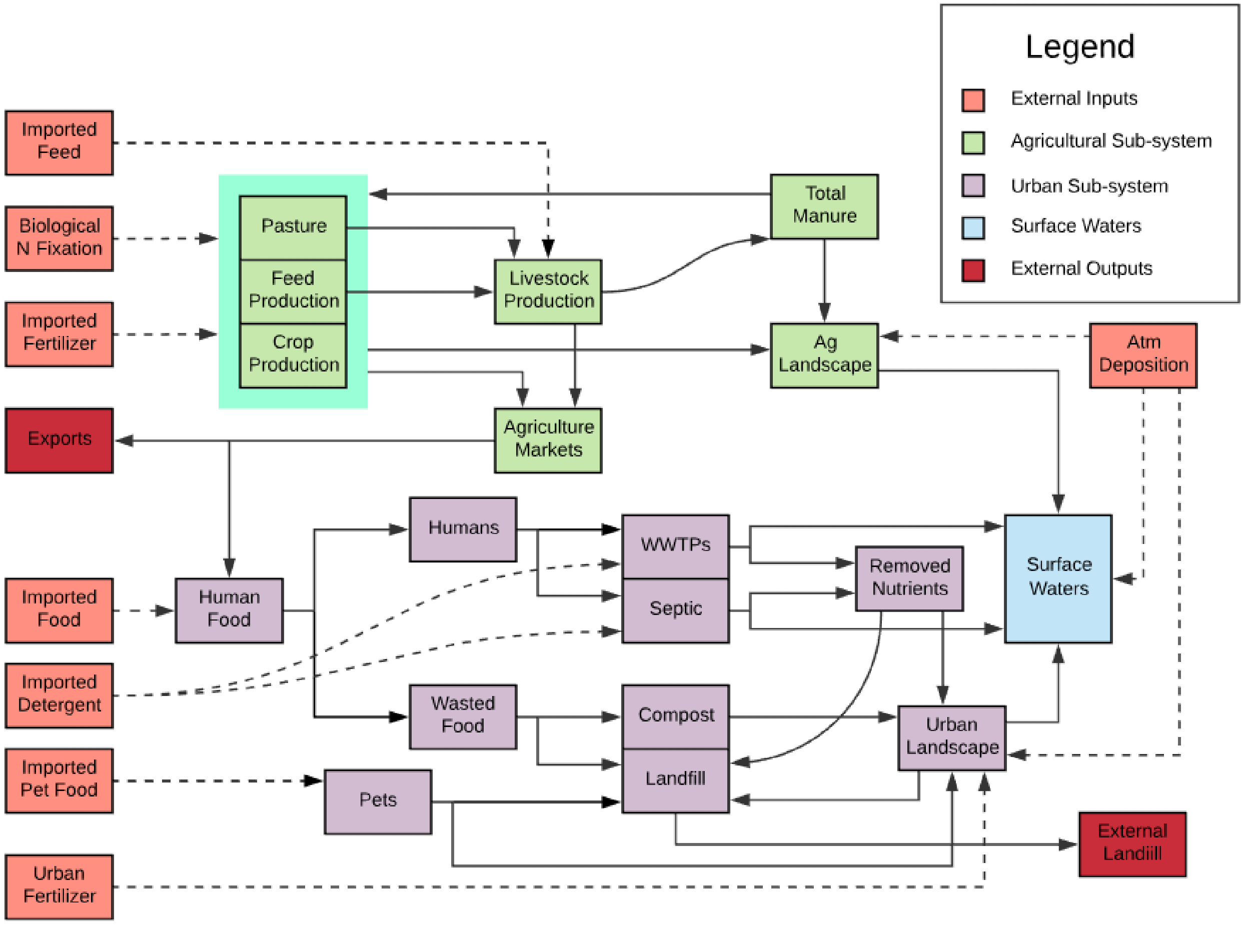

Figure 4: A flow diagram adapted by Roy, White, and Seibert 2014 of all the components in the urban metabolism study for the GTA in 2011. This includes external inputs (pink), the agriculture system (green), anthropogenic system (purple), exports (red), and surface waters (blue).

2.3 Nutrient Inputs to the GTA

Nutrient inputs into GTA occurred through food (humans, pets and livestock), fertilizers (cropland, lawns, parks, cemeteries and golf courses), atmospheric deposition, biological N fixation (BNF) and detergents (**Figure 5**). A brief overview of the methods used for estimation of these components is presented below, while detailed equations provided in **Table B1** in **Appendix B**.

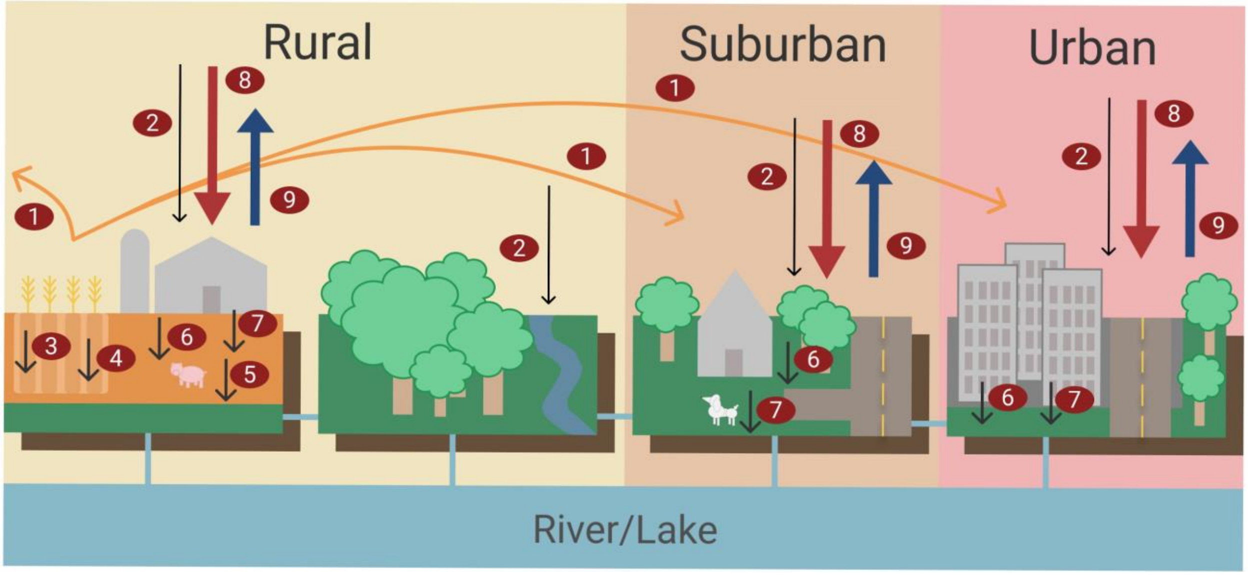

Figure 5: Mass balance demonstrating the various inputs for each subsystem. The rural subsystem was comprised of forested and agricultural area with inputs that included (2) atmospheric deposition, (3) agricultural fertilizer, (4) biological N fixation, (5) manure, (6) residential and park fertilizer, (7) pet waste, and (8) food and feed import. The outputs for this area included (1) crop production (exported and internal) and (9) waste to landfills external from the system. The suburban and urban areas had the following inputs: (1) crop production, (2) atmospheric deposition, (6) residential and park fertilizer, (7) pet waste, and (8) food import. The calculated major outflow for both the suburban and urban areas was (9) external landfills. There are also other outputs including WWTP outflows and septic tank leakages not shown here.

2.3.1 Food Imports

The food requirements for humans and livestock were assumed to be met either from imports or internal production, while the pet population's food was assumed to be dependent completely on imports. The total food import for humans and livestock was calculated as the difference between their nutrient requirements (including food waste) and the internal crop and livestock production (**Table B2.1),** while the total food import for pets was assumed to be equal to their nutrient requirements. Food inputs to GTA for human needs was assumed to be either consumed

(4.10 kg N/cap/year and 0.42 kg P/cap/year) or wasted (2.07 kg N/cap/year and 0.19 kg P/cap/year) (Statistics Canada 2009; Karp et al. 2012). These values are similar to other studies of human N and P consumption conducted in the United States and Canada (Baker et al. 2001; Han, Bosch, and Allan 2011; Boyer et al. 2002; Hong, Swaney, and Howarth 2011). In France, Esculier et al. (2018) estimated that the average Parisian consumes and wastes 7.3 kg N and 0.67 kg P on an annual basis which is slightly higher than our estimated value. Food inputs for pets (dogs and cats) were estimated using information on the number of breeds of cats and dogs in GTA and their average nutrient requirements as a function of their breed and weight (**Appendix B3**). Food for livestock was similarly estimated using the population of the different livestock types, their percent occupancy, and nutrient requirements (**Appendix B2.3**). The internal crop and livestock production were estimated as the difference between the internal food production and land available for grazing (assumed to meet 32% of the diets of grazing animals; Roy et al. 2014, **Table B2.3**) and the provincial export commodity percentages (**Table B2.2**). Wildlife and other animals were not considered at this time; the contribution for wild birds was briefly explored, but contributed a negligible amount to the total nutrient budget.

2.3.2 Fertilizer Inputs

Fertilizer application rates on agricultural areas were estimated using a combination of provincial data and literature values (**Table B.1**). Fertilizer sales data available for Ontario was downscaled to the 30m x 30 m grid-scale using cropped area and crop type information at that scale (**Figure 2**; AAFC 2011). Nutrient input on residential lawns was estimated using information on municipality-specific average fertilizer expenditure ($) per household (Survey of Household spending (SHS); Statistics Canada 2011; Statistics Canada and Income Statistics Division 2013) and lawn area in each municipality. Additionally, we considered the differences in fertilizer application rates between apartments, semi-detached dwellings, and single-detached dwellings. A detailed breakdown of the total residential fertilizer application as well as the rates are summarized in **Appendix B4**. Nutrient application rates on golf courses, parks and cemeteries were estimated based on various tender documents and reports, the calculations of which are detailed in **Table B1**.

2.3.3 Atmospheric Deposition, Detergents, and N Fixation

Nitrogen deposition was assumed to be equal to 4.6 kg N/ha based on measured data at a station in Egbert, Ontario (Environment and Climate Change Canada 2011). Phosphorus deposition was estimated to be equal to 0.2 kg P/ha in the Grand River Watershed, west of the City of Toronto (Winter and Duthie 2018). We assumed atmospheric deposition of N and P to be uniform across the GTA. Phosphorus inputs from detergents were estimated using a P content of laundry and dishwashing detergent as 0.15 kg P/per capita and 0.23 kg P/per capita, respectively (Han, Bosch, and Allan 2011). Biological N fixation was estimated as a function of crop yield of N fixing crops (**Table B2.1**; Hong, Swaney, and Howarth 2013).

2.4 Nutrient Outputs from the GTA

Nutrient outputs from the GTA occurred through agricultural markets, WWTP outfalls, landfills, runoff, and seepage into soil and groundwater.

2.4.1 Agricultural Markets

Nutrient output in crop production was estimated using crop data provided by Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA; 2011) as well as fruits and vegetables data from Statistics Canada (2012) combined with approximate nutrient content and dry matter for all the crops grown in the GTA (**Table B2.1**). Nutrient outputs through meat production was estimated as the difference between intake and excretion for livestock (**Table B2.3**) and an additional 10% lost due to waste. Crop and meat produced within GTA were either circulated internally to meet the food needs of the local population or transported out of GTA to external agricultural markets. Since trade information is only available at the provincial scale, the Ontario export estimates (**Table B2.2**) for different crops and meats were used to estimate GTA exports (Ontario Ministry of Agriculture and Food [OMAFRA] 2011).

2.4.2 Wastewater Management

Most of the wastewater for the urban and suburban areas in the GTA is centrally managed through 31 WWTPs. We used information from municipal and regional WWTPs reports and cross-checked these values with the National Pollutant Release Inventory (NPRI; Government of Canada 2011) to determine the amount of nutrients discharging from each WWTP. The GTA WWTPs disposed nutrients directly into water bodies as effluents, while the solids produced in the WWTPs went to internal or external landfills, land application, and incineration. Two of the WWTPs within the GTA discharged to other WWTPs. The proportion of nutrients discharged by the WWTPs through each of these different pathways was different, and the information was obtained from the individual WWTPs (**Table A2**). We then delineated "sewersheds" or the WWTP area coverages for the GTA in ArcGIS using a combination of online data and WWTP reports (**Table A2**). We then assumed that the population residing outside these sewershed boundaries were serviced via septic tanks (**Figure 6**).

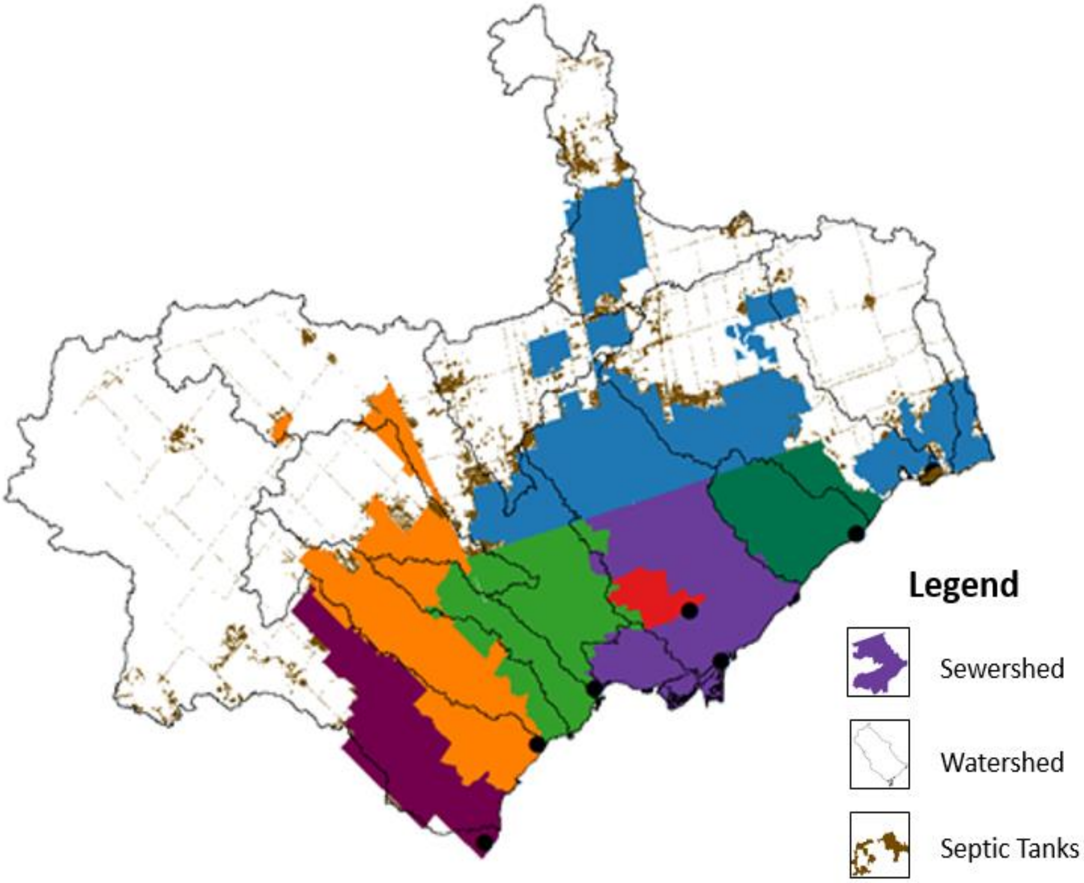

Figure 6: The major sewersheds in the GTA (coloured) shown with their associated overlapping watersheds. The scattered brown areas outside of the defined coloured sewersheds represent the households on septic tanks.

2.4.3 Solid Waste Management

There are five sources of solid waste within the GTA: (1) food waste, (2) biosolids from WWTP, (3) holdings in septic systems, (4) pet waste, and (5) manure (**Table B1)**. Food waste goes to either compost or landfills, and we assume that 45% efficiency for residents of the GTA compost their waste while the rest goes to landfills (Mustapha 2013). Biosolids from WWTP were applied to landscapes, transported to landfills, or incinerated. The total volume of biosolids was estimated separately for each WWTPs through individual WWTP reports (**Table A2**), the NPRI (Government of Canada 2011), and personal communication, and then subsequently multiplied by a typical nutrient concentration based on the Harmony Creek WWTP (Durham Region 2012). We assumed 40% of N and P diverted to septic tanks was removed from holding receptacles and sent to landfills (Ursin 2007; Withers et al. 2014). Pet waste was assumed to be equal to the nutrient intake and was either diverted to landfills or left on landscape based on surveyed homeowner habits, and pet types (**Appendix B3**). Finally, we estimated manure generated within the GTA using livestock population data coupled with excretion values (**Table B2.3**). It was surveyed that 48% of this manure was land applied to agricultural lands, while the rest went to pasture land (Dorff and Beaulieu 2014).

2.4.4 River, Lakes, Soils and Groundwater

Nutrients from the GTA enter rivers and lakes via the following pathways: (1) outflow from WWTPs, (2) septic tank leaks, and (3) runoff from the landscape. Nutrients are also retained in the soils and groundwater systems via the following pathways: (1) biosolids from WWTPs, (2) septic tanks, and (3) fertilizer and manure application on agricultural and urban lands. The N and P leakage from the WWTPs in GTA to the surface water system was estimated in tons/year, while the metrics N and P surplus (tons/ha/year) were used to quantify nutrient build up in the soil and groundwater system. Nitrogen and P surplus is defined as the difference between N and P inputs (fertilizer, biosolids, fixation, atmospheric deposition, pet waste, manure, septic leakage) and outputs (crop yield).

For WWTPs, we obtained information of treated and untreated (bypasses) wastewater discharging into lakes and rivers from individual WWTP reports, NPRI, and personal communication. These reports also had information on the quantities of biosolids from WWTPs that are applied to land that was used to estimate the N and P surplus values. We isolated the Ashbridges Bay WWTP, the largest in the GTA, to compare the effluent, bypass, and riverine output. We used a weighted regression method proposed by Hirsch, Moyer, and Archfield (2010) that analyzed the water quality and discharge data from the 1979 - 2013 (**Figure C1** for N and

Figure C2 for P) while accounting for seasonality for the Don Valley River Watershed (Government of Ontario 2011) to estimate the daily concentration and loadings for 2011.

For septic tanks, we assumed 20% of holdings were lost as leakage to nearby water bodies, 40% of nutrients from septic holdings remained in the soil as legacy and leached into the groundwater, and 40% went to landfills (**Section 2.4.3**; Ursin 2007; Withers et al. 2014). In urban areas, we assumed that 25% of all urban fertilizer (residential, park, golf, and cemetery) as well as pet waste applied to landscape would runoff into rivers and lakes, while 75% remains in the soil as N and P surplus (Howarth et al. 1996). In the cropland, we assumed that the difference between fertilizer and manure inputs and crop uptake either remained in the landscape as N or P surplus (75%) or entered as runoff (25%) to water bodies (Howarth et al. 1996). Finally, we also assumed that soil N surplus builds up over time due to N fixing crops like soybean.

2.5 Spatial Patterns of N and P Surplus

N and P surplus maps across the GTA were estimated at the 30 m x 30 m scale by fusing data of different spatial resolutions into a consistent framework. The urban fertilizer application information was available at a fine spatial scale based on locations of parks, golf courses, cemeteries, and residential lawns for each city. In contrast, atmospheric deposition data was available from only 1-2 stations and as mentioned, a uniform rate was applied across the region. For pet waste, we had pet data for only the City of Toronto ("Open Data Catalogue" 2017) and extrapolated this outward assuming pet population was proportional to human population. We applied agriculture fertilizer evenly across the GTA because it was available at the provincial scale and considered soybeans separately because of its dominance in this area and ability to fixate N. Livestock data and therefore, manure was applied evenly across all crop lands based on farmer user rate (48%) and the remaining manure was assumed to be spread across pasture land evenly for the GTA (Dorff and Beaulieu 2014).

3 Results and Discussion

3.1 Urban Metabolism: N and P Fluxes through the GTA

3.1.1 N and P Inputs and Outputs through the Subsystems of GTA

Nutrient inputs varied widely across the GTA and ranged from 621 kg N/ha (100 kg P/ha) in the urban area to 127 kg N/ha (20 kg P/ha) in the suburban area, and 70 kg N/ha (13 kg P/ha) in the rural area (**Figure 7** and **Table 1**). Due to its high area-normalized inputs, the urban area contributed to almost a quarter of the total N and P inputs to GTA (17.8 kton N and 2.8 kton P) despite occupying only 4% of the GTA's land area. The suburban area is more than six times bigger in size than the urban area, but has a similar contribution as the urban area (22.9 kton N and 3.5 kton P). The rural area covers more than 70% of the total land area of the GTA and contributes to approximately half of the total nutrient inputs.

For N, food import for human consumption was the largest component of the input to the urban core (16.1 kton N), followed by fertilizer for turfgrass (0.8 kton N), food for pets (0.7 kton N), and atmospheric deposition (0.1 kton N). Population density decreases from the urban to the suburban area and this leads to a proportional decrease in the contribution of food for humans (17.6 kton N), and an increase in the contributions of fertilizer on turfgrass (2.9 kton N). food for pets (1.7 kton N) and atmospheric deposition (0.8 kton N). It is interesting to note that food for pets is a larger component of the budget than atmospheric deposition in the urban and suburban areas. Few studies have included pet waste in their nutrient budgets (Baker et al. 2001; Hobbie et al. 2017; Roy, White, and Seibert 2014) and our study further highlights the importance of this component in an urban context. The suburban area has more than three times the fertilizer inputs than the urban area due to the larger green space in residential lawns (more single dwellings with greater lawn area) and parks. The picture is significantly different in the rural area where food input for humans become a much smaller component of the budget (3.7 kton N), and the inputs are dominated by BNF (9.3 kton N) and fertilizer on agricultural land (8.9 kton N), followed by food for livestock (8.6 kton N), atmospheric deposition (2.2 kton N), food for pets (0.7 kton N), and lastly, food for pets fertilizer on turfgrass (0.5 kton N).

Table 1: Summary of the urban, suburban, and rural inputs and outputs associated with Figure 7.

	Nitrogen [kton (% of total)]			**Phosphorus** [kton (% of total)]		
	Urban	**Suburban**	**Rural**	**Urban**	**Suburban**	**Rural**
Input						
Food (Humans)	16.1 (91)	17.6 (77)	3.7 (11)	1.6 (55)	1.7 (48)	0.4 (6)
Food (Pets)	0.7 (4)	1.7 (7)	0.7 (2)	0.1 (3)	0.2 (6)	0.1 (2)
Food (Livestock)	-	-	8.6 (25)	-	-	2.5 (40)
Biological N Fixation	-	-	9.4 (28)	-	-	-
Fertilizer (Turf)	0.8 (4.5)	2.9 (12.5)	0.5 (1.5)	0.2 (7)	0.5 (14)	0.04 (1)
Fertilizer (Agriculture)	-	-	9.0 (26)	-	-	2.9 (46)
Atmospheric Deposition	0.1 (0.5)	0.8 (3.5)	2.2 (6.5)	0.01 (0)	0.04 (1)	0.1 (2)
Detergent	-	-	-	1.0 (35)	1.1 (31)	0.2 (3)
Output						
Landfill	4.0 (22.5)	4.4 (19)	1.2 (3.5)	2.0 (69)	2.1 (60)	0.4 (6)
Compost	2.4 (13.5)	2.7 (11.5)	0.6 (2)	0.2 (7)	0.2 (6)	0.1 (2)
WWTP land application	0.1 (0.5)	0.1 (0.5)	0.01 (0)	0.2 (7)	0.2 (6)	0.02 (0.5)
Agricultural Markets	-	-	18.4 (54)	-	-	3.5 (56)
WWTP Effluent	8.6 (48.5)	9.1 (40)	1.2 (3.5)	0.2 (7)	0.2 (6)	0.03 (0.5)
Non-point source losses	2.6 (15)	6.7 (29)	12.7 (37)	0.3 (10)	0.8 (23)	2.2 (35)

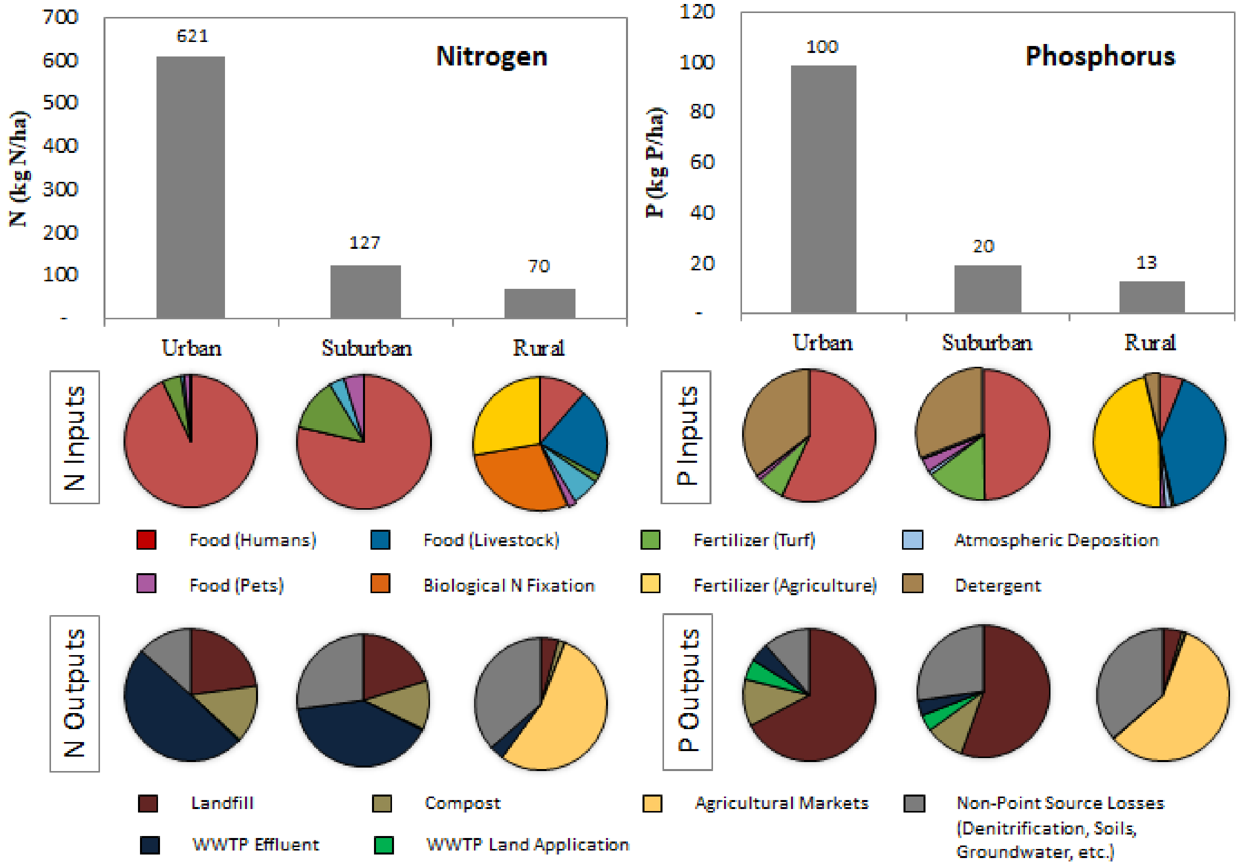

Figure 7: Nutrient inputs and outputs across the urban, suburban, and rural subsystems of the GTA. The area normalized N and P inputs in urban areas is more than five times higher than that of the suburban and rural counterparts. Food for humans and detergents dominate the inputs in the urban and suburban areas, while fertilizer, BNF and livestock feed dominate rural inputs. The urban and suburban nutrient outputs are dominated by WWTP effluents for N and landfills for P, while crop production dominates the rural outputs.

The P inputs to the different subsystems are similar to N inputs, except for the contribution of detergent P to the urban and suburban budgets, and the lack of BNF in the rural budget. Although the use of P in detergents has radically decreased since the 1970's due to legislation, there is still trace amounts of P in laundry and dish detergents, which lead to it being the second largest component of the input in the densely populated urban areas (Walz 1970). The P from detergents is 1.0 kton P for the urban, 1.1 kton P for the suburban area, and only 0.2 kton P for the rural area. Food for humans is still the largest component of the budget for the urban area (1.6 kton P), while turf fertilizer (1.6 kton P), food for pets (70 ton P), and atmospheric deposition (6 ton P) are the other three components. For the suburban area, food inputs dominate (1.7 kton P), and the three smaller components are turf fertilizer (0.5 kton P), food for pets (0.2 kton P), and atmospheric deposition (36 ton P). Rural inputs for P are dominated by fertilizer on agricultural land (2.9 kton P), followed by food for livestock (2.5 kton P), food for humans (0.4 kton P), atmospheric deposition (98 ton P), food for pets (72 ton P), and turf fertilizer (37 ton P).

Overall, our analysis of the N and P inputs reveal that the urban core of GTA acts primarily as a consumption-driven nutrient economy spearheaded by food imports, while the rural fringes have a more production-driven economy. Our findings also highlight the significant contribution of pet food and turf fertilizer in the urban and suburban budgets, which is a reflection of the high population density and the existence of green spaces (residential lawn space, golf courses, municipal parks, and cemeteries) in these areas.

The definitive outputs from the GTA account for 85% and 91% of the N and P inputs for the urban subsystem, 71% and 78% of the N and P inputs for the suburban, and 63% and 64% of the N and of P inputs for rural subsystem. These outputs include landfill, WWTP effluent, and agricultural crop and livestock export, with WWTP effluent dominating N outputs (8.6 kton N) and landfills dominating P outputs (2.0 kton P) for the urban and suburban areas. The higher landfill contribution for the P budget arises because P is not removed WWTP like N is through denitrification, and merely compressed in biosolids that are disposed to landfills. For the rural areas, 18.4 kton N and 3.5 kton of P outputs are comprised of crop and livestock production. The remaining portion of the inputs (shown as non-point source losses in **Figure 7** which amounted to 29% for N and 26% for P outputs), referred to as the N and P surplus, may either exit the system as runoff into lakes and rivers, denitrification in WWTPs and soil, or be retained in soils, groundwater, reservoirs and stream sediments as legacy N and P.

3.1.2 N and P Fluxes through the GTA

The N and P mass budgets for the various subsystems were aggregated to estimate N and P fluxes at the scale of the GTA. At the GTA scale, nutrient inputs are on the order of 73.2 kton/year for N and 11.9 kton/year for P (**Figure 8**, **Table 2**, and **Table 3**). These inputs are primarily in the form of food for humans (51% of total N inputs and 31% of total P inputs), demonstrating that GTA is characteristic of a consumption-driven nutrient economy rather than a production-oriented economy typical for agricultural regions. Approximately 70% of the food inputs is consumed, which then flows as waste to the WWTP (95%) or goes to septic tanks (5%).

Nutrients entering the WWTP and septic tanks are either lost through denitrification (9% for N), discharged to rivers and lakes (77% for N and 12% for P), exported to landfills as biosolids (11% of N and 80% of P), and land applied or incinerated and contributes to the soils and groundwater pool (3% of N and 8% for P) (**Table 2** and **Table 3**). The remaining 30% of the food inputs is wasted, and this food waste is either diverted to compost (45%) or sent to landfills (55%).

The next largest component of the inputs (18% of total inputs for N and 30% for total P) is fertilizer on crops and turf (lawns, parks, golf courses, and cemeteries). The fertilizer on crops flows primarily into agricultural markets through crop production (6.8 kton N or 76% of N crop fertilizer; 2.3 kton P or 82% of P crop fertilizer), while the remaining is either lost to rivers and lakes through runoff (0.5 kton N and 0.1 kton P), or builds up in the soils and groundwater in the landscape as legacy N (1.6 kton N) and P (0.4 kton P). The estimates of fertilizer lost through runoff and leaching are subject to significant uncertainty. The fertilizer on turf has no productive use, and a quarter of this amount ends up in rivers and lakes (1.1 kton N and 0.2 kton P) while the remaining seeps to soils and groundwater (3.2 kton N and 0.6 kton P).

Table 2: Summary of the N input and outputs for the GTA as a whole associated with Figure 8.

	Nitrogen (kton N)						
Component	**Total**	**Landfill**	**River/Lake**	**Soils & Groundwater**	**Agricultural Markets**	**Compost**	**Denitrification**
Fertilizer (Crop)	8.9	-	0.5	1.6	6.8	-	-
Fertilizer (Turf)	4.3	-	1.1	3.2	-	-	-
Biological N Fixation	9.4	-	-	1.6	7.8	-	-
Atmospheric Deposition	3.2	-	0.8	2.4	-	-	-
Food (Humans, consumed)	24.9	2.7	19.2	0.7	-	-	2.3
Food (Humans, wasted)	12.5	6.9	-	-	-	5.6	-
Food (Pets)	3.0	0.6	0.6	1.8	-	-	-
Food (Livestock)	7.0	0.1	0.3	0.9	5.7	-	-

Table 3: Summary of the P input and outputs for the GTA as a whole associated with Figure 8.

	Phosphorus (kton P)					
Component	**Total**	**Landfill**	**River/Lake**	**Soils & Groundwater**	**Agricultural Markets**	**Compost**
Fertilizer (Crop)	2.8	-	0.1	0.4	2.3	-
Fertilizer (Turf)	0.8	-	0.2	0.6	-	-
Atmospheric Deposition	0.13	-	0.03	0.1	-	-
Food (Humans, consumed)	2.5	2.0	0.3	0.2	-	-
Food (Humans, wasted)	1.1	0.6	-	-	-	0.5
Food (Pets)	0.35	0.1	0.05	0.2	-	-
Food (Livestock)	1.98	0.02	0.06	0.2	1.7	-
Detergent	2.2	1.8	0.2	0.2	-	-

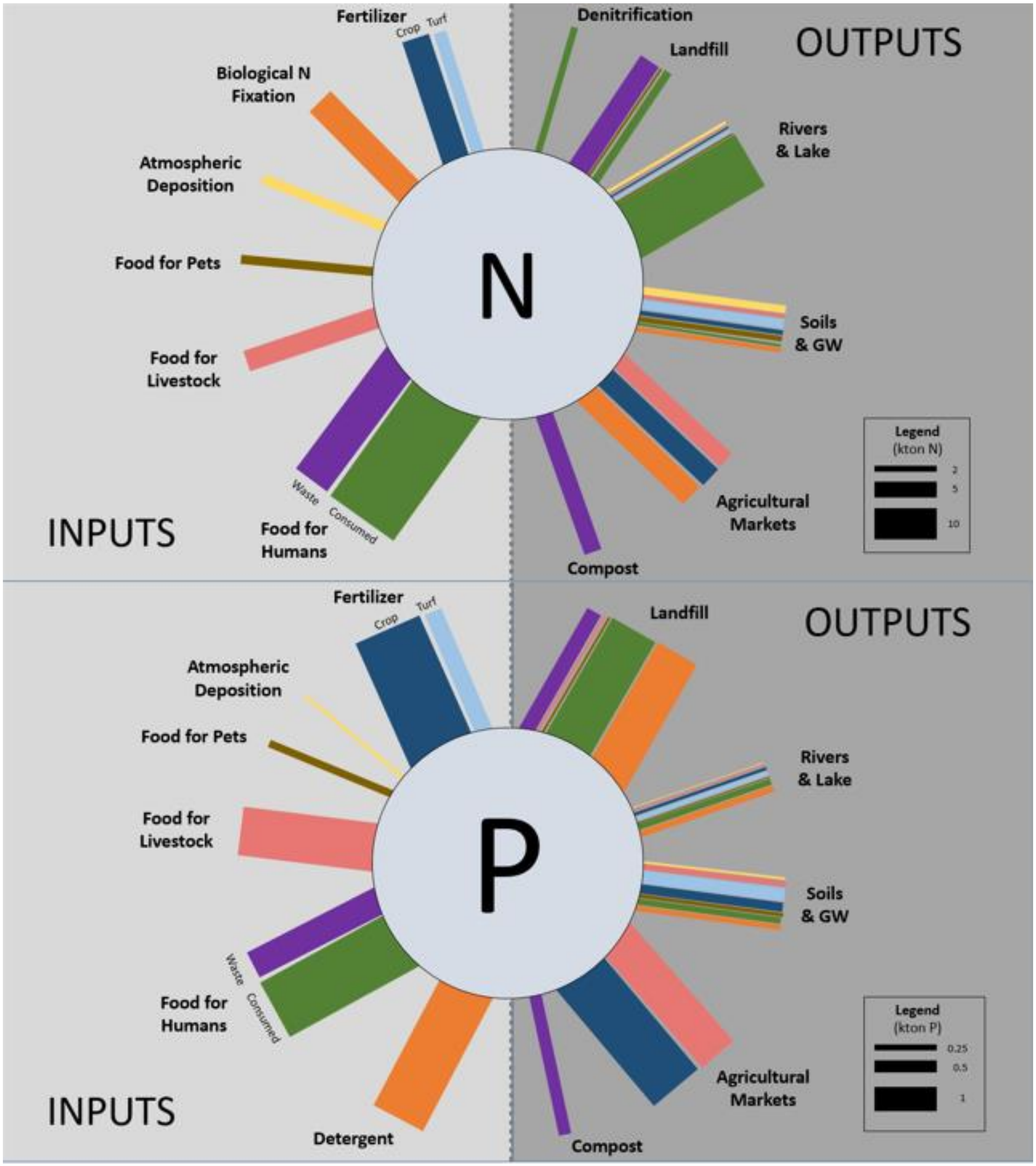

Figure 8: The GTA N and P flux demonstrating the different inputs and the flow of these to their various outputs.

Another significant component of P inputs is detergent P (18% of total P inputs) that is routed from households to WWTPs and septic tanks. and finally disposed in landfills (1.8 kton P or 82% of the total P detergent input), released to rivers and lakes (0.2 kton P), and the remaining seeps to soils and groundwater from septic tanks (0.2 kton P). For N, BNF for the GTA accounted for 13% of total N inputs and this was primarily taken up by crops (7.8 kton N or 83% of BNF inputs), while the rest goes to the environment (1.6 kton).

Food for livestock comprises the next largest component of the inputs (10% of total N and 17% of P). A portion of this input flows as meat, milk and egg sales into agricultural markets (1.9 kton N and 0.6 kton P), while the remaining is excreted as manure. We assume 5.7 kton N (48%) of this manure to be applied on croplands and 52% on pastureland. Manure applied on cropland is a productive use of waste, and a large fraction (36% of total N manure and 32% of total P manure) of this leaves the system as crop sales. The rest of the manure either leaves the system (leftover on crop fields and pastureland) as runoff into rivers and lakes (25%), or builds up in the system as N or P surplus (75%). Diverting more of this manure to croplands would reduce fertilizer sales, as well as environmental impacts.

Food for pets comprises 4% of the N inputs (3.0 kton) and 3% of the P inputs (0.35 kton). This gets transformed to pet waste that is either sent to landfills (20% of N pet food inputs or 0.6 kton N; 25% of P pet food inputs or 0.1 kton P), or runs off to rivers and lakes (0.6 kton N and 0.1 kton P) and the majority builds up on the landscape as nutrient surplus (1.8 kton N and 0.2 kton P). Picking up a larger fraction of the pet waste and reusing them as fertilizer would potentially reduce environmental impacts. Finally, atmospheric deposition accounted for 4% of the N input and 1% for the P inputs. It is interesting to note that for N, the magnitude of atmospheric deposition is comparable to pet waste in this area, due to the high population and pet density in the urban core.

The flow of inputs to the outputs provide important insight into the potential for efficient nutrient management within the GTA. First, the P outflow to agriculture markets is comparable in magnitude to the outflow to landfills, highlighting the potential of possible P recovery within the system. Similarly, the output for both N and P to the natural systems that are rivers and lakes as well as soils and groundwater are similar to output to agricultural markets and landfills. They are made of multiple input components in comparison to the other divisions and it is noteworthy to point out the dominance food N for humans has in the rivers and lakes due to WWTPs. Since this area is located within the Great Lake Basin which has particular emphasis on P management, we see a stark difference in the containment of these nutrients and raises questions on improvements in the handling of N.

3.2 Urban Footprint: Impact of GTA's waste on the surrounding environment

A significant fraction of the nutrient inputs ends up in rivers and lakes (22.4 kton N and 1.0 kton P), soils and groundwater (12.1 kton N and 1.1 kton P), and landfills (10.3 kton N and 4.6 kton P). Collectively these fluxes comprise the urban footprint of the GTA on the environment. Nutrient fluxes to rivers and lakes contribute to nearshore nutrient pollution and algal blooms in waterbodies, while nutrient build-up in soils and groundwater can lead to groundwater pollution, as well as future risk to pollution of surface water bodies from runoff. Landfills take up valuable land area, and while they are theoretically contained sources of pollution, they are known to leak over time into groundwater and rivers (Howard and Livingstone 2000). An efficient management of nutrients within the GTA requires productive recycling of these fluxes to reduce the urban footprint, as well as resource inputs into the GTA. While we have so far focused on aggregated spatial and temporal nutrient budgets, evaluation of the urban footprint requires exploring within-year and within-GTA patterns. Hot spots in nutrient inputs across the landscape and hot moments in nutrient fluxes across the year are known to be drivers of zones of excessive algal blooms in lakes (McClain et al. 2003; Bernhardt et al. 2017).

3.2.1 N and P Surplus across the GTA

The difference between manure, BNF, synthetic fertilizer, septic leakage, pet waste, atmospheric deposition, and crop uptake is the N or P surplus that builds up in soils and groundwater (**Figure 9a**). The cumulative nutrient surplus across the GTA was estimated to be equal to 12.1 kton N and 1.9 kton P. Surpluses varied over a factor of 3 from 0 kg N/ha (-1 kg P/ha) to 210 kg N/ha (24 kg P/ha). High surplus spots were located primarily in areas with moderate to dense human population locations in Toronto, Mississauga, and Brampton, where single or semi-detached dwellings were located in close proximity to each other. The higher surpluses in these urban areas can be attributed to high intensity of residential and golf course fertilizer application rates

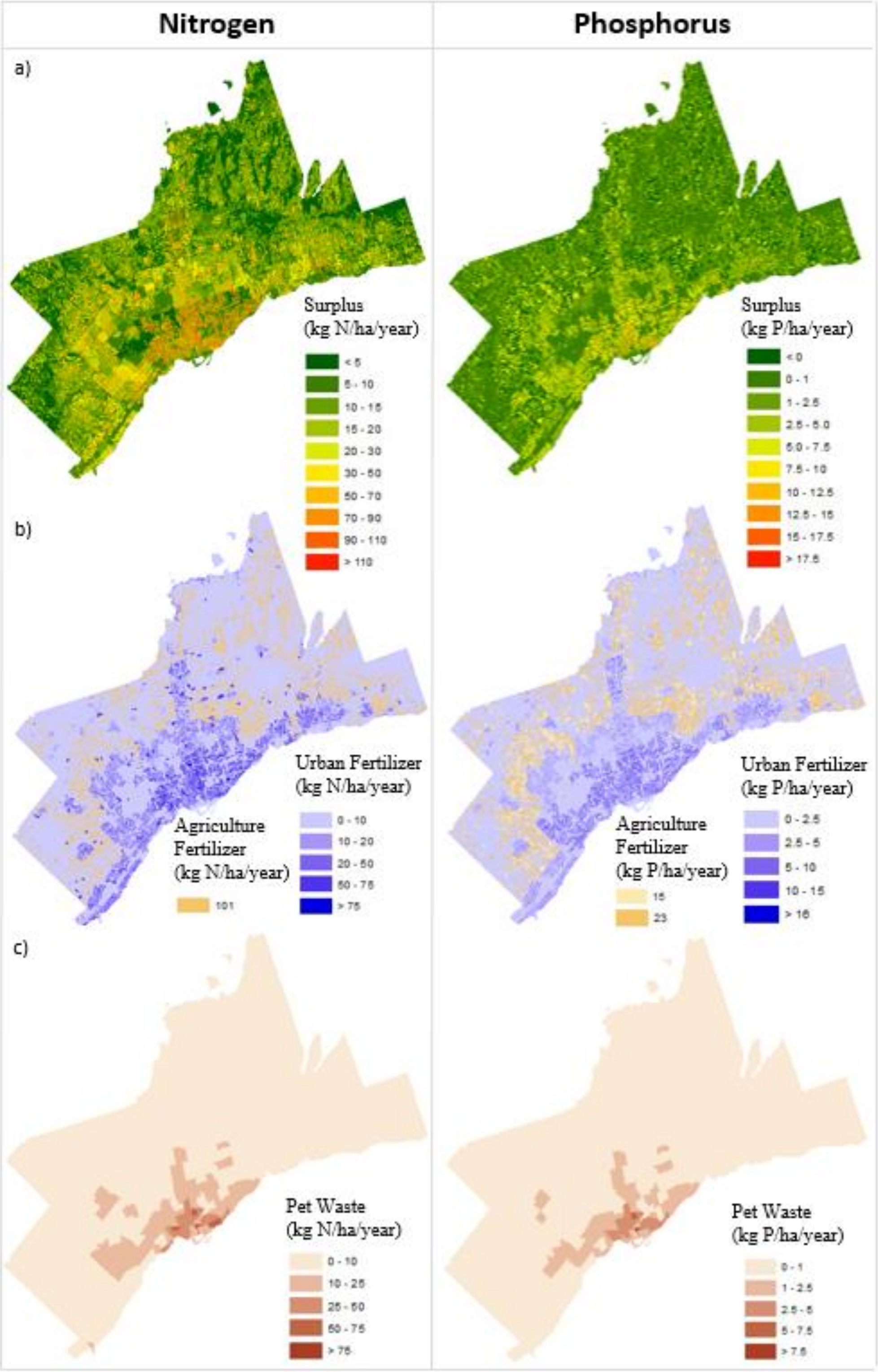

Figure 9: Spatial variation of nutrient fluxes and surpluses across the GTA.

(238 kg N/ha and 28 kg P/ha for residential, and 206 kg N/ha and 36 kg P/ha for golf courses). Note that these application rates are estimated using fertilizer sales data, and thus reflect actual behavioral patterns in application. Despite high intensity in application, urban lawns cover only a fraction of the 30 x 30 m grid cells, leading to lower spatially averaged application rates (average of 31 kg N/ha and 4 kg P/ha ; **Figure 9b**). The key difference between urban greenspace and surrounding agricultural areas is that in the latter a significant fraction of the fertilizer added leaves the system as crop output unlike turf grass, leading to lower surpluses. Higher N and P build up under urban soils have been observed in other studies (Hobbie et al. 2017). High surplus in the urban core is also attributed to higher intensity of pet waste (**Figure 9c**) which is not always picked up and poses risk of runoff to downstream waters.

3.2.2 N and P Fluxes to Surface Water and Landfills

There are three primary pathways through which nutrients can enter rivers and lakes: (1) outflow from WWTPs, (2) plant bypasses, and (3) surface and subsurface runoff from the landscape (**Figure 10**). The overall nutrient discharge from all the WWTPs to rivers and lakes in the GTA is 18.9 kton of N and 0.5 kton of P per year, of which 0.1 ktons of N and 0.06 ktons of P are discharged directly to the lake through bypasses (**Table A2**). This is comparable to our estimate of 3.5 kton N and 0.5 kton P per year that enters the lake as runoff. Note that the estimate of runoff is very approximate; future research would involve using stream water quality datasets and models to refine this estimate. Despite the uncertainty in the runoff component, this analysis highlights the critical role efficiency of WWTPs play in urban nutrient budgets. The effluent from the GTA's WWTPs are low for P in comparison to N because treatment efficiencies of the WWTP are relatively high for P, ranging from 84 - 99.6%, and these efficiencies have increased over time in response to eutrophication events and the need to contain P releases (Kidd 2016).

The GTA scale annual flux estimates, however, fail to capture hot spots and hot moments in nutrient fluxes that an urban area like the GTA generates. Seventeen of the thirty-one WWTPs in GTA are along the shores of Lake Ontario and discharge directly to the lake, creating hot spots in nutrient inputs, and contributing to localized high pollution incidents that lead to beach closures. The three largest WWTPs are located along the lakeshores, and discharge 6.8 kton N (0.19 kton P), 2.3 kton N (0.05 kton P), and 2.0 kton N (0.05 kton P) to the lake per year. In order to explore the concept of hot spots and hot moments further, we focused on the largest WWTP, the Ashbridges Bay WWTP (**Figure 10c**), and compared its effluent discharge with those of the Don River that discharges into Lake Ontario. This WWTP has the largest capacity among all of the others in the GTA and covers some of the highest densities in the City of Toronto (Toronto Water 2011a). Total P discharge in this 38 km section of the shore from the Don River and the WWTP is 0.19 kton P/year, with 63% contributed by WWTP effluent, 23% contributed by bypasses and 15% contributed by runoff. Thus, locally, bypasses can be a significant component of the nutrient budgets. Bypasses occur more frequently in this dense region of GTA since population expanded faster than the expansion in WWTP capacity. The situation is even more severe if we focused on the 128 hours of the year (1.5% of year) when bypasses occur.

Finally, a significant externality of the GTA is through landfills; approximately less than 10% of waste was landfilled locally in Halton Region and the Township of Brock for 2011. The majority of total wastes sent to landfill come from areas of high human population density and were sent as far as New York. Reducing food, pet, and manure waste to landfill is of interest to municipalities because scouting new landfills is a lengthy and expensive process in Ontario (**Section 3.5**). Though we did not consider leaching at this time, older landfills in the GTA constructed before standards of lining were set in place would be susceptible to nutrient infiltration (Millward 1992).

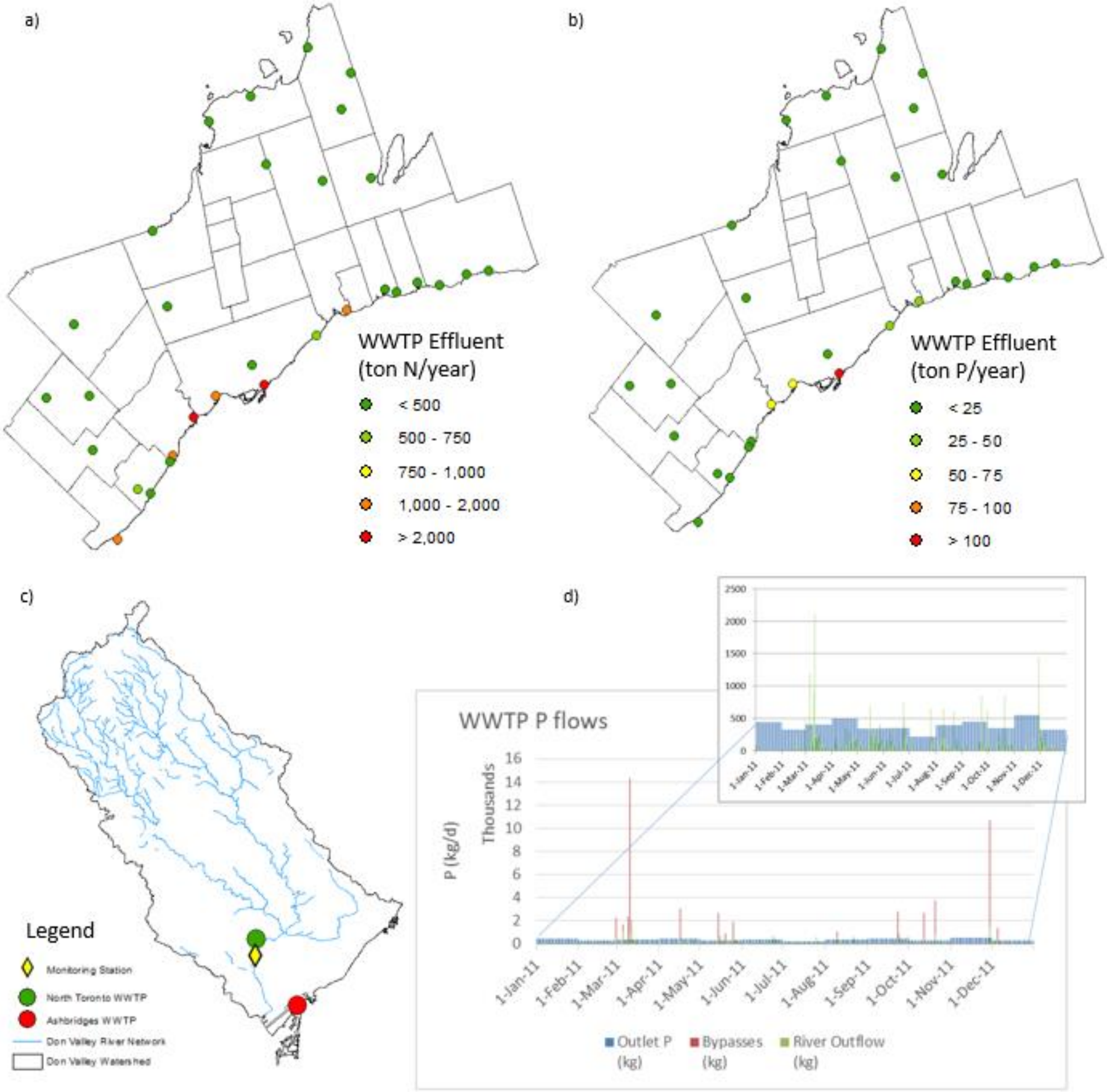

Figure 10: The annual effluent discharges for N (a) and P (b) for all the GTA WWTPs. The largest is the Ashbridges Bay WWTP and it located in the Don Valley Watershed along with North Toronto WWTP, which drains to the former in during overflow events (c). The cumulative P flows of the Ashbridges Bay WWTP (d) displaying high bypass events correlating with large storm events or plant maintenance. The corresponding river outflow is estimated using the WRTDS method using the monitoring station near the end of this watershed.

3.2.3 Impact of the GTA on Nutrient Ratios

Looking at the GTA as a black box with external inputs and exported nutrients, we find that the N:P molar ratios are generally off of the natural occurring Redfield ratio of 16:1, which is the optimal ratio of N:P for the growth of phytoplankton (**Figure 11**; Glibert and Burkholder 2011). The total inputs considered were imported food and feed, detergents, fertilizer imports, atmospheric deposition, and BNF. Other components previously mentioned are considered part of the internal cycling and not shown here, but captured within the black box. The ratio of the total input (not considering recirculated nutrients) and the agricultural exports are 14:1 and 11:1 respectfully, and is close to the Redfield ratio. We identified the outputs from the GTA to be WWTP effluent, WWTP denitrification (which may be skewed by unavailability of industry or WWTP influent data), disposal to landfills, and agricultural exports. Other than denitrification, the highest N:P molar ratio was seen in WWTP effluent of 119:1 because the GTA outlets to various Great Lakes that have a stringent focus on P and regulated removal operations (Kidd 2016; **Table A2**). This is of particular concern because this effluent acts as a high intensity nutrient deposit or hot moment and has the most imbalanced ratio. Landfill disposal had the closest N:P ratio of 5:1 because of high P content in biosolids.

From our study, we found two human-made systems, WWTPs and landfills, drastically alter the nutrient cycle. The coverages of WWTPs or “sewersheds” change the direction of flow of water and thus nutrients from natural watersheds (O’Hare 2015). If we compare the location of food consumption versus ultimate riverine disposal, we find that 59% of nutrients were rerouted to a different subwatershed and 4% of nutrients that should have drained to Lake Simcoe was discharged to Lake Ontario. Moreover, landfills divert waste mostly out of the GTA. Comparing where food waste occurs versus the end disposal, we approximated that over 90% of food waste is sent outside of the GTA to as far as America.

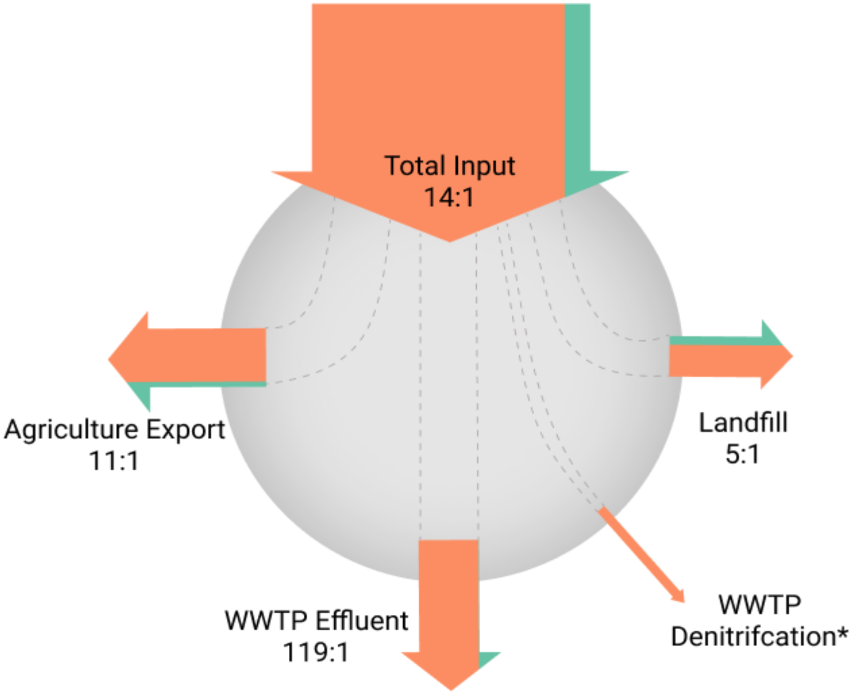

Figure 11: A visual representation of the molar ratios in total imported inputs and various external outputs. WWTPs play an important role in the management and manipulation of N and P quantities thus drastically skewing the N:P ratios.

3.3 The Circular Economy: Recycling Potential

Urban areas like the GTA have a large footprint on the natural landscape surrounding it, as well as the larger society through import of food and export of waste. As urban population density increases, it is important to design urban areas such that there is circularity in resource flows within the system, while external inputs and outputs are minimized. In this study, we have identified strategies and opportunities that can create a more circular economy and efficient metabolism for the GTA (**Figure 12).**

One of the major input of nutrients into the GTA is in the form of agricultural and urban fertilizers (13.2 kton N and 3.6 kton P), and one of the major outputs is food waste in landfills (10.3 kton N and 4.5 kton P). This creates an opportunity for circularity since the food waste generated can be converted into compost and re-utilized as fertilizer. Currently, approximately 45% of the food waste of GTA is composted (Mustapha 2013); however, this compost is not effectively reused and often goes to landfills (Welsh 2009). If we assume that 80% of the food waste is composted and the compost is used as fertilizer, this would reduce fertilizer imports from 13.2 kton N (3.6 kton P) to 2.5 kton N (1.1 kton P), by 81% for N (30% for P). A large fraction of the fertilizer imported is used to grow crops for livestock operations. Currently, only 48% of the manure is productively used as fertilizer on croplands, and if this is increased to 80%, we could reduce fertilizer imports further by 100% for N and 68% for P. Finally, the major source of nutrient inputs to the GTA is in the form of food, and the majority of the food waste flows through the WWTPs. Biosolids from the WWTPs can be land applied and reused as fertilizer, and we can reduce fertilizer imports completely by using 64% of P generated biosolids in this area. The rest of the biosolids can be exported to the nearby agricultural areas to be used as fertilizers under appropriate regulation and permits. Therefore, if we consider improved removals from WWTPs and the increased compost and manure reuse, we found that the GTA should be able to meet its residential, park, golf, and agriculture fertilizer requirements while producing excess.

Another major impact of an urban area on its surrounding ecosystem is the waste it produces, (1) to landfills and (2) discharge to lakes and rivers (effluent from WWTP and runoff). A large fraction (34% N and 40% P) of the waste in an urban area is routed through the WWTP plants, and in our idealized scenario, we assumed all WWTPs in GTA to be operating with a minimum P removal efficiency of 94% and N removal efficiency of 80% (Durham Region 2012; University of the West of England, Science Communication Unit 2013; Esculier et al. 2018). This reduces N and P effluent to rivers and lakes by 75% for N and 64% for P.

The GTA region produces 10.7 ton of N and 4.6 ton of P that goes to landfills which are either internally or external to the area. Landfills in the GTA area receive waste primarily from three sources: (i) pet waste, (ii) food waste, (iii) biosolids from WWTP and septic tanks. If we employ the methods above, landfill export may reduce by 59% for N and 93% for P. As mentioned, since it is becoming increasingly difficult to find new areas for landfill construction, this would significantly reduce the environmental footprint of the GTA.

Food import, specifically for the urban and suburban areas, comprises 83% of the N (54% of the P) inputs into the GTA, and external dependency on food can be minimized by using more local food. In an idealized scenario, we assume that all food grown in the GTA is consumed locally, and this reduces food imports by over a third, from 35.7 kton N (3.5 kton P) to 23.4 kton N (1.4 kton P). Here, the rural subsystem provides food to the urban and suburban systems. The food exports from the system is reduced to zero given that all the food produced internally is consumed by the local population. Though this may not be the most realistic scenario, given that all kinds of food needed by the population cannot be internally produced, but produces an upper bound on the extent of circularity possible in the system. Under this assumption, 39% N (64% P) of the food needed by GTA (including rural) could be produced internally, in contrast to 7% N (11% P) in the current scenario.

For P, the second largest component of the input is detergent P. While regulations on detergent P led to a widespread decline, levels in Canada were still approximately 0.42 kg P/capita/year up until July 2010, after which it dropped down to 0.051 kg P/capita/year as reported by Environment Canada (2011). This new regulated value is closer to low values found in Italy (the lowest of the European countries) of 0.03 kg P/capita/year (University of the West of England, Science Communication Unit 2013). We implemented the regulation set by Canada in the ideal case and this led to an 87% reduction in P detergent inputs.

Overall, we found that the GTA can improve its rural-urban collaboration by increasing the circularity of the identified components in **Figure 12**. The rural area does not generate sufficient compost to completely sustain its fertilizer needs, however, if we combine this with compost and biosolids from the urban and suburban areas, we can completely eliminate fertilizer imports to the GTA. With the large population in this area, there is enough compost and biosolids generated to export nutrients which can become a viable business opportunity for the GTA. It is interesting to note the synergy between the rural, urban, and suburban subsystems of the GTA – the rural system supplies food to the urban and suburban system, while the urban and suburban systems generate compost and biosolids that can be used to supply the fertilizer needs of the rural system. The benefit of this rural-urban interface includes reducing overall environmental footprint of GTA and increase circular economy.

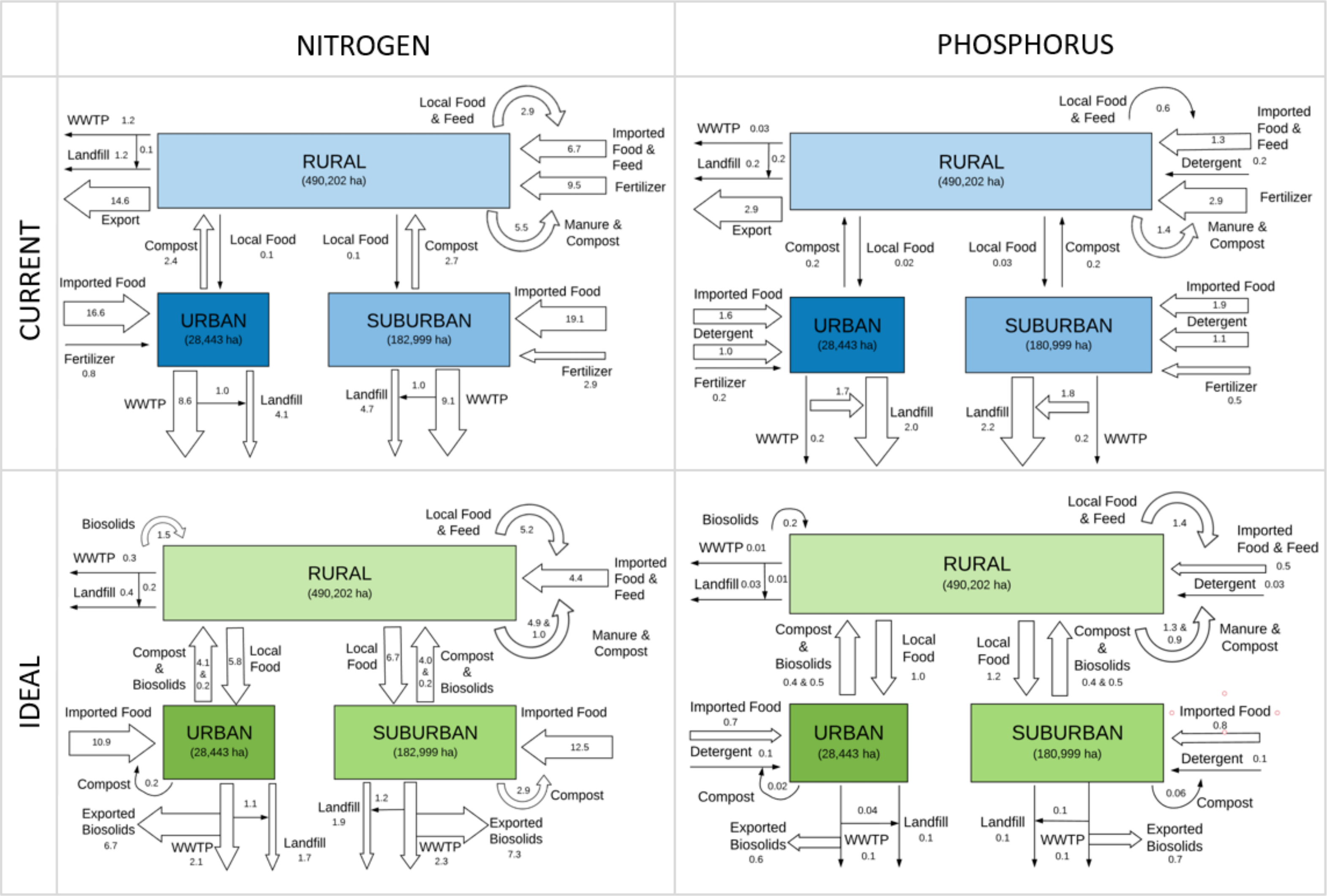

Figure 12: Nutrient fluxes across the various subsystems of the GTA under current and ideal conditions. Decreasing fertilizer applications, reusing internal nutrients, and assuming local foods supply the needs of the population drastically reduces imports, thus improving the GTA's circular economy. There is a net export in nutrients if fertilizer usage is managed according to needs and the full capacity of food waste and WWTP removals to generate composed is considered**.** Note that arrows represent approximate magnitude.

3.4 Comparison to Other Nutrient Studies

We compared the results of our urban metabolism study of the GTA to other nutrient studies conducted for N and P in urban areas, and found similar patterns. The food for humans is a large component of many budgets given the high population density (Esculier et al. 2018; Baker et al. 2001; Álvarez et al. 2018; G. S. Metson and Bennett 2015; G. S. Metson et al. 2012). For this reason, there have been studies that focus on food dynamics alone (Forkes 2007; G. S. Metson and Bennett 2015). In addition, the high residential fertilizer application was a signature for many cities such as St. Paul, Minnesota (Hobbie et al. 2017) and Baltimore, Maryland (Law, Band, and Grove 2004). The latter summarized studies that estimated homeowner fertilizer application that ranges from 24 kg N/ha to 298 kg N/ha that is close to the GTA's range of 10 kg N/ha to 238 kg N/ha (Law, Band, and Grove 2004). Furthermore, it was found that the contribution from dog waste exceeded the effects of atmospheric deposition in high residential areas in St. Paul, just as in the GTA (Hobbie et al. 2017). The setting of the urban city is important since more arid cities are more subject to congestion and atmospheric deposition (Baker et al. 2001).

Finally, many nutrient studies focused on urban areas display a low circular economy that is heavily consumption driven. The study of Paris Megacity by Esculier (2018) demonstrated only 3% recycling of N and much of its exports to waterbodies stemming from WWTPs. The GTA currently displays little circularity, but has the potential to increase N recycling by 80% by improving WWTP efficiencies, eating locally, and the reuse of compost and manure. In our study, the analysis of the WWTPs revealed the focus of P over N in terms of management. Other studies have revealed the variation in N:P ratios in components and the need to manage these equally, but differently; P exhibits high mobilization while N undergoes denitrification (Hobbie et al. 2017; G. S. Metson et al. 2012). The urban areas in other countries such as St. Eustatius (Firmansyah et al. 2017) and Spain (Álvarez et al. 2018) reveal a reliance on external markets for food and fertilizer. In Phoenix, nutrient recycling pathways were suggested to make use of the large amount of human waste, such as export of P from WWTP and reuse in steel production (G. S. Metson et al. 2012).

3.5 Policy Implications

"Approving a landfill in Ontario is not for the faint of heart."

- Adam Chamberlain, Toronto environmental lawyer (Waterloo Region Record 2011)

The results demonstrated the high impact of urban areas in nutrient flow, and this calls for better management at both the residential and government level. For the GTA, much of the urban area is located on the edge of Lake Ontario; large and rapid runoff as well as WWTP effluent are especially concerning for water quality. The little nutrient circularity has the potential to be improved through better composting habits and management through increased diversion of food and pet waste from landfills. Additionally, we noticed a larger focus on P through reports and data availability. Reducing and managing the eutrophication of the GTA waterbodies will need better monitoring of N that matches the stringent regulation of P that is set for the Great Lakes region.

We believe the promotion of a circular economy aligns well with municipal goals. First, a major concern for municipalities is landfill space. In Ontario, the process of scouting for a suitable space with the proper environmental assessments is a lengthy and expensive process through the provincial government (Waterloo Region Record 2011). As of 2011, a new landfill had not been approved in Ontario since 1999 and the lack of suitable local sites required the City of Toronto to truck as far as Michigan to dispose waste (Waterloo Region Record 2011; Clapp and Princen 2003). In an effort to lengthen the lifespan of landfills, cities aim to reduce waste tonnage through recycling and composting advocacy. Cities such as those in the Region of Peel have adopted a biweekly one-bag garbage policy coupled with weekly composting pick-up to encourage residents to divert organic waste from landfills (Region of Peel 2018). This reduces overall transportation costs to landfills located further away and extends the life of their current landfills (Lee-Shanok 2018). In developing policies that guide homeowners to better diversion, we can see an increase in nutrient circularity. Furthermore, pet waste contributes to landfill build-up and residents often complain if this waste is not picked up due to its unsightliness, especially in public parks (Kauri 2012). From a nutrient perspective, we see this as a great problem, particularly in the urban areas where there is high concentration of pets near more impervious surfaces. As an example of mitigation strategies, the City of Markham has installed receptacles that provide free pick-up bags and disposal units.

Another municipal responsibility is the regulation of flooding which has been carried out through the use of detention ponds and sewers. The latter, however, is a conduit for nutrient flow directly to rivers and lakes. Increasing buffer strips and strategizing the locations and functionality of detention ponds to better handle nutrients can be helpful with high rainfalls and flash floods (Donofrio et al. 2009). This provides municipalities with yet another opportunity to set goals that align with the importance of nutrient management. Further to the point, this research shows the high impact (spatially and temporarily) of WWTP bypasses and, along with the above mentioned mitigation strategies, there could be less frequent bypasses and, as a result, fewer high concentration nutrient disposals on receiving water bodies. This is particularly concerning when cities have combined sanitary and storm sewers which are prime culprits to high nutrient and pollution discharge during heavy rainfall events, and they are more susceptible to overwhelming the built-in system (Kneisel 2001).

We assumed industries had a negligible impact on the mass balance mostly due to the lack of available data. We looked at all the industries in the City of Toronto reporting to the NPRI (2011), and only 9 and 4 industries reported for N and P outlet respectfully. The combined amount of reporting industries represented less than 1% of Toronto WWTP effluent (Government of Canada 2011). The issue is that, at certain concentration levels, industries are not required to report their outlet and so the cumulative amount and effect is lost. Stricter monitoring of industries, such as detection devices nearby or in adjacent sewer systems, can better mitigate nutrient input to water bodies and track other environmental pollution issues like oil spills.

Moreover, we have the potential to reduce the overall fertilizer inputs by controlling rates of application. As mentioned, farmers and the average homeowner have a tendency to over-apply fertilizer (in frequency and magnitude) on their fields and lawns (Leslie et al. 2017). Farmers may apply less fertilizer on a kilogram per hectare basis than homeowners, but they tend to adhere to previous farming practices that do not always consider legacy nutrients and specific crop requirements. For instance, the Grand River Conservation Authority have been working collaboratively with farmers to protect groundwater sources through the Rural Water Quality Program and nutrient management plan workshops (Simpson and de Loë 2014). In fact, there is evidence of a net P removal from soils in the Grand River watershed as well as in Montreal and France agricultural fields due to greater awareness of the effects of P on fresh water bodies and regulations that are set to minimize P runoff to waterbodies (Van Meter, Basu, and Van Cappellen 2017; G. Metson, Aggarwal, and Childers 2012; Esculier et al. 2018).

Since the GTA is uniquely entangled with Ontario's Greenbelt (**Figure 13**), development has been carefully building around this area since 2005 (Government of Ontario 2017). Our results demonstrate the high and influential nutrient impact in urban areas. Soil surplus is generally lower in these areas because fertilizer and manure application are offset by crop uptake. The urban areas have high and unregulated nutrient application rates on lawns and general pollution that are quickly conveyed to water bodies due to impervious surfaces and sewer connections. By safeguarding the Greenbelt, Ontario can better buffer nutrient input to adjacent lakes and rivers. The urban impact is significant even beyond water quantity and quality; the Ontario government has the great potential to work with municipalities and conservation authorities to combine common objectives and protect the Greenbelt. For instance, the Ontario Ministry of the Environment has actively been working to reduce P loads to Lake Simcoe through the Lake Simcoe Protection Plan (The Louis Berger Group, Inc. 2010; Hutchinson Environmental Sciences Ltd. et al. 2012). Along with Hutchinson Environmental Sciences Ltd. et al. (2012), the government has created a standard for developers where they must first work outside of the Greenbelt boundaries and prove that both construction and post construction changes have P loadings that either match or better pre-existing P loads. Under this report, there is evidence that newly constructed urban areas release nutrients from previously undisturbed soils and continue to do so post construction (Hutchinson Environmental Sciences Ltd. et al. 2012). The new development further compromises the ability for soil seepage of water and nutrients due to the tendency of these lands to be heavily compacted during construction (Law, Band, and Grove 2004).

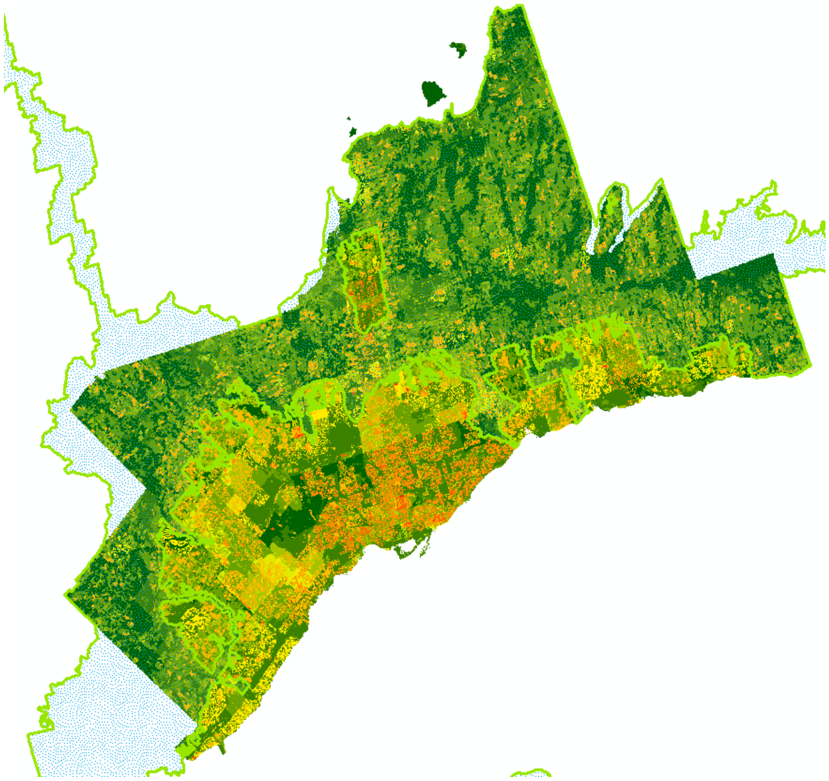

Figure 13: Much of the GTA is safeguarded by Ontario's Greenbelt (outlined in green) that was implemented in 2005 shown against our N soil surplus map. Much of the lower net nutrient concentrations are within this area and should be considered in future policy consideration. Development expansion into the Greenbelt could mean higher nutrient inputs.

3.6 Uncertainties

The calculations of the current and projected urban metabolism of the GTA were subjected to uncertainties due to data limitations and required assumptions. The assumptions were justified using literature references and extrapolations from available data, as outlined in this section.

Uncertainties in Urban Metabolism Calculations

We assumed a constant food consumption rate for all Canadians (Statistics Canada 2009; Karp et al. 2012) and did not consider variation in age as was done by Baker et al. (2001) since the Canadian values were represented as an average per person. Since we did not consider this separation, we assumed the waste sent to landfills through diapers as shown by Roy, White, and Seibert (2014) was routed as a typical resident of the GTA. Furthermore, we assumed that the number of tourists coming into the GTA equaled residents leaving on vacation. The reality of this could be tipped on either side. We briefly looked at the number of hotel rooms purchased in the GTA for 2011 (Tourism Toronto 2012), but this does not cover home rentals, staying with family or friends, or even the number of people staying in each hotel room. In addition, there was not a great estimate of vacationers or the number of people staying in the area temporarily for schools, work, or other reasons, who have reported to other census divisions.

Mustapha (2013) reported that 71% of Toronto residents participated in “some form of composting” in 2011, a vague statement when conducting an analysis that requires a set parameter value per capita. As a result, we used the lower Canada wide value of 45% to be more realistic of 2011 conditions in the area (Mustapha 2013). Additionally, there are composting habit differences between dwelling type with apartments displaying a low compost rate of 26% (Mustapha 2013). Household composting is difficult to manage due to contamination, low participation, and general low education on the subject. Furthermore, we took all compost to replace residential fertilizer needs, but this practice has not been perfected in the GTA. The City of Toronto received local complaints of the smell of fertilizer that are sourced from compost in small pilot programs across 20 local parks (City of Toronto 2018; Salvian 2017). There is further question on the management of compost. An investigation led by the Toronto Star reported that approximately one-fifth of Toronto’s organic waste was being disposed or incinerated in landfills (Welsh 2009). In the City of Toronto, diapers are accepted in the compost stream, however, the management company at the time would remove these straightaway and claimed it looked great for diversion numbers, but did not fully represent the actual situation (Welsh 2009).

For our analysis, we took the minimum efficiency of WWTPs in the GTA for P removal (94%) and applied these rates to all 31 WWTPs (**Table A2**). This is higher than the mandate by the European Urban Waste Water Treatment Directive (European Council Directive 91/271/EEC) for areas prone to eutrophication which requires WWTPs to remove 70% of N and 80% of P (Esculier et al. 2018). Realistically, each plant operates differently and has varying inputs and capacities. Changing rates for older WWTPs that service a large population is especially difficult due to constant usage that gives little time for upgrades.

We extrapolated pet population and breed data from the City of Toronto to the rest of the GTA. We assumed a relationship between human and pet population, however, the relationship may vary in the outer cities. We did not include stray animals for this analysis though this was available through the City of Toronto ("Open Data Catalogue" 2017); the stray population was a fraction of the reported and given the licensing adjustment for pets, it was assumed that the overall effect was negligible. As mentioned, we briefly explored the nutrient input by wild birds based on reported sightings and the contribution was deemed negligible. Therefore, we assumed the nutrient contribution by wildlife to be negligible as well.

The agriculture fertilizer and export estimates were based on provincial values and there is uncertainty in downscaling these values to the municipal level. These values may be skewed in either direction of high or low magnitudes. For instance, we found yield rates vary much between cities and the degree of urbanization may affect the rate application of fertilizer and overall production values. In addition, assumptions were made to adjust for the lack of livestock population and crop data stemming from privacy issues (**Appendix B5**). Also, there is uncertainty in these assumptions as well as the constant occupancy rates and nutrient concentrations applied to each livestock breed and crop type.

We based residential fertilizer on approximate household spending and the basis of this value came from surveys (Statistics Canada and Income Statistics Division 2013). The uncertainty of the survey implications were thus projected to the fertilizer calculations used in this study. Furthermore, we assumed a constant split of fertilizer and manure between runoff (25%) and seepage (75%) for the GTA though this value should realistically vary across the landscape (Howarth et al. 1996). For instance, the soil texture is important for seepage, and fertilizer or manure applied directly before rainfall has higher susceptibility to runoff. These calculations were beyond the scope of this work and are subject to uncertainty from both a spatial and temporal perspective. Similarly, the septic tank allocations to landfill (40%), seepage (40%), and runoff (20%) are subjected to uncertainties, as well (Ursin 2007; Withers et al. 2014). Realistically, these values vary between management capabilities and the surrounding environment. Among the other components, these runoff and soil estimates represent the largest uncertainty.

As mentioned, the reporting through the NPRI (2011) on industry nutrient output was low and the cumulative effect of the industries across the GTA was not quantified. Though the contribution of industries into WWTPs could not be measured, the outputs included these values. The associated denitrification value within WWTPs may be much larger than estimated due to the influence of industries. In addition, atmospheric deposition was represented at a constant rate though factors such as industry, car exhaust, and lake proximity may vary the deposition effects (Baker et al. 2001). The approximate atmospheric deposition was fairly small in comparison to the other components and so the variation of this component was assumed to be negligible.

For this study, we decided to restrict our work to larger components that would have the potential to directly impact waterbodies and soils, such as food and fertilizer. Other components such as construction material and clothing found in other similar studies (G. S. Metson et al. 2012) were not included at this time. Though one of the industries reported P removal sent to a cement company for reuse, the lack of data for other industries and associated recycling leaves these components unknown (Government of Canada 2011). They may express large nutrient flows to landfill or fixed structures, though we considered these as one way flows with little potential to be recycled or impact the environment as the other components in the urban metabolism study.

Uncertainties in Ideal Projections

In the ideal projection, we assumed that residents in the GTA consumed the locally grown food in the GTA before exporting, just as the NANI and NAPI framework. There is uncertainty in the feasibility of this assumption because there is high degree of specialization of certain crops and livestock in this area. For instance, the GTA has many dairy cows that produce a large amount of milk and it may be unrealistic to assume the population would rely on dairy to this degree for its nutrient requirement.

Furthermore, we assumed an increase of compost and manure application to lawns to equal jump from 45% (Mustapha 2013) and 48% (Dorff and Beaulieu 2014) respectfully up to 80%. As mentioned in **Section 3.4**, there are issues with the application of compost and reaching a recycling efficiency this high was subjected to uncertainty. Furthermore, we considered manure to replace the agriculture needs for the GTA. Though we did not consider the logistics of actual usage, we do recognize the importance in considering amounts, storage, willingness to participate, and the realistic transport over a certain distance (Werenka, *in production*). Furthermore, there is a stigma associated with using manure in replacement of fertilizer, especially in GTA. In 2000, there was an outbreak of E.coli in Walkerton, Ontario due to cow manure suspected to infiltrate a local water source and this led to the deaths of 7 people and leaving thousands more sick (Holme 2003). Globally, it is somewhat controversial to reuse human waste as fertilizer. In China, the use of “night soil” has been a common long-time practice on agricultural fields, but has been studied further recently to find connections with impacts to human health (Carlton et al. 2015). However, there are small accomplishments in changing perspectives on reusing waste such as the campaign to accept “reused grey water” (Allen, Christian-Smith, and Palaniappan 2010). Should this process be socially accepted, the appropriate permits associated with the export of biosolids would also have to be considered. Therefore, much of our efforts to create a circular economy and reuse our waste will need to involve changing the perspectives of residents.

It is very difficult to control the habits of homeowners and how they choose to fertilize their lawns. A similar situation can be seen for the lawn watering habits of homeowners who, even with imposed by-law restrictions, do not seem to properly follow these legislations (Finley *in production*). Farmers tend to over-fertilize their fields, though not as much as homeowners. We assumed that farmers would apply fertilizer based on crop needs, but this is not easily done, especially when soil nutrient concentration has high variation, both manure and compost may have varying concentrations of N and P, and farming practices are passed down through generations (Simpson and de Loë 2014; OMAFRA 2012). OMAFRA (2012) suggests soil testing and farmers could further reduce their applied fertilizer when considering legacy nutrients already in the soil (Van Meter, Basu, and Van Cappellen 2017). At this time, we did not consider the fertilizer application for the lawns of industries and institutions such as schools. The application amount and rate each vary significantly for these property types and they are often not differentiated in zoning by-law maps.

We may not be fully considering the efficiency that comes with emerging technologies. For instance, work by Gabriel et al.(2017) explored remote sensing in order to improve fertilizer application using drone technology and airplanes by being able to identify areas that require N fertilizer. Moreover, we currently considered the influence of roof gardens to be negligible due to low numbers and low estimated rates of atmospheric deposition. Realistically, there is variation in atmospheric deposition and roof gardens may be strategically placed though there is evidence they can act either act as a sink or source for N and P depending on conditions (Wang, Qin, and Hu 2017).

4 Conclusion

4.1 Summary

Our analysis of the GTA demonstrates the need to consider urban areas as unique entities that play an important role in a city’s metabolism. Cities, especially those which are densely packed, are characterized by man-made subsystems, such as WWTPs and garbage management, which displace nutrients differently than rural areas. The population of a city increases the impacts of pet waste, fertilizer usage, and consumption. Improving circular economy and a city’s metabolism will ultimately depend on one main driving factor: humans and their associated choices. The habits of humans and the systems they use directly and indirectly influence the movement of N and P. The study of N and P in conjunction has not been analyzed beyond food flows for the GTA, and therefore, the goal of this work was to identify the key drivers and flows of N and P. We looked at the functioning of the GTA’s subsystems to analyze its self-sufficiency and to identify ways towards a more closed-loop circular economy.

To accomplish our outlined goals, we determined the various components of the urban metabolism N and P framework applicable to the GTA. We hypothesized correctly that the anthropogenic influence would be a dominating factor in our analysis, as demonstrated in other mass balance and metabolism studies for large cities across the globe. On a per hectare basis, the urban areas have a larger nutrient input that was 5 to 6 times higher than the suburban areas and double in comparison to rural areas, primarily due to nutrient requirements for humans. We also found that the high pet population in the area was the same magnitude as atmospheric deposition, whereas this component is not always considered. In addition, nutrients from urban fertilizer do not have the opportunity to be taken up and we found that the overall nutrient surplus was concentrated in the urban and suburban turf areas, mostly located along the shores of Lake Ontario.

Furthermore, we found that the processes of WWTPs were essential in managing the high food consumption in cities. They play an integral role in disposing the waste, even though they currently have high nutrient concentration disposals, especially for N. Bypasses make up 14% of overall P effluent; limited WWTP capacity and the acceleration of climate change may increase the size and frequency of bypasses thus discharging heavier nutrient concentrations that has a high N;P ratio into receiving waterbodies. Furthermore, analyzing the WWTPs demonstrated the importance of sewersheds and governing administrative boundaries versus watershed boundaries. Decisions made by municipalities to manage WWTPs, implement low impact development solutions, and organize compost regulations are all important in ensuring the regulated flow of nutrients through the urban landscape.

The rural-urban collaboration was analyzed for the GTA and it was found that there is, currently, little interaction between the urban and suburban areas with the rural areas. The GTA relies heavily on imports of fertilizer and food. We generated an ideal scenario in which nutrients were recycled with local foods and a combination of compost, manure, and biosolids. Theoretically, we found that the GTA can completely eliminate fertilizer inputs and export 14.1 kton N and 1.6 kton P. In addition, we have the opportunity to reduce food imports by at least 30%. This reveals a potential to improve policies and increase the GTA's circular economy.

4.2 Future Work

An extension of this work would be to complete this analysis of the urban metabolism of the GTA on a longer time scale to analyze the influence of population growth, land use change, and agriculture specialization. The City of Toronto was founded in 1834 and its history is diverse and fairly well documented (Millward 1992). It would be interesting to spatially track the influence of specific land use changes and when impervious surfaces became dominating. In addition, many of the abandoned landfills are within these boundaries and have since been built over; nutrient leaching from landfills was not considered at this time, but may be important as a whole (Howard and Livingstone 2000). Furthermore, the animals kept throughout the years, from horses dominating to pets, may be tracked to see the waste impact on the landscape over time. Although horses may have larger nutrient input, there was a higher abundance of them in this area when the land was more pervious (Millward 1992). In addition, the influence and effectiveness of tracking policy changes, such as the detergent decline in the 1970s, may yield interesting results (Walz 1970). With this extension, the start of issues such as local beach closures can be tracked and be helpful in advising local conservation authorities as well as other large cities with similar urban and natural environmental characteristics.

In contrast, there is potential to take the lessons learned from this study to conduct a site specific analysis of an urban subdivision. We generalized components on a yearly basis, however, it would be interesting to explore how a model would perform with neighbours applying fertilizer at different times with some right before a rainfall event. We did not consider the potential influence stormwater management (SWM) ponds or large adjacent reservoirs may have on nutrient runoff in urban areas. Food analysis can be studied in greater detail to see the ratio of imported versus exported food. If this was restricted to watershed instead of administrative boundaries, more precise runoff flows could be calculated. A metric could be developed based on housing type, population density, and urban constructed water management facilities (sewers, SWM ponds, or other low-impact development solutions) in a given area that can inform future policy development.

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Appendix A

Supplemental Information on the GTA

Table A1: A summary of all the regions and their individual cities. Note that Toronto is its own region/city (AAFC 2011).

Region	**City**
Toronto	
Peel	Mississauga
	Brampton
	Caledon
York	Vaughan
	King
	Richmond Hill
	Markham
	Whitchurch-Stouffville
	Aurora
	Newmarket
	East Gwillimbury
	Georgina
Halton	Halton Hills
	Milton
	Oakville
	Burlington
Durham	Pickering
	Ajax
	Uxbridge
	Scugog
	Brock
	Whitby
	Oshawa
	Clarington

Table A2: Summary of the WWTP in the GTA and their associated reports.

WWTP	Regional Management	WWTP Report Citation	Sewersheds Citation
Acton Georgetown Mid-Halton Milton Oakville SE Oakville SW Skyway	Halton	(Halton Region 2012)	(GIS Data Management 2012)
Clarkson G. E. Booth Inglewood	Peel	Personal communication	(Blue Plan Engineering Consultants Ltd. and AECOM 2014)
Ashbridges Bay	Toronto	(Toronto Water 2011a)	(City of Toronto 2005)
Highland Creek		(Toronto Water 2011b)	
Humber		(Toronto Water 2011c)	
North Toronto		(Toronto Water 2011d)	
Keswick Kleinburg Schomberg Mount Albert Sutton	York	(York Region 2011)	(York Region 2011)
Duffin	Durham/York	(Durham Region 2012)	(Durham Region 2012)
Corbett Creek Courtice Harmony Creek Port Darlington Uxbridge Brook Beaver River 1 (Sunderland) Beaver River 2 (Cannington) Lake Simcoe Newcastle Pringle Creek Nonquon	Durham		

Appendix B

Supplemental Methods Table and Explanations

Appendix B1 – Summary of Calculations

Table B1: Summary of the equations used in the urban metabolism study with further detail for certain components as mentioned.

Input	Equation	Description
Soil Surplus		
N Soil Surplus (kg N)	$= \text{Crop fertilizer} + \text{Manure} + \text{Biological N fixation} + \text{Residential fertilizer} + \text{Golf fertilizer} + \text{Park fertilizer} + \text{Cemetery fertilizer} + \text{Atmospheric deposition} + \text{Pet waste} + \text{Leakage from septic tank} - \text{Crop yield}$	All units are in kg N and these components are detailed in this table.
P Soil Surplus (kg P)	$= \text{Crop fertilizer} + \text{Manure} + \text{Residential fertilizer} + \text{Golf fertilizer} + \text{Parks fertilizer} + \text{Cemetery fertilizer} + \text{Atmosperic depostion} + \text{Pet waste} + \text{Leakage from septic tank} - \text{Crop yield}$	All units are in kg P and these components are detailed in this table.
Humans		
Nutrient Requirement for Humans (kg N or kg P)	$= \text{Human population} \times \text{Nutrient intake for humans (kg N/cap or kg P/cap)}$	The human population was multiplied by the average annual Canadian nutrient consumption, 4.1 kg N/cap and 0.4 kg P/cap (CHASS 2011; Statistics Canada 2009; Karp et al. 2012).
Export Food (kg N or kg P)	$= \sum_{i=1}^{n} \text{Crop yield}_i \text{ (kg N or kg P)} \times \text{Crop export}_i\ (\%) + \sum_{j=1}^{m} \text{Livestock production}_j \text{ (kg N or kg P)} \times \text{Meat export}_j\ (\%)$	The production of different crops (*i*) with a total of *n* = 14 and meat products (*j*) with a total of *m* = 4 shown in **Table B2.1** is estimated to be exported outside of the GTA based on Ontario values shown in **Table B2.2**.
Local Food for Humans (kg N or kg P)	$= \sum_{i=1}^{n} \text{Crop yield}_i \text{ (kg N or kg P)} \times \text{Crop for humans } (\%) + \sum_{j=1}^{m} \text{Livestock production}_j \text{ (kg N or kg P)} - \text{Export Food (kg N or kg P)}$	The local food for humans was calculated from a combination of different crops (*i*) with a total of *n* = 14 and meats (*j*) with a total of *m* = 4 grown in the GTA. A portion of crops was allocated to humans as opposed to feeding livestock (**Table B2.1**). Exported food was subtracted to then the total local food for humans.

Imported Food for Humans (kg N or kg P)	$= \text{Nutrient requirement for humans (kg N or kg P)} - \text{Local food for humans (kg N or kg P)}$	The deficit between the nutrient requirement and local food circulation was estimated to be the imported food.
P Detergent for Humans (kg P)	$= \text{Human population } \times \text{Detergent (kg P/cap)}$	The human population was multiplied by the combined dishwasher and laundry detergent value of 0.051 kg P/cap (CHASS 2011; Han, Bosch, and Allan 2011).
Food Waste to Compost (kg N or kg P)	$= \text{Human population } \times \text{Food waste (kg N/cap or kg P/cap) x Compost habit (\%)}$	Total amount designated for compost was calculated as the food waste multiplied by an approximate compost habit of 45% (CHASS 2011; Mustapha 2013).
Food Waste to Landfill (kg N or kg P)	$= \text{Human population } \times \text{Food waste (kg N/cap or kg P/cap)} - \text{Food waste to compost (kg N or kg P)}$	The difference between the total food waste and compost was the estimated nutrients being contained in landfill.
N Leakage from Septic Tanks (kg N)	$= \text{Human population on septic tanks } \times \text{Human excrete (kg N/cap) } \times \text{ Septic tank leakage (\%)}$	Populations outside of sewer network coverages were assumed to be serviced via septic tanks. Excrete per person was 3.3 kg N/cap (CHASS 2011; Statistics Canada 2009) and leakages from septic tanks were estimated to be 40% (Ursin 2007; Withers et al. 2014).
P Leakage from Septic Tanks (kg P)	$= \text{Human population on septic tanks } \times [\text{Human excrete (kg P/cap)} + \text{Detergent (kg P/cap)}] \times \text{Septic tank leakage (\%)}$	Populations outside of sewer network coverages were assumed to be serviced via septic tanks. Excrete per person was estimated to be 0.2 kg P/cap (Statistics Canada 2009) and detergents have approximately 0.051 kg P/cap (Han, Bosch, and Allan 2011). Leakages from septic tanks were estimated to be 40% (Ursin 2007; Withers et al. 2014).
Pets		
Nutrient Requirement for Pets Outside Toronto (kg N or kg P)	$= \sum_{i=1}^{n} \text{Pet population}_i \text{ x Nutrient intake for pets}_i$ (kg N/cap or kg P/cap)	The nutrient intake for two (*n* = 2) domesticated animals (*i*), cats and dogs, were calculated using City of Toronto (2017) information the average dog requiring 4.2 kg N/cap (0.5 kg P/cap) and he average cat requiring 1.7 kg N/cap (0.1 kg P/cap). The population of domesticated animals for the rest of the GTA was assumed to be proportional to the human population (0.08 dogs/human and 0.11 cats/human). Note that a breakdown of the City of Toronto pet calculation was more specific and detailed in **Appendix B3**.

Dog Waste to Landfill (kg N or kg P)	$= \text{Nutrient requirement for dogs (kg N or kg P)} \times \text{Nutrient content in feces (\%)} \times \text{Pick up habit (\%)}$	Total intake was assumed equal to output and this amount was multiplied by content of feces which was 15.1% of N and 73.5% of P (Fissore et al. 2011; Baker et al. 2007). An additional waste pick up value of 60% by owners was applied (Swann 1999).
Dog Waste to Landscape (kg N or kg P)	$= \text{Nutrient requirement for dogs (kg N or kg P)} - \text{Dog waste to landfill (kg N or kg P)}$	The difference between nutrient intake for dogs and landfilled nutrients was assumed to go directly to landscape.
Cat Waste to Landfill (kg N or kg P)	$= \text{Nutrient requirement for cats (kg N or kg P)} \times [\text{Nutrient content in feces (\%)} + \text{Nutrient content in urine (\%)} \times \text{Litter box portion (\%)}]$	Total intake was assumed equal to output and this was multiplied by content of feces, 15.1% of N and 73.5% of P, which we assumed to be similar to that of dogs (Fissore et al. 2011; Baker et al. 2007). We assumed that all feces and 50% of urine were taken away from litter box to landfills (Baker et al. 2001).
Cat Waste to Landscape (kg N or kg P)	$= \text{Nutrient requirement for cats (kg N or kg P)} - \text{Cat waste to landfill (kg N or kg P)}$	The difference between nutrient intake for cats and landfilled nutrients was assumed to go directly to landscape. For cats, this was essentially 50% of urine to account for outdoor cats (Baker et al. 2001).
Livestock		
Nutrient Requirement for Livestock (kg N or kg P)	$= \sum_{i=1}^{n} \frac{\text{Livestock population}_{\text{i}}}{\text{Occupancy}_i (\%)} \times \text{Nutrient intake for livestock}_i \text{ (kg N/cap or kg P/cap)}$	The livestock population per species (*i*) with a total of *n* = 17 species was adjusted based on the average occupancy (**Table B2.3**) on a farm in a typical year. The individual populations were multiplied by their respective average nutrient intake (**Table B2.3**) and summed to find the total nutrient requirement for livestock.
Local Food for Livestock (kg N or kg P)	$= \sum_{i=1}^{n} \text{Nutrient requirement for livestock}_{\text{i}} \text{ (kg N or kg P)} \times \text{Pasture diet (\%)} + \sum_{j=1}^{m} \text{Crop yield}_j \text{ (kg N or kg P)} \times [1 - \text{Crops for humans}_j (\%)] \times [1 - \text{Crop export}_i (\%)]$	It was estimated that each of the grazing animals (*i* and starred in **Table B2.3**, with a total of n = 10 species) obtained 32% of their diet from pasture land (Roy, White, and Seibert 2014). Similar to local foods for humans, we estimated each of the local crops (*j*) with a total of *m* = 14 contributed to livestock diet by summing the remaining crops available after exports and after allocation to humans.

Imported Food for Livestock (kg N or kg P)	$= \text{Nutrient requirement for livestock (kg N or kg P)} - \text{Local food for livestock (kg N or kg P)}$	The deficit between the nutrient requirement and local food circulation was estimated to be the imported food.
Manure (kg N or kg P)	$= \sum_{i=1}^{n} \frac{\text{Livestock population}_i}{\text{Occupancy}_i\ (\%)} \times \text{Nutrient excrete from livestock}_i\ (\text{kg N/cap or kg P/cap})$	The livestock population per species (*i*) with a total of *n* = 17 species was adjusted based on the average occupancy (**Table B2.3**) on a farm in a typical year. Each population per breed was multiplied by their respective average nutrient excrete (**Table B2.3**) and summed altogether to find the total manure.
Livestock Production (kg N or kg P)	$= [\text{Nutrient requirement for livestock (kg N or kg P)} - \text{Manure (kg N or kg P)}] \times [1 - \text{Loss in waste (\%)}]$	The difference between intake and excrete was assumed to be production for meat including a 10% loss in waste. Note that the animals listed in **Table B2.3** that were not sold for meat include horses, llamas, and rabbits.
Urban Fertilizer		
Residential Fertilizer (kg N or kg P)	$= \sum_{i=1}^{n} \sum_{j=1}^{m} \text{Number of dwellings}_{ij} \times \text{Rate of fertilizer application}_{ij}\ (\text{kg N/ha or kg P/ha})$	For each city (*i*, with a total of *n* = 25 cities), the number of apartments, semi-attached dwellings, and single-detached dwellings (different housing types represented as *j*, with a total of *m* = 3) were multiplied by individual rates that were dependent on approximate spending per household (CHASS 2011). Note that a breakdown of the residential fertilizer can be found in **Appendix B4.**
Park Fertilizer (kg N or kg P)	$= \text{Total park area (ha)} \times \text{Rate of park fertilizer application (kg N/ha or kg P/ha)}$	Park fertilizer rates were estimated to be 3.5 kg N/ha and 0.6 kg P/ha based on City of Toronto fertilizer purchases (Enriquez 2012). These are generally low to avoid fast growing turf, ultimately reducing mowing frequency.
Cemetery Fertilizer (kg N or kg P)	$= \text{Total cemetery area (ha)} \times \text{Rate of cemetery fertilizer application (kg N/ha or kg P/ha)}$	Cemetery fertilizer rates were estimated to be 150 kg N/ha and 16 kg P/ha (Tsiplova et al. 2007). These rates are generally high due to importance of aesthetics.

Golf Fertilizer (kg N or kg P)	$= \sum_{i=1}^{n} \sum_{j=1}^{m} \text{Total golf course area}_i (\text{ha}) \text{ x Golf component area}_\text{j} (\%) \times \text{ Rate of golf component fertilizer application}_j \text{ (kg N/ha or kg P/ha)}$	The approximate area coverage of each of a golf course's main components (*j* which represented each of the green, fairway, tee, and rough, totalling *m* = 4 types) calculated by Tsiplova et al. (2007) for 9-hole, 18-hole, and other courses was multiplied by general fertilizer rates for each of these specific components (King et al. 2001) for all 171 GTA golf courses (*i*, with a total of *n* = 171). See **Table B2.4** for complete area percentages and fertilizer rates.
Agriculture		
Agriculture Fertilizer per Region (kg N)	$= \text{Ontario Fertilizer Sale (kg N)} \times \frac{\text{GTA Agriculture Area (ha)}}{\text{Ontario Agriculture Area(ha)}} \times \text{Fertilizer usage (\%)}$	The N sales of fertilizer in Ontario (189 kton N) were proportioned to the GTA's fertilized agricultural area and multiplied by a usage factor of 90.6% (Statistics Canada, 2016) to determine the fertilizer used per region.
Agriculture Fertilizer per Region (kg P)	$= \text{Ontario Fertilizer Sale (kg P)} \times \frac{\text{GTA Agriculture Area (ha)}}{\text{Ontario Agriculture Area(ha)}} \times \text{Fertilizer usage (\%) x 436.4}$	The phosphate (P_2O_5) sales of fertilizer in Ontario (139 kton P) were proportioned to the GTA's fertilized agricultural area and multiplied by a usage factor of 90.6% (Statistics Canada, 2016) as well as a conversion factor of 436.4 from P_2O_5 to P in order to determine the fertilizer used per region.
Crop Yield (kg N or kg P)	$= \sum_{i=1}^{n} \text{Crop production}_\text{i} (\text{kg N or kg P}) \times \text{ dry matter}_i (\%) \times \text{Nutrient content}_i (\%)$	OMAFRA (2011) production data for 12 harvest crops was used as well as Statistics Canada (2012) production data for fruits and vegetables, where *i* represents each crop type and totalled *n* = 14 types of crop. Dry matter and nutrient content for each crop is summarized in **Table B2.1**.
Biological N Fixation (kg N or kg P)	$= 1.5 \times \sum_{\text{i}-1}^{n} \text{Crop production}_i \text{ (kg N)} \times \text{ dry matter}_i (\%) \times \text{N content}_i (\%) \times \text{Fixation}_i (\%)$	The production values, dry matter content, and N content for the two (*n* = 2) fixating crops (*i*, which were hay and soybeans) were the same as listed under Agriculture Fertilizer. An additional fixation value was applied to each (82% for hay and 74% for soybeans) as well as a factor of 1.5 to account for above and below ground inputs (Han and Allan 2008; Hong, Swaney, and Howarth 2013).

Other		
Atmospheric Deposition (kg N or kg P)	= Total area (ha) × Deposition rate (kg N/ha or kg P/ha)	Total area was multiplied by atmospheric deposition rates of 4.55 kg N/ha (Environment and Climate Change Canada 2011) and 0.2 kg P/ha (Winter and Duthie 2018).

Appendix B2: Supplementary Tables

Table B2.1: Summary of the allocation for human use, dry content, average N and P content for all crops grown in the GTA, and biological N fixation. Note that the value indicated for fruits and vegetables represent an average nutrient content for the wide variety grown in the area (Hong, Swaney, and Howarth 2013, 2011; Howarth et al. 1996).

Crops	Crops to Humans (%)	Dry Content (%)	N Content (%)	P Content (%)	N Fixation (%)
Winter Wheat	61	88.5	2.15	0.37	-
Oats	6	89.4	2.05	0.32	-
Barley	3	88.9	2.11	0.37	-
Mixed Grain	3	88.9	2.11	0.32	-
Grain Corn	4	86.7	1.64	0.28	-
Soybeans	2	90.6	6.54	0.59	55.5
White beans	2	90.6	6.54	0.59	-
Fodder Corn	0	28.4	1.25	0.05	-
Hay	0	86.7	1.27	0.45	15.3
Spring Wheat	61	88.5	2.15	0.37	-
Canola	61	100	3.00	1.37	-
Coloured Beans	2	90.6	6.54	0.59	-
Fruits*	100	100	0.10	0.01	-
Vegetables*	100	100	0.26	0.03	-

***** representing average nutrient content for a wide-array of reported fruits and vegetables

Table B2.2: Percent exports of various Ontario commodities (OMAFRA 2019).

Commodity	% Export
Red meats	34.5
Poultry and eggs	28.0
Dairy products	29.0
Other animal products	69.5
Grains	32.1
Oilseeds	69.7
Animal feeds	30.5
Fruit and nuts	5.4
Vegetables	32.4
Other agri-food products	33.6

Table B2.3: Summary of each livestock found in the GTA that includes its average occupancy per year as well as nutrient intake and excretion values on an annual basis. Note that the animals not sold for meat include horses, llamas, and rabbits (Hong, Swaney, and Howarth 2013; Howarth et al. 1996; Hong, Swaney, and Howarth 2011).

Animal	**Occupancy per year** (%)	**Intake**		**Excretion**	
		N (kg N /animal)	**P** (kg P /animal)	**N** (kg N /animal)	**P** (kg P /animal)
Beef cows*	175	66.8	27.7	58.5	21.3
Milk cows*	550	156.0	33.2	121.0	26.8
Heifers*	550	47.7	15.2	41.8	10.5
Steers*	300	51.3	17.5	45.0	13.3
Bulls*	300	66.8	40.2	58.5	25.4
Calves*	67	15.2	5.0	13.3	4.3
Hogs and pigs	50-300	8.5	7.1	5.8	3.3
Sheep and lambs*	25-500	6.0	2.2	5.0	1.5
Hens and chickens	11-167	0.8	0.2	0.6	0.1
Horses*	600	61.5	18.2	52.7	14.4
Turkeys	38	1.3	0.9	1.0	0.7
Other poultry	63	1.1	0.6	0.8	0.4
Goats*	265	8.2	0.7	4.2	0.4
Llamas	1,750	9.9	4.0	9.1	3.0
Rabbits	177	11.0	2.7	7.4	2.1
Bison*	2,125	55.1	27.7	52.9	21.3
Eggs	n/a	n/a	n/a	0.0010	0.0001

***** Grazing animals

Table B2.4: Summary of the average sizes (in terms of percent of the total area) of the grassed components of standard golf courses along with nutrient application rates (Tsiplova et al. 2007; King et al. 2001).

Golf Course Component	**Average Size per Course** (% of total golf course area)			**Application N Rate** (kg N/ha)	**Application P Rate** (kg P/ha)
	9 Hole Course	**18 Hole Course**	**Other**		
Green	2.31	2.24	2.22	187.7	7.1
Fairway	16.38	18.68	17.75	146.0	36.1
Tees	2.04	2.03	1.77	206.2	0
Rough	36.47	32.44	32.82	49.0	0
Percent of course area	57.20	55.38	54.57		

Appendix B3: Detailed Breakdown of Domestic Cats and Dogs Calculations in Toronto

B3.1: Food for Dogs (Toronto)

The food consumption by dogs was estimated as a function of the weights of the different breeds of dogs found in Toronto (**Equation B3.1**). Available data from 2011 indicated the number of licensed dogs per forward sortation area (the areas encompassing the first three numeric-digits of postal code areas) and the specific names of 234 breeds in Toronto (City of Toronto 2017). The dog population was adjusted to account for an estimate of 30% of dogs actually being licensed (Alcoba 2011). The average breed weight was multiplied by the recommended nutrient intake per weight (**Table B3.1**) for all breeds to calculate the total nutrient input due to food for dog requirements. There is a linear trend between a dog's weight and nutrient intake and, for any dog that exceeded 40 kg in weight, we extrapolated nutrient intake to reflect this trend. We assumed that food for dogs were all imported from outside of the GTA.

$$\text{Total Toronto nutrient requirement for dogs (kg N or kg P)} =$$

$$\sum_{i=1}^{n} \frac{\text{Population dogs}_\text{i}\,\text{(cap)}}{\text{Licensed dogs}_\text{i}\ (\%)} \text{ x Average weight}_i \left(\frac{\text{kg dog}}{\text{cap}}\right) \text{ x Nutrient intake}_\text{i} \left(\frac{\text{kg N}}{\text{kg dog}} \text{ or } \frac{\text{kg P}}{\text{kg dog}}\right)$$

Equation B3.1

Using the weighted average for all dog breeds (*i*, with a total of *n* = 234) available in data from Toronto, we established an average weight of 17.5 kg per dog and applied this to the dog population outside of Toronto where specific data per municipality is not readily available. Toronto was the only city that had detailed and available data on pets, therefore assumptions for the rest of the GTA cities were made based on these values. We assumed that the pet population density was proportional to that of humans based on Toronto values of both (0.08 dog/human).

Table B3.1: N and P content in food intake as per dog weight (Baker et al. 2007).

Dog Weight (kg)	N (kg/year)	P (kg/year)
10	2.5	0.5
20	5.6	1.2
30	8.2	1.7
40	10.7	2.3

B3.2: Food for Cats (Toronto)

Sim Similarly, food consumption by cats was estimated using data from 2011 on 43 breeds of cats in Toronto per forward sortation area (**Equation B3.2**) (City of Toronto 2017). The cat population was adjusted to account for an estimate of 10% of cats actually being licensed (Alcoba 2011). The average breed weight was multiplied by the recommended nutrient intake per weight (**Table B3.2**) for all breeds to calculate the total nutrient input due to food for cat requirements. We assumed that cats eat a diet of half wet and half dry food. It was also assumed that any cat that surpassed the limits of the table still consumed the amount listed in the uppermost bound since the overall sizes of cats do not vary as much as dogs.

$$\text{Total Toronto nutrient requirement for cats (kg N or kg P)} =$$

$$\sum_{i=1}^{n} \frac{\text{Population cats}_\text{i}\,(\text{cap})}{\text{Licensed cats}_\text{i}\ (\%)} \text{ x Average weight}_i \left(\frac{\text{kg cat}}{\text{cap}}\right)$$

$$\text{x } 0.5 \left[\text{Nutrient in dry food}_\text{i} \left(\frac{\text{kg N}}{\text{kg cat}} \text{ or } \frac{\text{kg P}}{\text{kg cat}}\right) + \text{ Nutrient in wet food}_i \left(\frac{\text{kg N}}{\text{kg cat}} \text{ or } \frac{\text{kg P}}{\text{kg cat}}\right)\right]$$

Equation B3.2

We calculated the weighted average for all cat breeds (i, with a total of n = 234) in Toronto to be 4.8 kg and used this to estimate the N and P cycling for cats in the rest of the GTA where data is not available.

Table B3.2: Feeding chart and nutrient content for both dry and wet cat food (“Pushing Pet Nutrition Forward - Purina® Pet Food & Products” n.d.).

Weight of cat (kg)	**Dry Food**		**Wet Food**	
	N (kg/cat)	**P** (kg/cat)	**N** (kg/cat)	**P** (kg/cat)
2.0-4.0	0.79	0.10	0.73-1.45	0
4.5-6.5	1.58	0.20	1.45-2.36	0

Appendix B4 – Detailed Breakdown of Residential Fertilizer Calculations

For each of the 25 municipalities, we matched the approximate spending on fertilizers, herbicides, and pesticides per population center (**Table B4.1**) to determine the respective household spending. For those municipalities with population falling under unpublished data categories, we linearly interpolated the prices between known values. We assumed that 77.6% of this spending was designated for fertilizer alone (Statistics Canada and Income Statistics Division 2013).

Table B4.1: Summary of average expenditure per household for fertilizers, herbicides, pesticides, soil and soil conditioners classified by size of population centre (Statistics Canada 2011).

Size of Population Centre	Average expenditure per household for fertilizers, herbicides, pesticides, soil and soil conditioners ($)
Over 1,000,000	46
500,000 – 999,999	F
250,000 – 499,999	47
100,000 – 249,999	F
30,000 – 99,999	F
1,000 – 29,999	85
Rural	F

* F signifies unreliable and unpublished results

We classified housing in each city into three main groups (apartments, semi-attached dwellings, and single-detached dwellings) to distinguish multi-dwelling housings where fertilizer application is less frequent. We obtained zoning maps for each city, even though not all explicitly differentiated these housing types (City of Toronto 2017; City of Oshawa 2011; Town of Ajax 2011; Open Newmarket 2011; Personal communication). We overlaid zoning maps that labelled the residential areas with a map with dwelling density to find the area coverage and dwelling numbers. We assumed that apartments were in areas with more than 50 dwellings per hectare, single-detached dwellings had less than 25 dwellings per hectare, and semi-detached dwellings were in between 25 and 50 dwellings per hectare. We then used **Equation B4.1** to calculate the approximate expenditure per housing type.

$$\mathrm{S_T \, x \, S_F} = \frac{\mathrm{A_1 \cdot x_1 + A_2 \cdot x_2 + A_2 \cdot x_2}}{\mathrm{A_1 + A_2 + A_3}}$$

Equation B4.1

where S_T is the total spending on gardening treatment (\$), S_F is the portion spent on fertilizer specifically (77.6%), A_1 is the number of apartments, A_2 is the number of semi-attached dwellings, A_3 is the number of single-detached dwellings, x_1 is the amount of fertilizer spent per apartment (\$/cap), x_2 is the amount of fertilizer spent per semi-attached dwelling (\$/cap), and x_3 is the amount of fertilizer spent per single-detached dwelling (\$/cap).

We applied two constraints to **Equation B4.1** to establish the spending per dwelling type. We assumed a base case fertilizer application that is standard for residential housing by outside contractors to be 100 kg N/ha and 12 kg P/ha shown in **Equation B4.2** (Law, Band, and Grove 2004). In addition, we assumed that any fertilizer costs would be split in half between the duplex owners (representing minimum housing number for semi-attached dwellings) to fertilize the same lawn area as shown in **Equation B4.3**.

$$\mathrm{x_1}\left(\frac{\$}{\text{cap}}\right) = \frac{\text{Fertilizer converter }\left(\frac{\$}{\text{kg fert}}\right)\text{ x Base fertilizer}\left(\frac{\text{kg N or kg P}}{\text{ha}}\right)\text{ x Area (ha)}}{\text{Typical nutrient content }\left(\frac{\text{kg N or kg P}}{\text{kg fert}}\right)}$$

Equation B4.2

where x_1 is the amount of fertilizer spent per apartment (\$/cap), fertilizer converter is \$4.99 per kg fertilizer, the base fertilizer application is 100 kg N/ha and 12 kg P/ha for apartments, area is the total “softscape” area (area excluding building footprint, asphalt, driveway, and the such) for apartments, and nutrient content for a typical bag of fertilizer of 22% N and 3% P. This constraint is dependent on lawn area of apartments and will differ for each city.

$$\mathrm{x_3} = \frac{\mathrm{x_2}}{2}$$

Equation B4.3

To obtain the fertilizer converter value, we tallied up the average price (before taxes) and nutrient content in bags sold at various major retailers in Canada. We estimated that there is a \$4.99/kg fertilizer relationship with approximately 22% N and 3% P for each bag.

We first solved for x_1 and then used **Equation B4.1** with the above constraints as well as the values shown in **Table B4.1** to solve for x_2 and x_3. We then set out to establish fertilizer rates and display this spatially. The residential lawn area was calculated using each municipality or region's available (open or restricted access) zoning maps that indicate different types of households such as single detached dwellings, semi-detached dwellings, townhouses, and apartments. For some municipalities, property boundaries and even building footprints for each resident were available. These were superimposed onto the defined residential areas to equal the lot coverage (**Figure B1**). For apartments, it was assumed that 10% of the area is fertilized greenspace and for other residential areas and based on trends between municipality property standards, it was assumed that up to 50% was landscaped (minus building footprint) and 40% of this area was "softscape" and actually fertilized. And thus we established fertilizer rates for each dwelling type (*i*) in each city as shown in **Equation B4.4**.

$$\text{Fertilizer Rate } \left(\frac{\text{kg N or kg P}}{\text{ha}}\right) = \frac{\text{A}_i \cdot \text{x}_i \cdot \text{Typical nutrient content}}{\text{Fertilizer converter} * \text{Area of all A}_i}$$

Equation B4.4

Figure B4.1: An example of a residential area in the GTA. The roads and building footprints were removed to best estimate the remaining area also known as the lot coverage**.**

With each municipality's dwelling number and residential fertilizer rate application, we solved for the total fertilizer in **Equation B4.5** as shown in **Table B1**.

$$\text{Total fertilizer (kg N or kg P)} = \sum_{i=1}^{n}\sum_{j=1}^{m} \text{Residential Area}_{\text{ij}} \text{ x Rate of fertilizer application}_{ij}$$

Equation B4.5

where *i* represents each municipality for a total of *n* = 25 and *j* represents each dwelling type for a total of *m* = 3.

Appendix B5: Assumptions for Incomplete Data

Livestock Population/Fruits and Vegetable Production

Some of the livestock population data (Government of Canada 2018a, 2018b, 2018c, 2018d, 2017a, 2017b) was masked on the Canadian census to safeguard the privacy of farmers since it was typical to find only 1-2 farms for a specific livestock commodity per region. To estimate the total livestock population, we used a conservative method with three steps, and should the first step not be applicable, we proceeded to the second and then the third. Our aim was to work with the most reliable data available, and the below three steps were followed:

1. When comparing the 2011 and 2016 population data, if the number of farms reported was consistent, we used the number indicated. If there was a slight change, we proportioned the population based on the number of farms reported. For example, if 2016 reported 3 farms that had 15 beef cows, we assumed the 2 farms in 2011 had 10 beef cows.
2. If 2016 population data was unavailable, we estimated individual animal subcategories based on the total number reported in the overall classified category. For example, if 30 cows were reported for one region, then the number of beef cows, milks cows, heifers, steers, bulls, and calves would need to reflect the reported total amount. Based on trends in other regions, we distributed population amongst these subcategories to add up to 30 cows. If this overarching category was available, we verified twice that proportioned amounts in Step 1 did not exceed these values.
3. Finally, if both Step 1 and Step 2 were not feasible, we calculated the lowest animal per farm ratio among the 25 regions in the GTA in order to be conservative and applied it to the missing areas. For example, if Region A had the lowest ratio of sheep to farms (0.4), we applied this to Region B and Region C that had missing values for this category.

A similar approach was followed for missing data for fruits and vegetables. We used Step 1 and Step 3 to estimate unknown values.

Crop Yield Data

Crop yield data is only available on a regional basis and as a result, we proportioned production considering the area of land used for agriculture for each municipality with the total for the region. Since crop production is relatively low in Toronto, Census Canada does not provide crop yield values for them. The overall yield data was divided by the total harvested acres for the other four known regions to estimate a suitable yield rate for Toronto.

Appendix C

Supplemental Results Figure

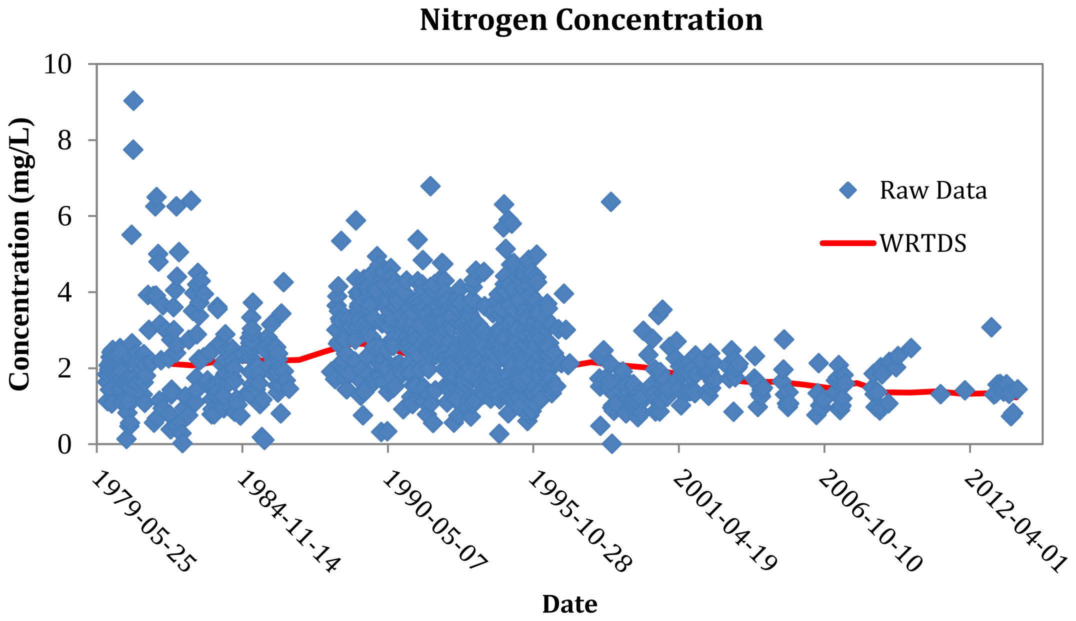

Figure C1: Nitrogen concentrations for the Don River monitoring station between 1979 and 2012 used to estimate the concentration and loading of N for 2011 (Government of Ontario 2011; Hirsch, Moyer, and Archfield 2010).

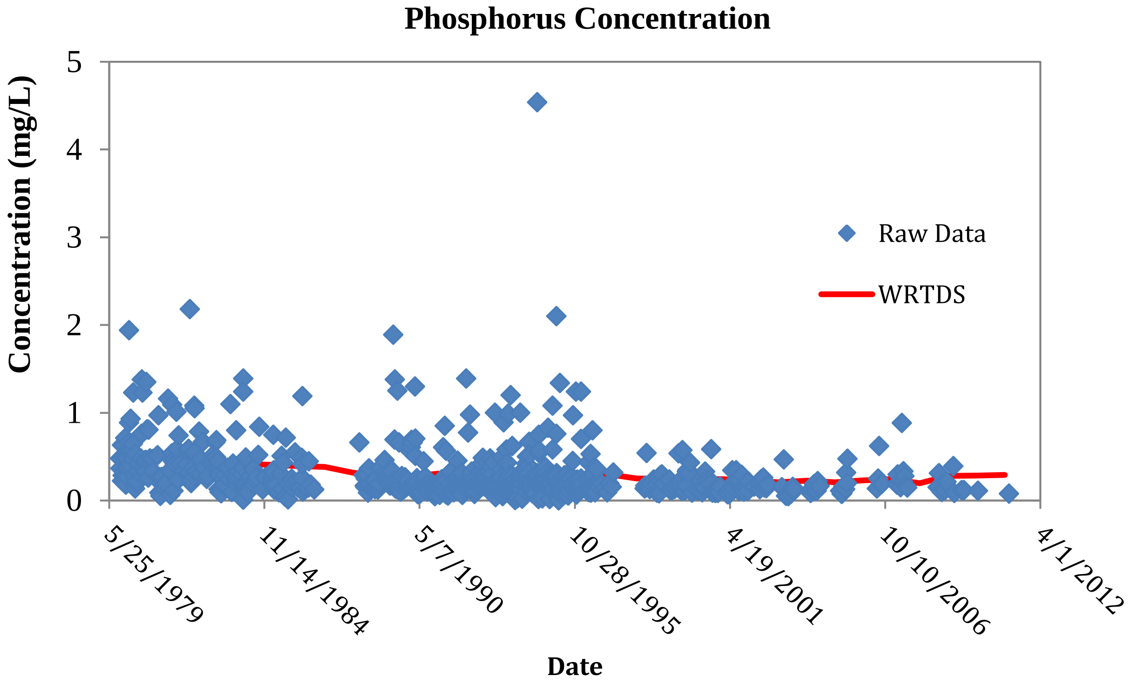

Figure C2: Nitrogen concentrations for the Don River monitoring station between 1979 and 2012 used to estimate the concentration and loading of N for 2011 (Government of Ontario 2011; Hirsch, Moyer, and Archfield 2010).

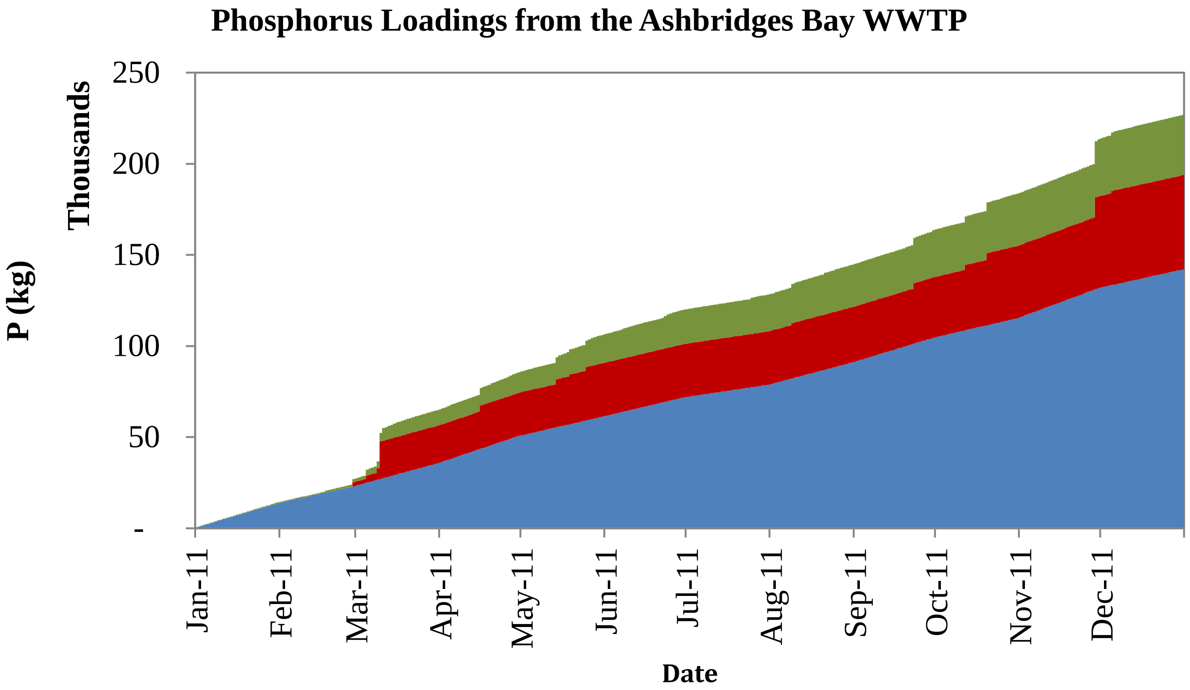

Figure C3: The Ashbridges Bay WWTP effluent, bypass, and Don River outflow represented as P loading (Toronto Water 2011a; Government of Ontario 2011).