LOCAL SUSTAINABILITY ASSESSMENT FOR HUMAN WELL-BEING USING GLOBAL ECOLOGICAL FOOTPRINT DATA

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Abstract

This proof-of-concept study examined an approach to downscaling the ecological footprint (EF) at the local level. In this study, an EF disaggregation methodology was applied, using national EF data and adjusting them to the local level (Dissemination Area (DA)) using ratios informed by recent data. The study then employed a citizen science methodology to enhance and calibrate the EF data at the DA level. Data from 429 participants (403 complete) on consumption habits were analyzed using the Greater Golden Horseshoe Area (GGHA) average EF as a baseline. Linear regression, correlation analysis, t-tests and Cohen's *d* tests validated findings across two Canadian demographic groups. The methodology focused on the Region of Peel in the Greater Toronto Area (GTA) to compare the EF of consumption and related health and well-being outcomes between two demographic groups: recent immigrants and established Canadians. The study aimed to address a gap by utilizing a citizen science method to gather local insights.

The relationship between those two methods and two community groups was explored. The disaggregation method differed significantly from the citizen science method ($p < 0.05$). For example, despite having a national average of 7.42 gha/cap, established Canadians in the study area exhibit an EF of 11.5 gha/cap, while recent immigrants have an EF of 10.75 gha/cap, exhibiting a statistically significant difference ($p \leq 0.05$) using the disaggregation method, with a ratio adjusted to reflect more recent data. The citizen-science-based approach revealed that established Canadians in the study area exhibit an EF of consumption of 8.73 gha/cap, compared to 8.07 gha/cap for recent immigrants, exhibiting a statistically significant difference ($p \leq 0.05$).

Thus, it was found to enhance the granularity and relevance of EF measurements, revealing important differences between population groups. As a proof-of-concept, the study demonstrates the value of local sustainability assessments, revealing differences between recent immigrants and established Canadians in the Region of Peel. Future attempts to employ this disaggregation approach to calibrate EF estimates should have sufficient citizen science data to adequately represent local phenomena.

Dedication

This page is dedicated to my late parents and my late big brother in their memory,

and

dedicated to my wife Elizabeth, daughter Alina, and my son Kaleb for their unconditional love and support.

Acknowledgements

This study would not have been possible without the support of lots of people. First of all, I would like to thank my wife, Elizabeth Paudel, for putting up with me all these years while balancing the family, during which I was constantly working on my PhD. Thank you to our daughter, Alina, and son, Kaleb, for encouraging Daddy to finish his PhD, including by going to bed early most nights so Daddy could get some work done. A big thank you to all my friends and colleagues who have supported me throughout this journey, along with some occasional nudge of 'are you done yet' to push me closer to the finish line. I wish my parents were alive to see me completing this PhD journey. I am sure they would have been very happy to see this phase of my academic achievement. I lost my big brother, Tol Raj, during the COVID-19 pandemic after I started my PhD. He was one of my biggest cheerleaders to see me complete my PhD and become a 'doctor' one day. This is in memory of my parents and his!

My advisor, Martin Bunch, has been there from day one, supporting and encouraging me, providing practical guidance and helping me find ways to address local conservation and ecological issues. It was Martin's participation in the practical aspects of conservation, environmental health, and well-being that inspired me to pursue this path as a mature student, despite having 'enough commitments' in my personal and professional life! Thank you for encouraging me every step of the way. My advisory committee members, Peter Mulvihill and Justin Podur, have always encouraged me with their positive feedback from the get-go. Thank you for your support in this endeavour.

I would like to thank Environics Analytics for providing the secondary data for this study. The Region of Peel and Credit Valley Conservation Authority (CVC) staff have been very supportive of me during different phases of the study, including the data collection portion. Although the data collection process took longer, with some ups and downs due to COVID-19, in the end, it was the participants in my study who made the project worthwhile. Thank you to all the participants! CVC has been very supportive of my studies by providing the flexibility I needed, particularly in my early days for coursework and field studies. I am thankful to my colleagues at CVC for their support and encouragement.

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Table of Contents

List of Tables

List of Figures

Chapter One: Introduction

This research adopts an interdisciplinary approach to investigate local sustainability and evaluate its relationship with health and well-being. In the context of local sustainability, communities are increasingly striving to balance ecological integrity with social and economic vitality. We are navigating an era marked by a mounting concern about environmental degradation, reflected in increasing resource consumption (e.g. as measured by ecological footprint (EF)) and coupled with a heightened emphasis on personal and community health and well-being (Gibson, 2017; Richardson et al., 2023; Rockström et al., 2009; SSHRC, 2020; Steffen et al., 2015; World Health Organization, 2019). This convergence highlights the growing recognition that sustainable local actions are not only critical for reducing environmental impacts but also essential for fostering healthier, more resilient and equitable communities.

In light of this paradigm shift, this dissertation investigates the intricate and interconnected relationship between our consumption, as indicated by ecological footprint (EF), and its impact on community health and well-being. The decisions that people make daily, including dietary habits, transportation preferences, and residential choices, have significant and cascading impacts on the planet's resources, ecosystems, and the fundamental aspects of human life (Allan, 2011; Chapin et al., 2010; Estes et al., 2011; European Commission, 2013; Rockström et al., 2009; SSHRC, 2020; WCED 1987; World Health Organization, 2019). This research adopts an interdisciplinary approach to investigate how local sustainability (as measured by EF) intersects with individual and community health outcomes. The goal here is to elucidate the dynamic interactions among local sustainability assessments, ecological footprint, and the overall health and well-being of communities.

In this exploratory proof-of-concept study, I assess local sustainability from a human well-being perspective using EF data. While EF data are often reported at the national scale, this research narrows the scope to a local case study: the Region of Peel (ROP) in the Greater Toronto Area (GTA), intending to enhance EF data using a citizen science approach. Within the study area, I compare two demographic groups, recent immigrants and established Canadians, to determine whether differences in their consumption patterns (as reflected in EF) are associated with differences in health and well-being. The Region of Peel (ROP) represents a substantial portion of the province of Ontario's population (1,499,917 out of 14,223,942, or 10.55%), which significantly contributes to provincial resource consumption and EF (Statistics Canada, 2021). The GTA, which includes the Region of Peel, has also been the subject of several explorations into the relationship between environmental factors and human health and well-being (Awuor & Melles, 2019; Campbell et al., 2014; Macfarlane et al., 2015; Perrotta, 1999).

The terms ″recent immigrants″ and ″new immigrants″ are used interchangeably in the literature. In the context of this study, the term *recent immigrants* is used. Statistics Canada refers to recent immigrants as those who landed in Canada within the last 5 years (Statistics Canada, 2025), whereas the Government of Canada sometimes uses 10 years to identify the same category of immigrants (Gilkinson & Sauve, 2010). Allen (2006) highlights that adjusting to a new country and new economy typically takes between 10 and 20 years. Based on previous studies, it takes 10 to 20 years for new immigrants to reach parity with native-born citizens in terms of earning good incomes and becoming homeowners (Chiswick and Sullivan 1995, p. 262). In addition, health-related studies, such as age-standardized mortality rate comparisons, have been conducted with the Canadian-born population and those who have been in the country for 20 years or more to evaluate the healthy immigrant effect (Ng, 2011). The current study examines the relationship of ecological footprint (EF) with income and expenditure, as well as its connection to health and well-being. During this 20-year period, the immigrants begin to show consumer and health behaviours similar to those of the Canada-born population. For this study, *recent immigrants* were therefore defined as individuals who moved to Canada within the last 20 years from the start of the research in 2021. This was done to better reflect immigrants' long-term consumption behaviour and lifestyles, allowing comparison with established Canadians. According to Statistics Canada, an immigrant is generally defined as "…a person who is, or who has ever been a landed immigrant or permanent resident. Such a person has been granted the right to live in Canada permanently by immigration authorities" (Government of Canada, 2016). These *recent immigrant* communities were compared with *established Canadians* (long-term residents) to examine whether their EF is related to their health and well-being. The GTA is a part of Canada that represents a cultural mosaic with a very high concentration of immigrants (Kelley et al., 1998; Peach, 2005; Porter, 2015; Schneider, 1998). A total of 18% of Ontario's immigrant population lives in the ROP, located within the GTA (Region of Peel, 2021). While maintaining diversity, the GTA has high concentrations of communities that comprise both predominantly recent immigrants and established Canadian populations as their primary residents. The two types of communities were used to explore relationships between EF and health and well-being.

The region has undergone a tremendous demographic transformation in recent years. To put it in context, the Region of Peel has the highest percentage of immigrants (51.5% of the total population) in the Greater Toronto Area, according to the 2016 census (Figure 1) (Region of Peel, 2020).

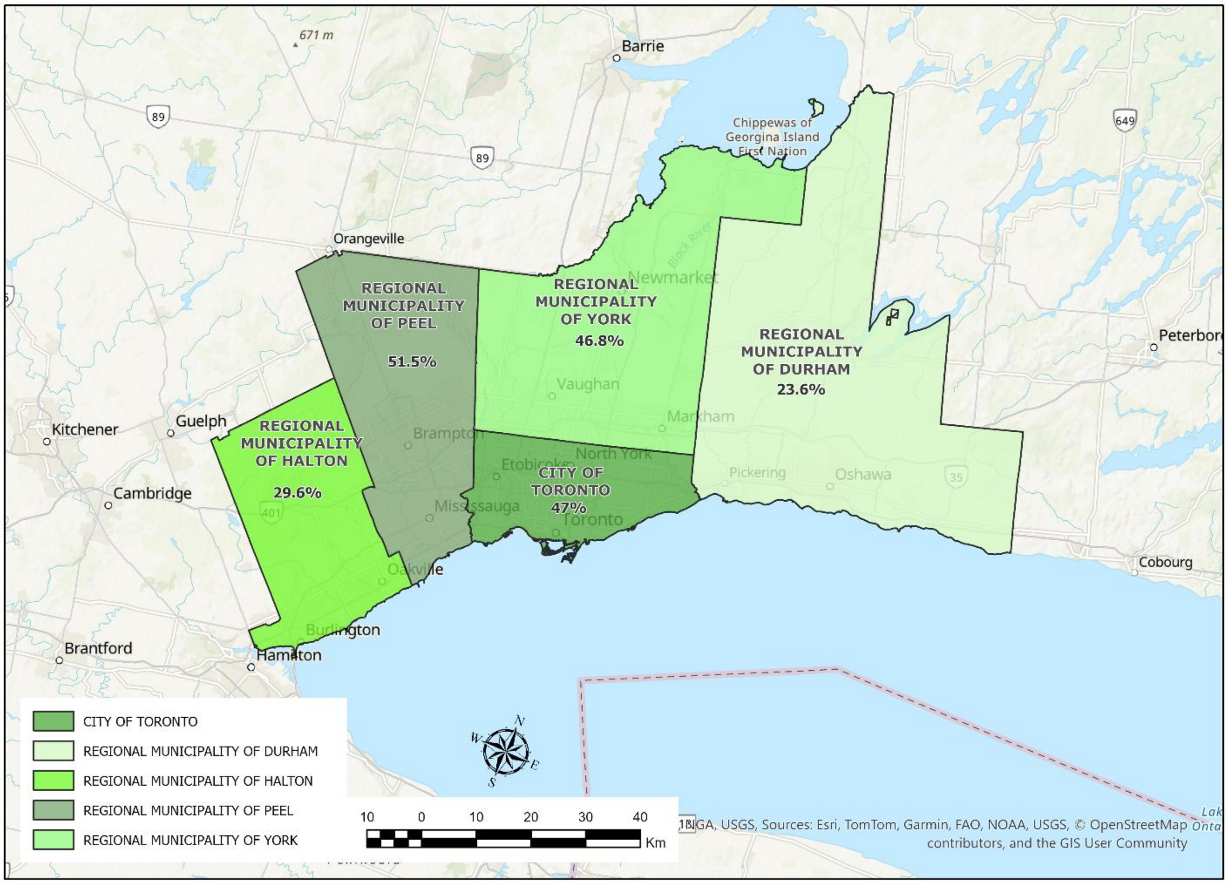


Figure 1. Immigrant population in Greater Toronto Area, census 2016 (Region of Peel, 2020). *Note.* Recent immigrants, distinct from immigrants, are defined as those who moved to Canada 20 years before the study began.

Figure 1 shows that the Region of Peel has the highest concentration of immigrants, surpassing the City of Toronto, according to the 2016 census. It shows that more immigrants live in the Region of Peel than in any other region or city in the GTA.

Sustainable future and human health and well-being

Health is, according to the World Health Organization (WHO), "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (World Health Organization, 1948). Achieving comprehensive human health and well-being is a long-term pursuit rather than a short-term goal. In the Canadian context, rapid population growth and demographic changes driven by immigration have exerted increasing pressure on local resources. The sustainability of resources relies on public policies made by decision-makers, our consumption patterns, and learned behaviours. Sustainability is a global requirement (United Nations, 2016; 2019). However, according to the Millennium Ecosystem Assessment, increased human pressure on the global environment has impaired our ecosystem, leading to adverse health outcomes (Figure 2) (Corvalán et al., 2005a).

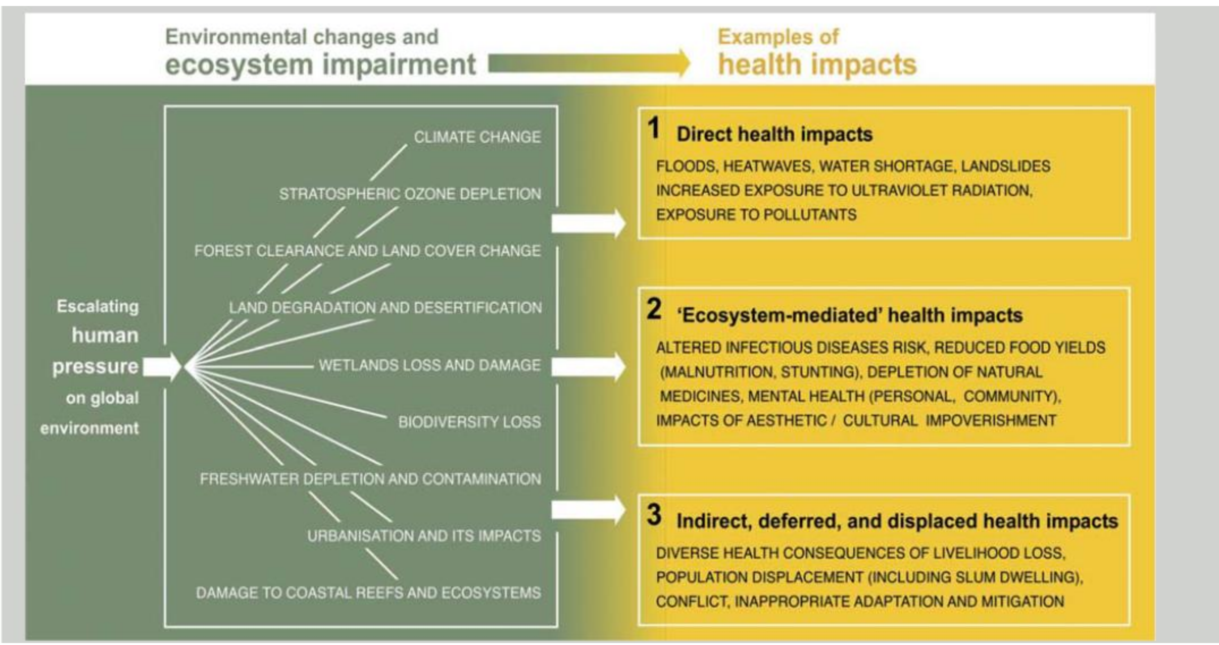


Figure 2. Effects of global pressure and its adverse effects on the ecosystem and human health (Adapted from Corvalan et al., 2005).

Long-term sustainability and societal well-being depend on our capacity to regenerate resources and ecosystem services. Those resources and services are assumed by decision-makers in most policy decisions to be limitless (Costanza et al., 1997; Max-Neef, 1995; Rockström et al., 2009). However, our planet has a limit. The planetary boundary framework quantifies the critical thresholds for Earth's systems. Exceeding Earth systems could adversely impact our socio-ecological resilience due to potential non-linear changes, such as extreme micro-weather patterns resulting from the global effects of rising surface temperatures (Rockström et al., 2009). In addition, crossing those "Tipping Points" could lead to the reorganization of the global climate system, undermining the resilience (Max-Neef, 1995; Meadows, 1999; Rockström et al., 2009).

Global pressure on resources and associated challenges have been identified at both the regional and national levels. The Social Sciences and Humanities Research Council of Canada (SSHRC) has been publicly seeking solutions to challenges related to resource consumption and the pressures of climate change, driven by population growth (SSHRC, 2020). Potential long-term challenges, including population pressure on resource consumption, environmental degradation, and climate change, can have a profoundly adverse impact on local health and well-being (Hall et al., 2017). On the contrary, an increased greenness in the neighbourhood is associated with better-perceived health and well-being as shown in a study of Toronto neighbourhoods by Kardan et al. (2015). The study found that having 10 more trees in a city block improves perceptions of human health, comparable to an increase in annual median income of $10,000 or being 7 years younger.

Human health and well-being are extensively researched domains that have been integrated into Canada's policy framework. Within this framework, a range of key determinants of human health have been identified and emphasized (Corvalán et al., 2005b). Some of the most common and critical ones are income and social status, social support networks, education and literacy, employment and working conditions, social environment, physical environment, personal health practices and coping skills, healthy child development, biology and genetic endowment, health services, gender, and culture (Ecohealth Ontario, 2017; Government of Canada, 2019; Government of Canada, 2020). According to the Government of Canada (2020), the social determinants of health are a set of social and economic factors that shape health, including people's place in society, income, education or employment, as well as the discrimination and trauma they may have experienced. However, a notable research gap exists regarding the relationship between human health and well-being and local resource consumption, particularly when using metrics such as the ecological footprint to quantify it.

I seek to explore the cross-section of the cumulative impact of our lifestyle choices (what we eat and how we use our energy), and how it reverberates, putting additional pressure on our ecosystems and our health and well-being. Addressing key questions, such as "What are the potential impacts of the global peak populations?" and "How are they connected to our sustainable future and human health and well-being?", identified as challenges by SSHRC (2020), requires a holistic understanding of those issues. In this dissertation, I aim to contribute to that understanding by examining the ecological footprints we create and exploring ways to enhance sustainability assessments to provide a more comprehensive view of human-environment interactions. In the context of the growing recent immigrant population within the Region of Peel (Region of Peel, 2021), I seek to cover the cross-section of ecological data, the human potential to improve the quality of information, and existing data from primary and secondary sources on consumption patterns and to link them to human health and well-being of sub-populations (recent immigrants and established Canadians) in the Canadian context. This is an interdisciplinary work that identifies and reflects on how environmental, behavioural, and demographic changes interrelate. This inquiry is inherently interdisciplinary, addressing how environmental factors, human behaviours, and demographic changes interrelate. The current study uses a novel *mixed-methods* approach to address those complex questions, incorporating ecological footprint analysis, sustainability assessment tools, and participatory citizen science, as detailed in subsequent chapters.

The comparison between recent immigrants and established Canadians is intended to explore the existence and nature of any differences between these populations. Globalization and the global "power-geometry" (Massey, 1994) of social interconnectedness and migration have strongly supported Canada with skilled citizens. For individuals who have emigrated to Canada and established new lives, the lifestyles they develop in this new environment can, over time, lead to varied outcomes. These outcomes may range from experiences of uncertainty, frustration, and diminished health and well-being to successful integration, contributing positively to society's prosperity.

Multiple social frameworks have been proposed to explain health and well-being (Borjas, 2003; Castañeda et al., 2015; Choi et al., 2009; Kasirye et al., 2005; Liu et al., 2009; Pasick & Burke, 2008). Three frameworks described by Castañeda et al. (2015) include:

a. **structural framework**, that focuses on access to health care and the influence of social forces;
b. **behavioural framework** that targets individual health behaviours for causes and intervention, mostly under the "Health Belief Model (HBM)" (a psychological model to explain and predict health behaviours); and
c. **cultural framework** that implies that an ethnic membership influences health outcomes.

The cultural framework suggests that over time, immigrants adjust their lifestyles to align with the dominant group, a process commonly referred to as *acculturation.* However, research has generally found that acculturation often negatively impacts health and well-being at the individual level, largely due to the adoption of mainstream health behaviours, such as poor dietary habits and insufficient physical activity (Choi et al., 2009; Kasirye et al., 2005; Liu et al., 2009). However, due to a lack of strongly defined cultural variables and evidence-based research, those approaches have been criticized (Castañeda et al., 2015; Hunt et al., 2004). While these frameworks outlined here are great options for understanding targeted key outcomes, a comprehensive, integrated model to explain health and well-being in the nexus of cultural, behavioural, structural, and environmental factors is not addressed by them.

Based on an alternative lens that is provided by the *socio-ecological model (SEM)* (UNICEF, 2023) of health, augmented with *ecohealth* approaches (Bunch, 2016; Bunch & Waltner-Toews, 2015; Waltner-Toews & Kay, 2005; Webb et al., 2010), we may be able to help bridge the gaps of inequities in immigrant health and well-being. Those inequities are generally created by our social structures, built environments, institutions, and policies.

The SEM framework recognizes that health outcomes emerge from interwoven factors at multiple levels: individual (knowledge, attitudes, behaviours), interpersonal (family, social networks), community (economic, environmental, cultural contexts), and societal (policies, institutions) (UNICEF, 2023). By incorporating ecohealth principles, we recognize that human health is inextricably linked to and influenced by the broader ecosystem. This combined perspective is promising for addressing health inequities among immigrants, which are often created or exacerbated by social structures, built environments, institutional practices, and policies. In the context of Canadian society, such an approach may be key to meeting the health and well-being needs of diverse families in the coming decades. Immigration is a pursuit of better well-being, but it can result in a labyrinth of identity crises. The overarching question that exists is: *Can socio-economic and environmental data help us understand the relationship between the environment and the health and well-being of recent immigrant populations?* This question creates a framework for this study's intent to connect environmental metrics with human outcomes in a meaningful way.

Ecological Footprint

There are several different approaches to sustainability assessments (Corvalán et al., 2005) that are discussed in detail in subsequent chapters. One of them is based on Ecological Footprint (EF). EF is defined as "a measure of the demand populations and activities place on the biosphere in a given year, given the prevailing technology and resource management of that year" (Borucke et al., 2013, p. 519). The EF metrics are typically expressed in global hectares per capita (gha/cap). A global hectare is defined as "one hectare of biologically productive land with the world's average biological productivity for a given year." (Global Footprint Network, 2023).

I chose to explore the Ecological Footprint (EF) approach among those sustainability assessments for this study to gain a deeper understanding of it at a local level. I chose this approach because it is an *indicators-based, integrated* sustainability assessment that goes beyond traditional index-based measures, such as Gross Domestic Product (GDP), which fail to account for environmental factors. A few other reasons include this approach's global accessibility and ease of use in helping make decisions at national, regional, and local levels, compared to other existing assessments. More details on the approach are discussed in the subsequent chapters. The availability of data and wider access to tools for sustainability assessment for broader users were among the motivations to use this approach in this study.

Data and methods exist to broadly examine demographic trends and projections, and to support a variety of methods for measuring environmental pressures and resource consumption, such as EF and its evaluation of biocapacity. Although some limitations around the misunderstanding of applicability of EF for policy relevance have been discussed by Galli et al. (2016) and Kitzes et al. (2009), Ecological Footprint Accounting (EFA) is considered the first approximation of overall human pressures on ecosystems based on the available tools because it is one of most comprehensive approaches to explore national and global ecosystems resiliency in a quantifiable approach (Galli, 2015; Lin et al., 2015). As an indicator of sustainability assessment, EF is an integrated accounting tool introduced by Wackernagel and Rees (1996) to evaluate resource consumption and other necessities of the population, given the available land area. EF has been used globally in recent years (Costa et al., 2019; Isman et al., 2018; Kakon & Reza, 2016; Wackernagel & Rees, 1998; Wackernagel et al., 2004), including by Canadian municipalities such as the City of Calgary (City of Calgary, 2024; Global Footprint Network, 2023). The Global Ecological Footprint Calculator has been used over 2 million times annually to calculate ecological footprints online (Global Footprint Network, 2023).

In collaboration with the Ecological Footprint Initiative at York University (https://footprint.info.yorku.ca/), the Global Footprint Network (GFN) releases National Footprint Accounts (NFA) on an annual basis (York University Ecological Footprint Initiative & Global Footprint Network, 2023). The NFA data includes the ecological footprint and biocapacity of over 200 countries worldwide and is the most comprehensive database of EFs

(Global Footprint Network, 2023; Kitzes & Wackernagel, 2009). NFAs calculate only "…*how much biocapacity humans demand in comparison to how much is available* - not all aspects of sustainability, nor all environmental concerns" (Borucke et al., 2013, p. 519). In summary, EF would benefit from enhancements to provide local-level insights and to be calibrated to reflect reality at the scale of a city or municipality, such as the Region of Peel. This study uses national-level ecological footprint data and applies them within the framework of a local sustainability assessment through citizen science integration. The concept of the ecological footprint is examined extensively in subsequent chapters, particularly in relation to sustainability assessment, citizen science, and its implications for human health and well-being. In this research, the ecological footprint is used as a metric to evaluate factors contributing to higher ecological footprints at the local level within the study area. These investigations are explored in depth using both primary and secondary data sources.

Citizen Science

Citizen science is a "…science for the people…to place technical expertise at the direct service of the people" (Irwin, 2002, p.5). It is public engagement and participation in a collaborative effort to advance scientific knowledge. This citizen science method, which involves collecting and validating data, alleviates the limitations imposed by authoritative data.

Citizen science is used in this study to enhance our understanding of EF and its linkages to health and well-being from a "bottom-up" perspective. Citizen science serves multiple purposes, including enhancing our understanding of ecological footprints, human health and well-being, and local sentiments from a grassroots perspective. One motivation for using a citizen science approach in this study is to mitigate the limitations imposed by relying solely on authoritative data. Authoritative data collected and maintained by various bodies (e.g., government agencies responsible for parcel data management and land-use policymakers) generally rely on dated and modelled information at regional, national, or global scales. Decisions are made based on those scales without consulting and involving locals in many instances (Cohn, 2008; ESRI, 2010). This has the potential to create a gap between local knowledge and decisions made at a "high level". The citizen science approach has the potential to fill in the gap with local knowledge. The process, overall, is expected to democratize information from both the collection and dissemination perspectives. It supports organizations in collecting data, facilitating research through collaboration to generate data that would otherwise be impossible to collect due to the labour required, and providing communities with access to scientific information (Bonney et al., 2009, 2014; Cohn, 2008).

Citizen science projects can be designed with varying levels of public involvement (Bonney et al., 2009):

- **Contributory projects:** Professional scientists design the project, and the public contributes data according to prescribed methods, tools and protocols. This is essentially crowdsourcing scientific data.
- **Collaborative projects:** The public is involved at different levels, not only in data collection but may also help refine project design, analyze data, or disseminate findings, working alongside scientists.
- **Co-created projects:** The project is jointly designed by scientists and community members, and all parties are actively involved in most or all steps of the scientific process.

This dissertation research uses a contributory project model, which relies on participants' contributions to a research project designed to achieve a scientific outcome. In a contributory project, others contribute/participate, and it refers to a project designed by professionals or scientists. An example of such a project is public participation in Butterfly Blitz projects, where participants help create an inventory of butterflies within a jurisdiction (Credit Valley Conservation, 2024). Although a promising field of science, citizen science has its own limitations. The arguments for and against citizen science, as presented by critics, are discussed in detail in subsequent chapters.

Research Questions and Hypotheses

In this study, I explore the relationship among the EF, citizen science, sustainability assessment and human health and well-being. The approach applied here is a participatory citizen science method (contributory project) that supplements local EF calculations. To investigate these interrelationships, I seek answers to the following questions:

I. **Estimating Local EF:** How can we better estimate the EF at the local level in the study area, using data produced at a national level? and

II. **Comparing Communities:** What type of differences, if any, exist between the EF of the recent immigrant communities and the established Canadian communities, and how do these differences relate to their health and well-being?

To answer the research questions, two sets of hypotheses were formulated:

- **$H0_1$ (Null Hypothesis 1):** There is no difference between the EF calculated using citizen science at the local level compared to nationally reported EF disaggregated for the local level.
- **H1 (Alternative Hypothesis 1):** There is a significant difference between the local EF of consumption derived from the citizen science approach and that obtained via disaggregation of national EF data.
- This may be useful to use as a coefficient to calibrate the EF of consumption at the local level.
- **$H0_2$ (Null Hypothesis 2):** There is no difference in EF of the recent immigrants versus the established Canadian communities in the study area.
- **H2 (Alternative Hypothesis 2):** There is a significant difference in the EF of consumption between recent immigrants and established Canadian populations in the study area.

Both of these hypotheses were tested at the $\alpha = 0.05$ (5% significance level). In other words, if a result yields a p-value < 0.05, it would lead to rejecting the null hypothesis in favour of the alternative, indicating a statistically significant difference.

To answer those questions, these are the objectives that need to be achieved:

- **Objective 1**: Develop an effective way to use the EF data for a local sustainability assessment.
- **Objective 2:** Employ a citizen science methodology as an enhancement to improve the data quality of the ecological footprint at a local level; and

- **Objective 3**: Compare two communities – recent immigrants and established Canadian populations – at dissemination area (DA) levels within the Region of Peel and compare their ecological footprint to health and well-being.

Globally, the EF data is calculated at the national level. It has been utilized in numerous previous studies for global and regional assessments (Isman et al., 2018; Lee et al., 2015; Wackernagel et al., 2004). Generally, EF-related applications can be categorized into two approaches: *top-down* (compound) and *bottom-up* (component) (Baabou et al., 2017; Moore et al., 2013; Pearson, 2013; Wilson & Grant, 2009). The top-down approach uses national data and scales it to the city or local level using household income and/or expenditure surveys and related data, whereas the bottom-up approach directly uses city-level data to calculate city-level footprint values. The bottom-up approach is resource-intensive and more complex, yet easily understood by the authorities (Moore et al., 2013).

This study starts with a top-down approach to identify an effective method for utilizing the national EF database in local sustainability assessments. An exploration of existing local sustainability assessment approaches was required, which were then used to develop an approach for employing EF-based assessments at this scale. This study employs a citizen science approach to augment local sustainability assessments by calibrating data through bottom-up contributions. As the final step of the research, this study examines whether higher ecological footprints at a local level are associated with the health and well-being of recent immigrants and established Canadian populations. Figure 3 shows an outline of the high-level decision-tree framework for this project to address those research questions:

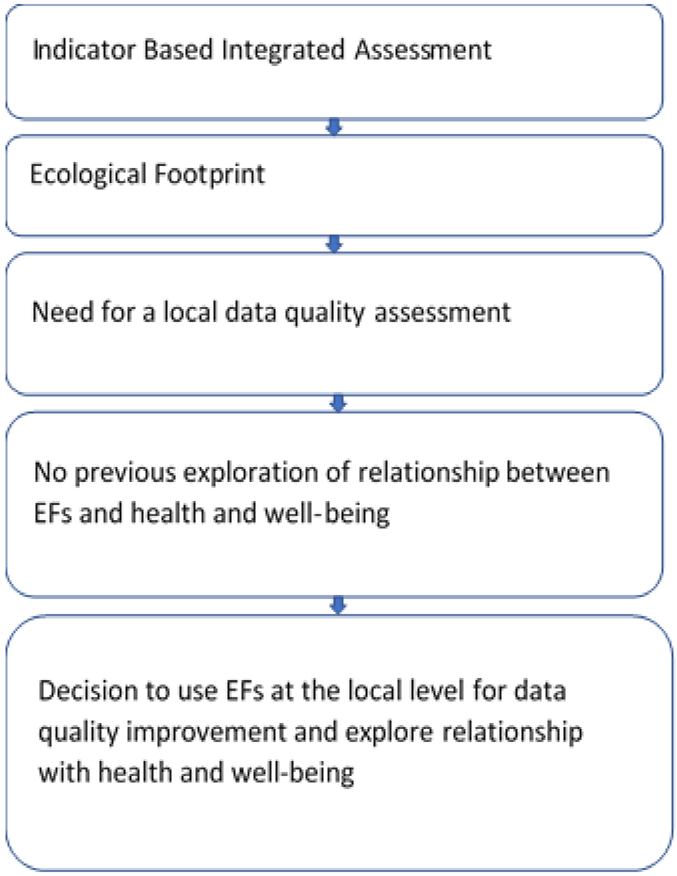


Figure 3. High-level decision tree to scope out how the research explores answers to the research questions.

Summary

The study aims to address a critical gap in sustainability assessment by enhancing the granularity and relevance of ecological footprint data at the local level and by investigating its relationship with community health and well-being. This process involved disaggregating national EF data to a fine-grained local scale (the Region of Peel) and innovating with a citizen science approach to explore opportunities to enhance data quality. The research proceeded in two major phases.

Phase 1 focused on methodology: adapting an established EF disaggregation methodology for local estimation, updating the base model with the latest available data, and comparing the results with primary data obtained through citizen science. Because national EF data are compiled from heterogeneous sources and broad assumptions, an important part of the exploratory analysis was to evaluate how well the top-down disaggregation aligns with the bottom-up, citizen-derived data. This comparison highlights the potential benefits and accuracy gains of incorporating citizen science into local sustainability assessments.

Phase 2 of the research examined the substantive questions of interest: do recent immigrants and established Canadians in the Region of Peel exhibit different EF of consumption, and are these differences statistically significant? Furthermore, how do these differences relate to indicators of health and well-being in each group? The analysis revealed measurable disparities in EF between the two groups. A moderate positive correlation was observed between EF and health/well-being scores, suggesting that higher resource consumption was associated with higher reported health and well-being in this context (details of these results are presented in Chapter 5).

The subsequent chapters will delve into the background context and literature review of those key concepts and their interrelationship, including sustainability assessments (Chapters 2 and 3), provide details on the methodology (Chapter 4), present the data and findings (Chapter 5), and discuss the implications of those findings (Chapter 6). By integrating sustainability science with public health and community engagement, this proof-of-concept research aims to generate new knowledge on building sustainable, healthy communities amid profound environmental challenges and demographic shifts.

Overall, this chapter has laid the foundation for understanding why such a study is crucial at this time of global environmental and social change. To understand the human impact on the environment, multiple frameworks exist. I chose an SEM-based framework as a foundation, with EF as an approach for local sustainability assessment. EF could benefit from enhancements to provide local-level insights, such as those offered by the Region of Peel. I chose a citizen science approach to generate local-level insights, aiming to enhance the EF approach by leveraging readily available data, tools, and citizen science methods. Given that multiple types of citizen science exist, I chose a contributory project option so that citizens can add local insights on EF to help identify differences across communities (established Canadians vs recent immigrants) within the Region of Peel. In this study, I highlight how citizen science can fill those gaps, how different communities have distinct EFs, and how these relate to the health and well-being of those communities.

Chapter Two: Sustainability Assessment (SA) with a Focus on the Local Level

Introduction

The term "Sustainability," with its roots in 18th-century silviculture, refers to the amount of wood that can be removed from a forest so that it can grow sustainably (Carlowitz, 2000; Klöpffer, 2003). The term has been defined more broadly in recent years, such as in the Brundtland Commission report (WCED, 1987), due to its more inclusive and integrated nature (WCED, 1987; Sze, 2018). According to Sze (2018, p. 31), the sustainability umbrella is a broader, inclusive concept that requires alignment with the time, place and motivation to effectively create measurable goals.

There are a few schools of thought about the meaning of sustainability. A school of thought is a set of opinions held by a group of people about a subject. The definition of sustainability within the first school of thought emphasizes that sustainability is part of the green movement or a necessity in society, and that any strategic decision-making must include sustainability as a 'pre-requisite' (Gibson, 2001; Pope et al., 2004). This concept highlights the idea behind planetary boundaries and the finite nature of resources. The definition of the second school of thought emphasizes extending sustainability beyond the environment, recognizing that the economy and society also play significant roles. This concept refers to the "three-pillar" or "triple-bottom-line" (TBL) model of sustainability (Gibson, 2001; Gibson & Hassan, 2005; Pope et al., 2004). It is essential to note that sustainability is a long-term goal. In contrast, sustainable development, which is sometimes used interchangeably with sustainability, refers to a process or pathway to achieve sustainability. Sustainability comprises three major dimensions, known as the foundational pillars (Gibson, 2001; Pope et al., 2004; Sze, 2018). The three pillars (Figure 4) are also known as the “3 Es”: economy, environment, and equity (in society) (Sze, 2018).

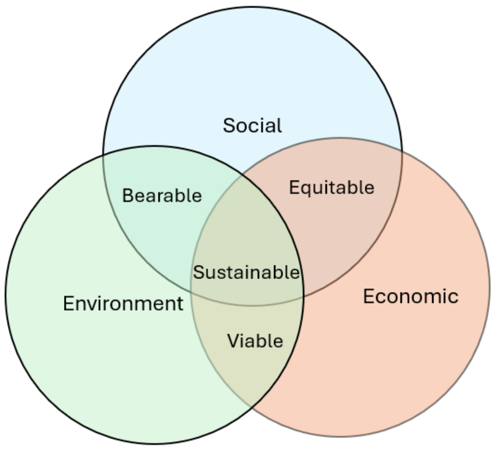


Figure 4. Three-pillar view on sustainability.

The equity component also encompasses the social dimension. Sze (2018) refers to Leach et al. (2010) in further generalizing those three pillars into “human well-being, ecological integrity and equity” (p. 32). Fundamentally, the TBL model refers to the same conceptual framework as the “three pillars”. The triple bottom line is also a consideration for businesses that aim to “balance” financial, environmental, and social outcomes (Atkinson, 2000; Elkington, 1998; Molnar & Mulvihill, 2003). Elkington (1998) proceeds with “Seven Revolutions”, also known as “7-D thinking”, which is poised to lead the future toward more sustainable corporations through the seven dimensions of sustainability (Elkington & Rowlands, 1999). The “7-Ds” include markets, values, transparency, life-cycle technology, partnerships, time and corporate governance. Those seven dimensions play a role in exploring sustainable development for corporations through their processes and pathways to achieve sustainability. However, the term “sustainability” is “at best a paradoxical prospect”, as it becomes divisive when it is defined too specifically and loses tangible meaning if it is defined too broadly (Mulvihill & Milan, 2007). Nevertheless, the summary of the Brundtland Commission report indicates that societal and ecological well-being are interdependent, and the pillars of sustainability are integral foundations for our future (WCED, 1987).

Sustainability Assessments: Theories and Frameworks

Sustainability assessment encompasses a high-level guiding structure or framework, the tools used for assessment, and the objective measures or indicators employed in the assessment. The frameworks are integrated, allowing for the comparison of alternatives. The tools are analytical methods for measuring the indicators. To promote consistency and guide sustainable development, scholars in the field developed the Bellagio principles in 1997 (Jesinghaus, 2014) to provide guidance and best practices related to sustainable development (Pinter et al., 2012). Gibson (2001) defines sustainability as part of a larger society, where the economy, environment, and social aspects all contribute to it as a triple-bottom-line (TBL) approach (Gibson, 2001; Gibson & Hassan, 2005; Pope et al., 2004). The standards for sustainable development, grounded in the TBL concept, led to the development of the Global Reporting Initiative (GRI) framework (Pinter et al., 2012, p. 22). However, tool-focused, indicator-based, and integrated, overarching frameworks can all coexist (Ness et al., 2007). A more fulsome discussion on the origin of sustainability and sustainability assessment frameworks is outlined in *Appendix A.*

This study focuses on the frameworks by Ness et al. (2007), despite the existence of multiple frameworks. It is because of their distinctive, comprehensive categorization, which aligns with the approach taken in this study. Ness et al. (2007) present a guideline that divides sustainability assessment tools and approaches into three categories: (a) indicator/indices, (b) product-related, and (c) integrated assessment. In addition, the authors acknowledge that monetary valuation can be an umbrella term that encompasses any of these approaches. Ness et al. (2007) provide a straightforward, easy-to-understand explanation of these types of sustainability assessments through a flowchart. This study uses the tools developed by Ness et al. (2007) for sustainability assessment to provide context for the analysis conducted in this research, given their simplified framework. Adapted from Ness et al. (2007), the following *three frameworks* are discussed below (Figure 5):

I. Indicator/indices-based framework
    a. Ecological Footprint (*an integrated indicator-based assessment*; EF falls under one of the three sub-categories (non-integrated, regional-flow indicators and integrated indicator frameworks))
II. Product-based framework
    a. Life Cycle Assessment and Life Cycle Costing
    b. Product material flow analysis and energy analysis
III. Integrated framework
    a. Impact Assessments
    b. Environmental Impact Assessment
    c. Strategic Environmental Assessment

In addition, *three* additional socio-ecological sustainability frameworks are discussed in detail below:

IV. Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM)
V. Millennium Ecosystem Assessment (MEA)

VI. Planetary Boundaries

I. Indicators/indices-based Framework

Indicators are quantitative measurements that generally have a defined study area. If various measurements are combined, they create an index or indices. As per the authors (Ness et al., 2007), the indicators are expected to provide trends and are suitable for monitoring and prediction. They can be categorized into three different types: non-integrated indicators, regional flow indicators, and integrated indicators (Figure 5). Non-integrated indicators do not integrate into society; for example, Environment Pressure Indicators (EPIs) by Eurostat (Ness et al., 2007). It provides comparable and comprehensive data for EU countries and regions, which are coordinated and collected collaboratively with statistics officials from EU countries. It can also be used to create an index by combining all indicators and grouping them into different policy areas as needed. Regional flow indicators focus on the physical flow of materials and energy, identifying efficiency within a system; they do not integrate. For example, if an indicator is related to environmental flows, it does not integrate with economic flows. Examples such as Material Flow Analysis (MFA), Substance Flow Analysis (SFA), and Input-Output Energy Analysis (IOEA) belong to this group (Ness et al., 2007). MFA examines the physical metabolism of a society to help reduce environmental losses related to the extensive resources consumed by societies. The SFA, a life-cycle stage tool used to determine the inflows and outflows of substances, enables identification of environmental impacts so that mitigations can be targeted and applied. An example of total suspended solids (TSS) analysis, as used by local conservation authorities in Ontario, Canada, is a form of local Substance Flow Analysis. On the other hand, the IOEA "analyzes the trade between different industries in the economy" (Ness et al., 2007, p. 503).

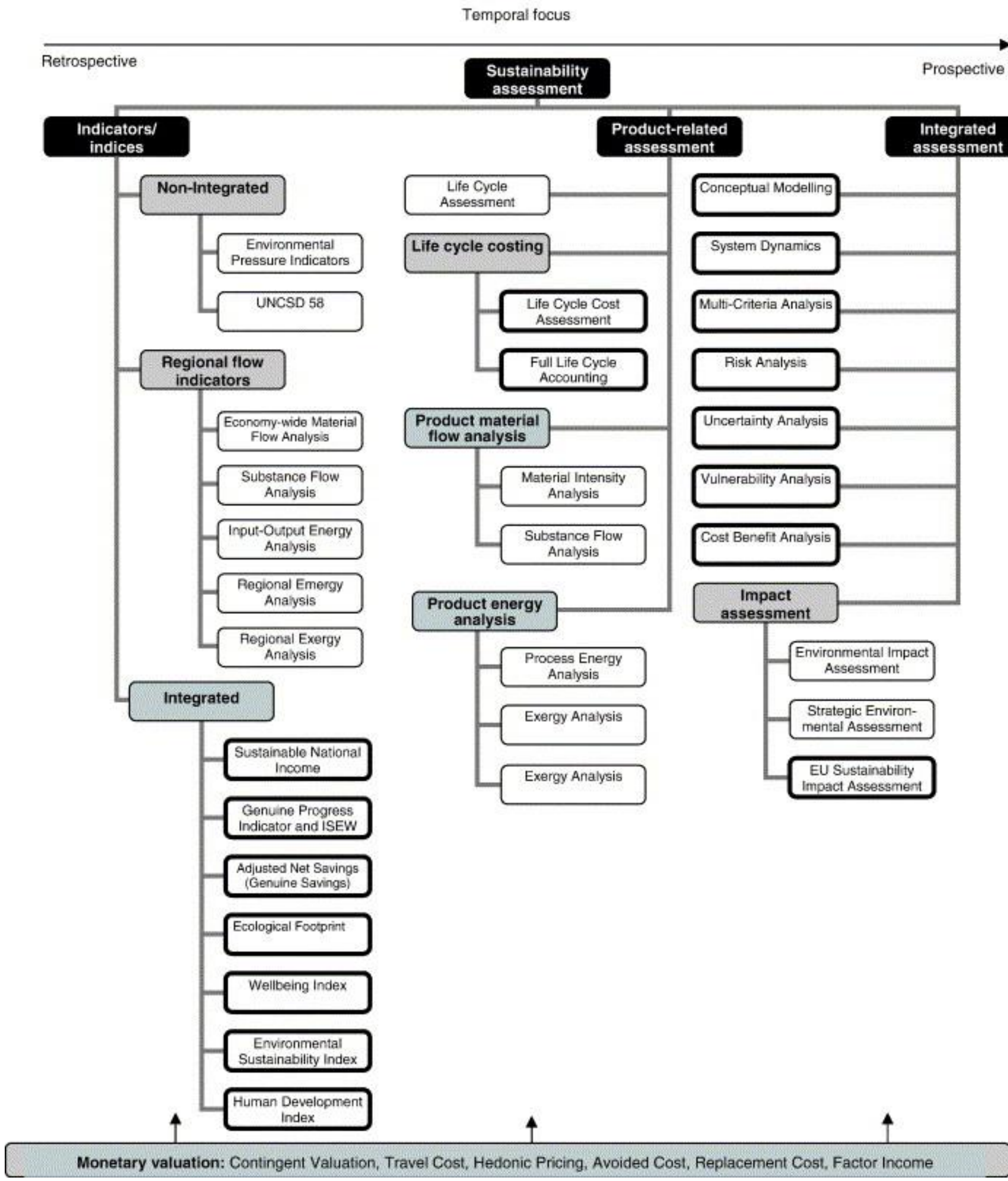


Figure 5. Three types of sustainability assessment tools/approaches discussed by Ness et al., 2007. Reprinted from Ness et al., 2007, © 2006 Elsevier B.V.

Ecological Footprint (an indicator-based, integrated tool): EF is an accounting tool that serves as an integrated sustainability indicator (Ness et al., 2007). Originally, a part of a PhD dissertation by Wackernagel (1994), EF was later introduced by Wackernagel and Rees (1996) to evaluate the resource consumption and other necessities of a population given the available land area. The EF has been widely used globally in recent years, including by Canadian municipalities, such as the City of Calgary. In recent years, the Global Footprint Network (GFN), in collaboration with the Ecological Footprint Initiative at York University, has released National Footprint Accounts (NFAs) annually (York University Ecological Footprint Initiative & Global Footprint Network, 2023).

Statistics Canada's ecological footprint workshop in 2008 highlighted a target that the Global Footprint Network (GFN) would like to see EFs adopted as indicators in at least 10 countries by 2015 (Crummey & Victor, 2008). By 2008, six of the targeted 10 countries: Switzerland, the United Arab Emirates, France, Belgium, Japan, and Ecuador already had research collaborations with the GFN. At present, GFN tracks EF data of more than 200 countries (Global Footprint Network, 2023). The report, a conclusion of the workshop with key partners and founders of the EF and NFA, such as Mathis Wackernagel, reiterates that EF doesn't necessarily include all dimensions of human environmental impacts. They highlight that the major exclusions include non-ecological aspects of sustainability, metrics for the depletion of non-renewable resources, waste flows, and other areas with limited data availability (Crummey & Victor, 2008, p. 8).

Some integrated indicators/indices, such as EF, aim to encompass all pillars of sustainability, using indicators that reflect reality. They go beyond traditional measurements, such as Gross Domestic Product (GDP) which fail to account for environmental factors. Some recent literature does not support the integration of certain indicator/indices tools, such as EF, as a single integrated measure (e.g., Galli et al., 2016; Baabou et al., 2017); instead, it highlights the resource accounting nature of these tools. Ness et al. (2007) presented these tools as integrated because they incorporate environmental and social factors. Indices such as the well-being index, the human development index, the environmental sustainability index, and the ecological footprint belong to this category. Among those indicators/indices, the ecological footprint is discussed in more detail below. These indicator-based integrated tools span "the economic, social and environmental dimensions" (Ness et al., 2007, p. 501). These tools, such as EF, despite being categorized as indicator-based tools, integrate consumption patterns, environmental degradation, and the depreciation of natural capital. In the context of the General Progress Indicator (GPI), Cobb et al. (1995) highlight the importance of attempts to combine different nature-society dimensions into a single indicator. There have been several attempts in recent years to integrate multiple community footprint tools and nitrogen footprint tools, incorporating indicator-based tools into other dimensions of society to reflect sustainability metrics (Dukes et al., 2023; Galloway et al., 2024).

It is important to note that EF is presented in this study as an indicator-based assessment tool integrated across multiple dimensions of society, as per Ness et al. (2007), who categorized sustainability assessment tools into three major categories. In this study, the argument for EF being integrated indicator stems from its integration of consumption patterns (e.g., reflecting social behaviours), input and output of materials world-wide and their transportation and supply chain maagment measurements such us the use of Leontief Inverse Matrix (Global Footprint Network, 2023; Baabou et al., 2017), and the tracking of environmental resource consumption and resulting environmental degragdation to estimate the earth overshoot timeframes. To summarize, EF is an indicator-based assessment that is well-integrated in other dimensions of sustainability, in contrast to some other indicator-based assessments, such as the clean drinking water access index in cities or municipalities.

Value of Integrated Indices-based SA such as the Ecological Footprint

Within the broader family of indicator-based sustainability assessment, EF is an integrated resource accounting tool (Ness et al., 2007). According to the Global Footprint Network (GFN) (2023), several countries, such as the Philippines, and many cities, including Calgary, San Francisco, and Barcelona, have recently signed on to use EFs as indicators in their integrated assessments. One of the recent studies was the first of its kind to estimate EF and biocapacity for a city, Wroclaw, Poland, and to estimate EF for Food (EFF) using both a top-down and a top-down-bottom-up assessment (Swiader et al., 2018). The study concludes that the top-down results showed a 1% greater footprint than the hybrid results and that the EF_F exceeded 10 times the biocapacity of the city boundary.

Several assessments using EFs have been conducted since GFN's foundation in 2003. In one of the recent studies, Lee et al. (2015) used EF in a life cycle assessment (LCA) in the USA and concluded that "EF can be applied to any product system but is especially valuable when analyzing trade-offs between functional alternatives that have land and greenhouse gas (GHG) emission trade-offs, such as FFs (fossil fuel) and biofuels" (p. 424). Similarly, Costa et al. (2019) employ the EF methodology as an assessment tool to analyze the Portuguese textile industry, investigating energy and other resource and material consumption throughout the entire textile industry process in the country. The EF methodologies have been used at various scales over the years, from global to metropolitan levels, along with the use of an individual and household EF calculator (Global Footprint Network, 2023). An EF assessment of a carbon footprint subcomponent in 15 Canadian census metropolitan areas (CMAs) and cities found that carbon footprint is the most significant contributor to the ecological footprint and that carbon footprints related to housing varied by electricity source (Isman et al., 2018). The study highlights that CMAs, with a higher concentration of renewable energy sources, have a comparatively lower carbon footprint than other areas, and that the operation of personal transportation was the second-largest contributor among all consumption categories, based on the consumption land use matrix (CLUM) of Canada.

However, a research gap exists: the use of EF at the local level to inform policies has been criticized for its relevance to policy (Giampietro & Saltelli, 2014), due to a misunderstanding of the structure and purpose of EF accounting (Galli et al., 2016; Goldfinger et al., 2014). Galli et al. (2016) have addressed the concerns regarding the validity and policy usefulness of EFs. Critics argue that a high level of media coverage and trust in EF without understanding the underlying background may lead to over-excitement and adverse policies. These academic debates suggest an acknowledgment that there is room to improve EF data quality, making it a more effective measure, particularly at the local level. As a means of a sustainability assessment, the EF approach, as an integrated tool, has recently gained worldwide momentum. Most assessments are still done at the national, regional or city level. A few recent studies used the Ecological Footprint Extended Multi-Regional Input-Output analysis (EF-MRIO) to scale down the national EF to the city-level EF. In the Mediterranean, 19 cities use the national-to-city-level household expenditure ratio for this assessment (Baabou et al., 2017).

Another study by Galli et al. (2020) employed a similar approach in Portugal to estimate city-level EF using the top-down method, applying the results to the economic MRIO Global Trade Analysis Project (GTAP) 9.0 model to produce a national CLUM. It was then used in combination with local and international data, along with the estimated household expenditures for the six municipalities from 2011 to 2016. Both studies use Oxford Economics data to apply a ratio to scale household expenditure from the national to the municipal level. Tsuchiya et al (2021) also used a similar approach to scale down national EF accounts, however, at the regional level (prefectures in Japan, similar to provinces or states in the North American context). However, these studies were done at the city or regional level, not at the neighbourhood level. Although an individual EF calculator exists (Global Footprint Network, 2023), these measurements have not yet been evaluated at a local level to understand the factors influencing consumption, nor to assess local-scale data quality and its usefulness for endeavours such as public education and policy-making. A brief discussion on the potential data calibration and enhancement options is presented in the subsequent sections.

II. **Product-based Framework**

Product-based assessments focus on "...flows in connection with production and consumption of goods and services" (Ness et al., 2007, p. 503). Instead of focusing on a regional type of flow, which is generally found in the indicator/indices, this type of assessment focuses on products and services (Figure 2). Although these approaches allow both retrospective and prospective assessments, they do not generally integrate with nature-society systems.

Life Cycle Assessment (LCA) and Life Cycle Costing (LCC): The LCA refers to the approximate pressure a product puts on the environment from the raw material extraction to final production and disposal (Ness et al., 2007). The full life cycle starts from the raw material extraction to its disposition and other implications related to it. LCC, an economic approach, refers to the total cost that a product would incur over its lifetime, given the total cost of production and processes discounted over the product's lifetime; it is more akin to an investment calculation (Ness et al., 2007). There are various LCCs, such as Life Cycle Cost Assessment and Full Cost Environmental Accounting.

Klöpffer (2003) argues that "[l]ife cycle thinking is the prerequisite of any sound sustainability assessment" (p. 158). LCA, in the field of sustainability, is experiencing rapid growth. Zamagni (2012) analyzed 600 papers that contain the words 'sustainability' and 'LCA' and concluded that the number of papers published in 2010 was three times as many as those in 2007. Although Ness et al. (2007) characterize LCA and LCC as separate and product-related assessments, these various life cycle approaches have morphed into something new in recent years. The Natural Step approach proposed in late 2000 was formalized into Life Cycle Sustainability Assessment (LCSA), which combines the LCA, LCC and S-LCA (Social Life Cycle Assessment) (Klöpffer, 2008; Zamagni, 2012). All these evolutions show that there is value to be added with the integration of product-related independent assessments.

Product Material Flow Analysis and Energy Analysis: The product material flow analysis is an analysis of all material flows associated with a product. Some of the examples of this type include Material Intensity Analysis (MIA) (Herendeen, 2004; Ness et al., 2007) and Substance Flow Analysis (SFA) (Herendeen, 2004; Ness et al., 2007). These types of analyses help to identify and track the flow of a source. On the other hand, product energy analysis measures energy to produce a product or a service (Herendeen, 2004; Ness et al., 2007). Energy flow analysis includes exergy and emergy analysis. Emergy analysis investigates the production process of a single product, whereas exergy analysis is meant for an energy system analysis, such as heating (Ness et al., 2007).

III. Integrated Framework

Integrated assessments include modelling and impact assessment families that are integrated with the environment, economy and society. The tools within this category are designed for decision support and policy development (Ness et al., 2007). Approaches such as system dynamics and conceptual modelling, multi-criteria analysis (MCA), scenario development, risk and uncertainty analysis, and cost-benefit analysis fall within this category. Due to the integrated nature of that approach, they are increasingly being used in designing optimal policy outcomes. Conceptual modelling, where the causal relationships exist among various parameters, is characterized and modelled using flow charts and diagrams. These are designed so it is easier to visualize, detect, and change a part of the flow or diagram to achieve better sustainability outcomes. Soft-system modelling is commonly used in some socio-ecological models, such as eco-health (Bunch, 2016; Bunch & Waltner-Toews, 2015; Bunch et al., 2011). Similarly, other approaches, such as MCA, include both quantitative and qualitative assessments. Risk analysis and vulnerability analysis, on the other hand, focus on an assessment of potential damage and vulnerability, respectively. Mostly tied to economic integration, the cost-benefit analysis (CBA) "…is used for evaluating public or private investment proposals by weighing the costs of the project against the expected benefits" (Ness et al., 2007, p. 504). CBA is one of the most common assessment types because it analyzes various costs and benefits of using a comparison of different alternatives. However, Mulvihill and Kramkowski (2010) argue that there are key barriers to implementing some of the integrated assessments, such as scenario development (potential stories of the future that might happen and can assist in identifying the task at hand), due to four major factors: “(1) The persistent predictive orientation of sustainability planning exercises; (2) the relatively low level of interest in weak signals and their implications; (3) institutionalized aversion to long-term planning; and (4) the predominance of an essentialist perspective” (Mulvihill & Kramkowski, 2010, p. 2449).

Impact Assessment (IA): Generally, impact assessments are used as a part of a project approval process. Their primary goal is to develop an assessment as a decision-support tool for either policy or project-level use, utilizing standard methodologies. Impact assessments draw upon multiple disciplines, ranging from engineering to ecology and from economics to planning, while also incorporating stakeholder comments and inputs. This makes IA a holistic approach where multiple dimensions of systems are integrated. With the introduction of the National Environmental Policy Act (NEPA) in the US, a formal environmental assessment (EA) was created in the 1970s to facilitate different types of impact assessments (Fischer, 2003). The origins of EAs are based on rational planning theories from the 1950s, which serve as a proactive tool to address acute environmental consequences before practical actions are taken.

Environmental Impact Assessment (EIA): Based on previous literature, Pope et al. (2004, p. 599) state that EIA-related assessments take place at a later stage of the project, hence having minimal effects on decision-making. Their concerns and limitations are also well understood in these processes. The “EIA-driven” assessments are generally reactive courses of action that have already been defined, with very few alternatives left.

In recent years, EIAs have been introduced in legislation in many countries. For example, Canada has recently updated the Environmental Act, known as the Canadian Environmental Assessment Act, 2012 (CEAA, 2012). As a legal requirement, the primary role of EIAs is to mitigate the environmental impact of projects, involving a process that includes consultations with stakeholders and the application of both qualitative and quantitative approaches. Stratos (2004) discusses various EIAs that took place in Canada until the early 2000s, for example, the Voisey's Bay project, a mineral project that aimed to extract nickel in northern Labrador, in the Atlantic region. A panel method in the project was used, where the panel and the proponent company issued the environmental impact statement guides, public comments were collected, Aboriginal input was considered, and a panel conclusion was made. The panel concluded the project could proceed without significant damage to the ecosystem. Many sustainability assessments fall under this category.

Strategic Environmental Assessment (SEA): SEA is "…a decision-making support instrument for the formulation of sustainable spatial and sector policies, plans and programmes, aiming to ensure appropriate consideration of the environment" (Fischer, 2003, p. 156). SEA-related assessments take place at a very early stage of strategic planning, with the potential for much broader applications and influence in the decision-making process (Gibson, 2001; Gibson, 2017; Gibson et al., 2010; Pope et al., 2004). The "SEA-driven" assessment, also known as "objectives-led SEA", is a proactive approach and is generally a part of the process of creating policies, plans and programs that seek comprehensive analyses of alternatives in advance (Pope et al., 2004; Sheate et al., 2003). Starting around the 1990s, strategic environmental assessments (SEA) were developed to evaluate the future impacts of strategic decisions (Fischer, 2003; Gibson, 2001; Gibson et al., 2010; Mulvihill & Baker, 2001; Mulvihill et al., 2013; Ness et al., 2007). The SEA, as the name suggests, is used at the strategic stage of a project or plan and is, therefore, an earlier option. In contrast, the EIA is applied at the project level and is, therefore, used at a later stage. According to Sheate et al. (2003), "[i]ntegrating the environment into strategic decision-making is an essential pre-requisite for moving towards sustainable development" (p.2). It can primarily fulfill two major roles: one being an appraisal of the already existing plans and policies, and the other being a systems-based approach to plan, assess, implement, and monitor policies, plans, and programs (Sheate et al., 2003).

At the SEA stage, the data and supporting documentation might be lacking, and political motives can be a big influencing factor. In addition, implementation of the SEA can be hindered by various situations of social dilemmas, such as 'not-in-my-backyard' (NIMBY) and 'locally-unwanted-land-use' (LULU) attitudes at the local levels (Fischer, 2003). Gibson (2001) reiterates that the potential damage caused by SEA is generally higher due to its irreversibility, which is a result of the complex and long-term nature of the process, in comparison to EIA, which provides more concrete information and its impacts remain at the project level.

The systems approach is one of the keywords used in recent impact assessments to reduce the fragmentation and sectoral approaches taken in the past. Integrated models work better in addressing the systems approach. In the context of Canada, the Mackenzie Valley Pipeline project is an example of a SEA application (Gibson et al., 2010). Although different federal and provincial agencies were involved, the authors note that the records show mostly "ad hoc" initiatives, and the national/federal SEA was not as credible due to its secretive nature. The project was cancelled by the main investment partner in 2017 due to regulatory delays. All the sustainability tools discussed in this section may be accompanied by a monetary valuation;

however, some of these approaches, such as CBA and LCA, include monetary valuation as a requirement.

Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): With an overarching goal of addressing biophysical requirements and the complexity of the Earth System as it relates to the impacts of human activities, this framework is used for resource accounting for sustainability assessment (Bianco et al., 2019; González-López & Giampietro, 2017). MuSIASEM, with its roots in various fields such as bioeconomics, cybernetics and complexity science, was founded by Mario Giampietro and Kozo Mayumi (Giampietro & Mayumi, 2000). It aims to address sustainability issues by comparing internal feedback between societal changes with external feedback that governs ecological processes. By integrating with society and ecological processes, MuSIASEM aims to assess sustainability and determine when and where interventions may be required.

It differs from the traditional assessment framework in that it does not employ reductionist approaches, as it is designed to address complex systems and problems at various scales. MuSIASM evaluates societal metabolism by examining various societal components, such as households or the industrial sector, and analyzing flows (e.g., fuel, food) as well as funds (e.g., managed land). This approach creates a network and pattern of feedback loops, providing insights into the interactions and dependencies within the system (Bianco et al., 2019). Those feedback loops are then compared with the ecological feedback loop scenarios to determine the feasibility of a society's metabolic pattern in surviving within the system (Bianco et al., 2019; González-López & Giampietro, 2017). González-López and Giampietro (2017) found that the study involving charcoal production done in rural villages shows that the MuSIASEM has the potential to provide very useful results that highlight functional elements of human time (activity allocation). They found that in this case, the opportunity cost associated with human time would determine the noticeable pattern of activities. These feasibility scenarios can be run at multiple scales, ranging from global to local; therefore, they are broader than some other frameworks, such as the planetary boundary framework, which limits its scope to a global scale.

Millennium Ecosystem Assessment (MEA): The MEA framework is "…a multi-agency initiative which will provide decision-makers and the public with relevant scientific information on the conditions of ecosystems, consequence of its change and options for responses" (World Health Organization, 2019). It was developed in coordination with the United Nations Development Program, along with a multi-stakeholder steering committee (Corvalan et al., 2005). The MEA assessed how ecosystems have been changing globally and identified causal relationships between human pressure on the environment and their outcomes on human health and well-being (Bianco et al., 2019; Corvalan et al., 2005; Reid et al., 2005). This is an integrated sustainability assessment that examines human well-being in relation to the direct and indirect drivers of change. The conceptual framework of this assessment is presented in Figure 6 (Corvalan et al., 2005; World Health Organization, 2019):

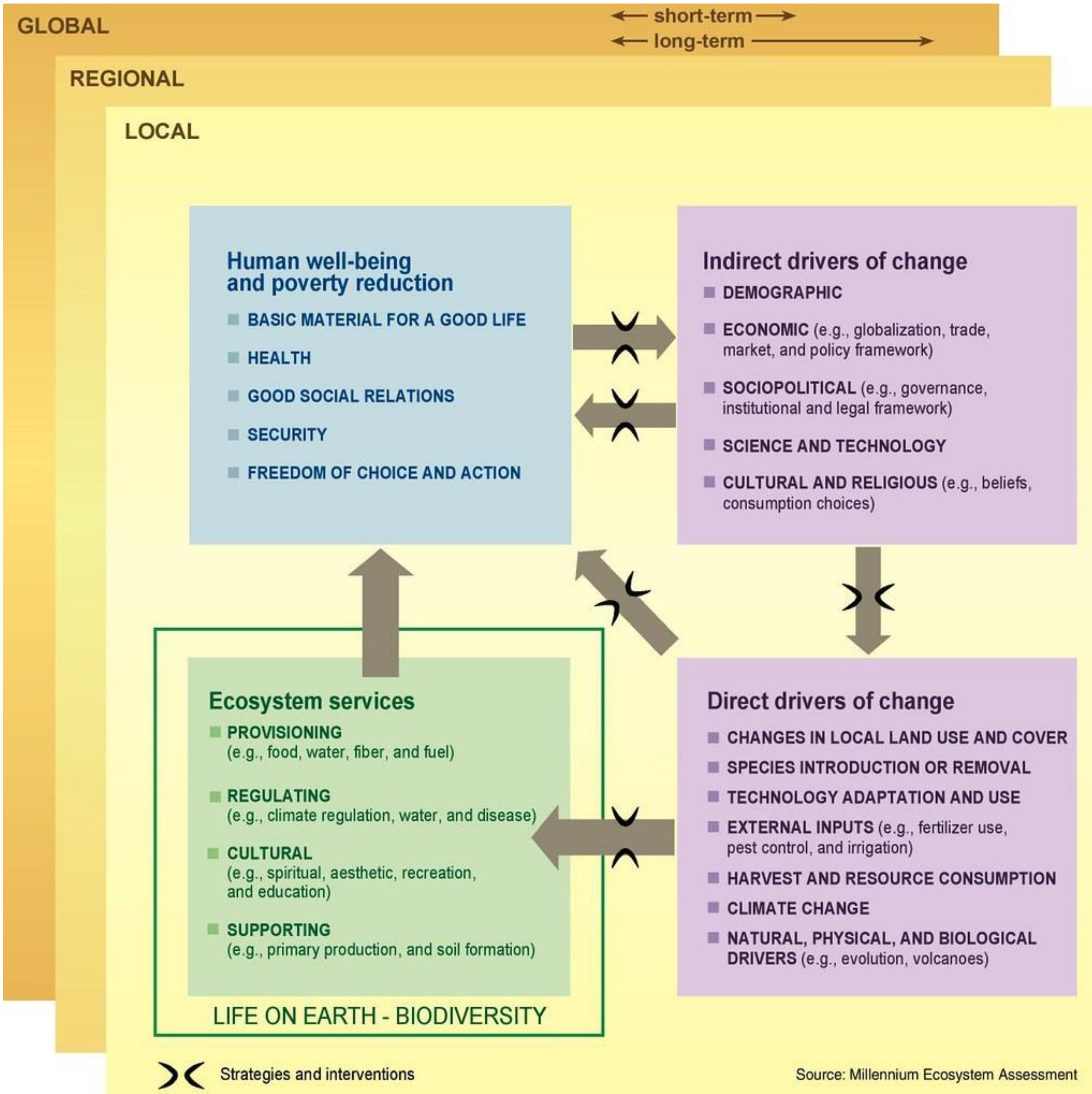


Figure 6. A conceptual framework of the Millennium Ecosystem Assessment (Corvalan et al. 2005, p.13).

MEA evaluates short- and long-term sustainability, in which ecosystem services can be assessed in relation to human health and well-being within a local or regional context, and the impacts on them are evaluated from both direct and indirect effects of other drivers of change (World Health

Organization, 2019, Figure 6). Corvalan et al. (2005) describe the causal relationship between human pressures on the environment, which, as a result, cause various health consequences (Figure 7). The diagram highlights how direct, ecosystem-mediated and indirect health impacts are caused.

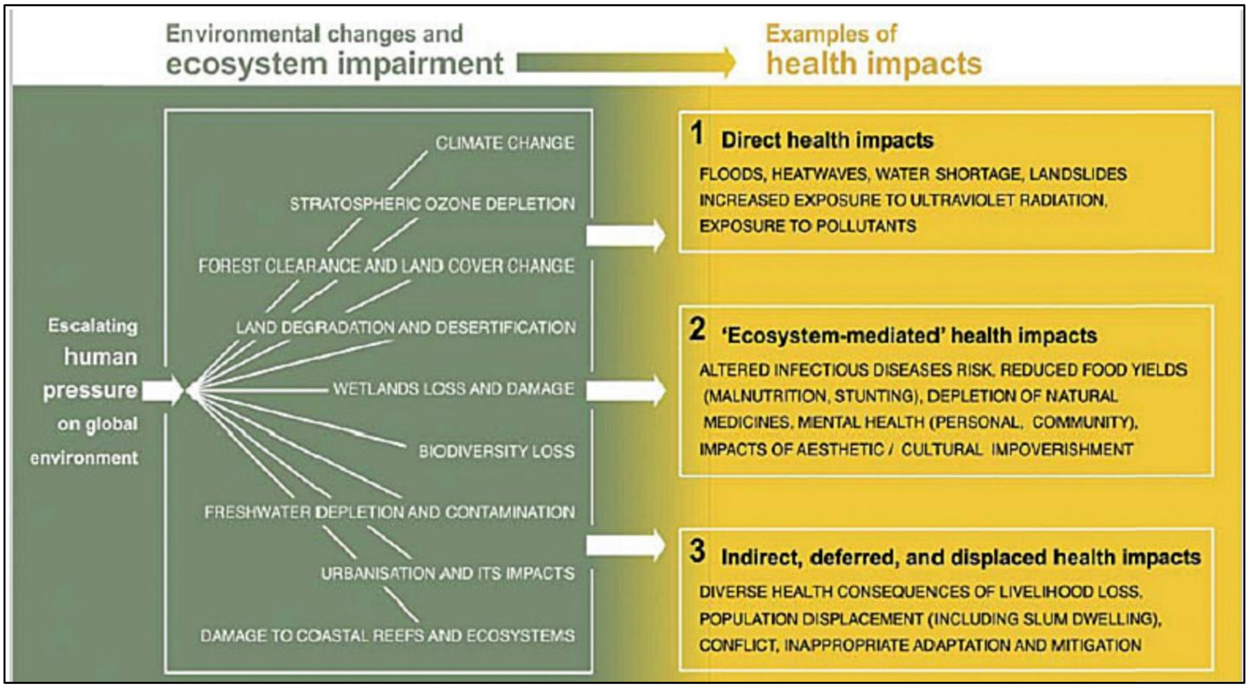


Figure 7. Harmful effects of ecosystem change on human health (Corvalan et al. 2005, p.1).

Figure 8 shows how the four types of ecosystem services, supporting, provisioning, regulating, and cultural, constitute the basis of human well-being (Corvalan et al. 2005). Figure 8 effectively communicates the importance of ecosystem services to the general public (Bianco et al., 2019).

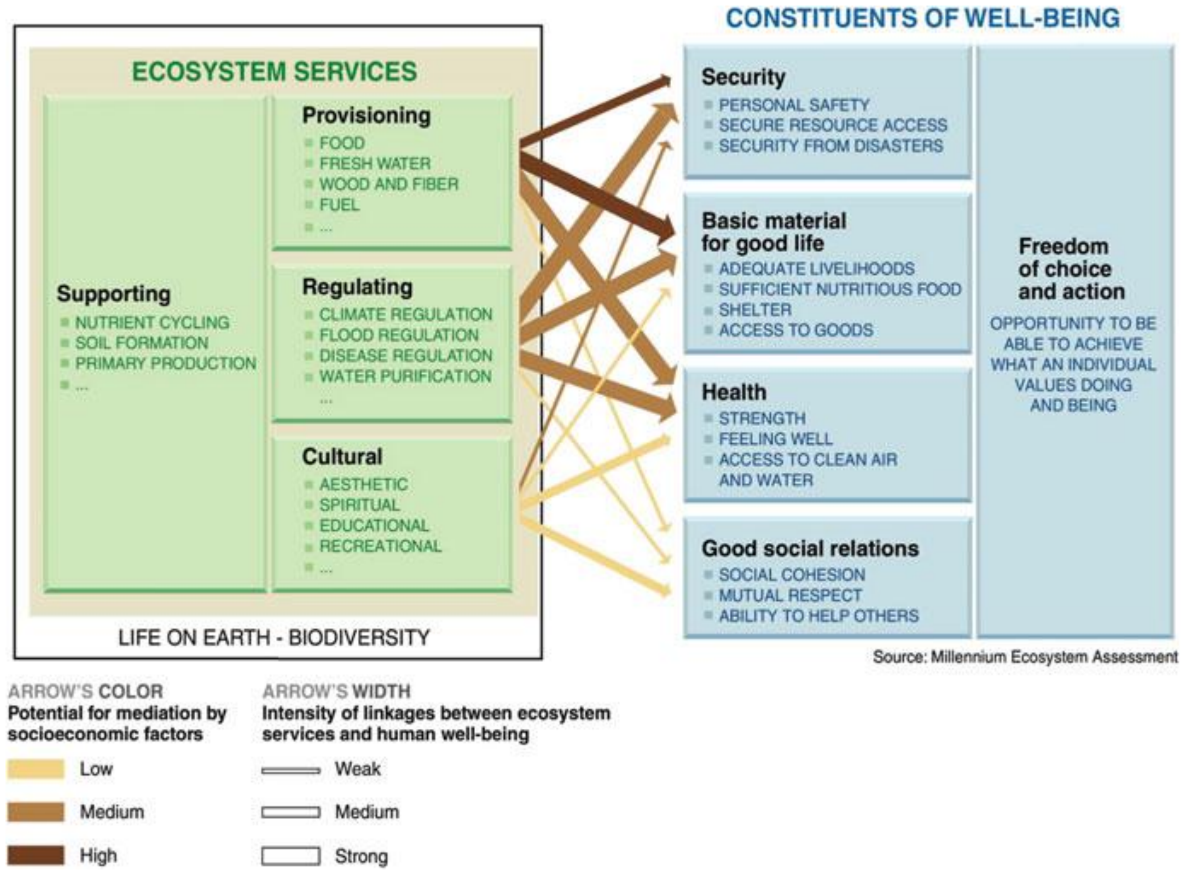


Figure 8. Connections between ecosystem services and human well-being (Corvalan et al., 2005, p.15).

Planetary Boundaries: The Planetary Boundary (PB) framework has its roots in boundary concepts such as sustainable production or limits to growth (Brooks, 2013; Meadows et al., 1972). The PB was conceptualized by a group of scientists led by Johan Rockström and Will Steffen to identify a safe operating space for humankind (Rockström et al., 2009). The authors argue that crossing those boundaries will "…trigger non-linear, abrupt environmental change within continental-to-planetary scale system" (p. 31). The framework also aligns with the leverage point concept, a point in a complex system where a slight shift in one area can trigger significant, potentially catastrophic changes across the system (Meadows, 1999). Meadows (1999) highlights that "...complex systems are, well, complex. It's dangerous to generalize them"

(p. 3). The PB framework evaluates the entire planet as a complex system and highlights the need to assess its sustainability, rather than breaking it down into various regional or local scales.

The PB framework also correlates to the "threshold hypothesis" that Max-Neef (1995) explains. The hypothesis states:

> …for every society, there seems to be a period in which economic growth (as conventionally measured) brings about an improvement in the quality of life, but only up to a point - the threshold point - beyond which, if there is more economic growth, quality of life may begin to deteriorate. (Max-Neef, 1995, p. 117).

With economic growth, the EF of the developed nations have skyrocketed. A higher EF has a direct and adverse relationship with quality of life at a planetary scale because of the potential to cross a critical threshold leading to catastrophic damage. The PB framework (Steffen et al., 2015) has the following critical processes to regulate planetary systems:

i. climate change;
ii. stratospheric ozone depletion;
iii. ocean acidification;
iv. biochemical flows;
v. freshwater use;
vi. land-system change;
vii. novel entities;
viii. atmospheric aerosol loading; and
ix. biosphere integrity.

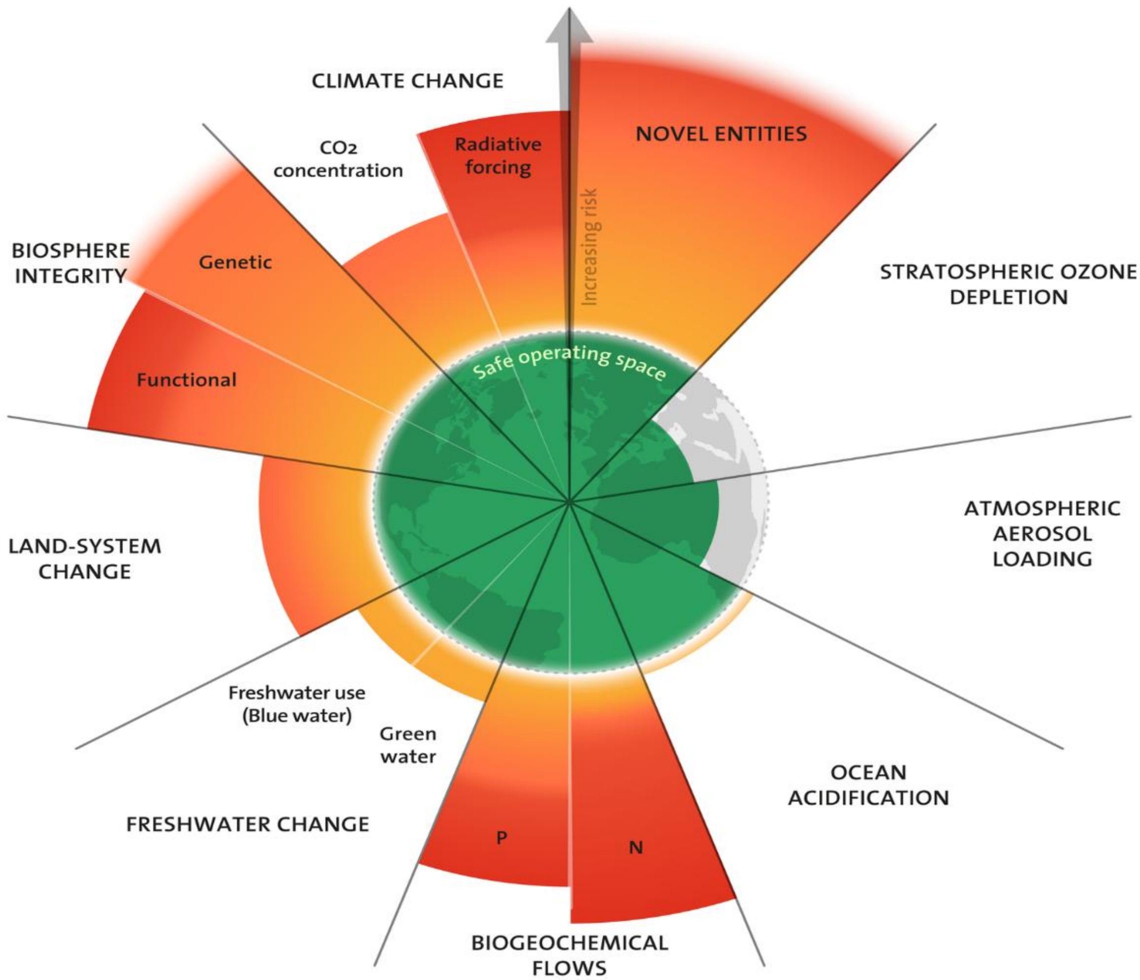


Figure 9. The 2025 update to the Planetary boundaries.
Note: From Azote for Stockholm Resilience Centre, based on analysis by Sakschewski et al., 2025. CC BY-NC-ND 3.0.

Figure 9 shows the planetary boundary. As of 2025, seven of the nine have already exceeded the estimated limits, according to researchers (Kitzmann et al., 2025; Richardson et al., 2023; Steffen et al., 2015). The authors highlight that, as of 2025, our plants have experienced greater stress in those critical processes.

Given that those sustainability frameworks have their own ways of assessing sustainability, EF has emerged as an easy-to-understand tool that can be applied at different scales for varied purposes (Baabou et al., 2017; Galli et al., 2016; Global Footprint Network, 2023). Although EF has been criticized for its policy relavency (Giampietro & Saltelli, 2014), due to a misunderstanding on the purpose of it, EF presents several advantage in practical usefulness scale for local municipalites and authorities, such as, (a) easy to understand metrics using the global hectares per captia, (b) regular publication of global footprint accounts, (c) potential to downscale to differing levels using a combination of approaches (Baabou et al., 2017; Galli et al., 2020; Global Footprint Network, 2023; Tsuchiya et al., 2021). Due to those reasons, the study uses EF as an assessment tool. As discussed in previous sections, the EF estimation at the local level has had its limitations; this study explores options to enhance the local data quality through data calibration.

Ecological Footprint: Potential Data Enhancement Options

A few options can be explored to enhance and calibrate data at the local level. In this regard, two avenues can be explored: local/Indigenous knowledge and citizen science.

a. Indigenous and Local Knowledge

Indigenous knowledge refers to "… a cumulative body of knowledge, practice and belief, evolving by adaptive process and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Berkes, 1999, p.8; Indigenous and local knowledge | IPBES secretariat. (n.d.)). One of the ways to assess sustainability in an area is to understand the local evolution and combine the body of local knowledge. Indigenous knowledge emphasizes the evolution of knowledge through adaptive processes, where the cultural transmission and environmental relationships of living beings are highlighted. The concept of Indigenous local knowledge (ILK) is a narrowed-down version of Indigenous knowledge (Berkes et al., 2007). ILK is understood as "…dynamic bodies of integrated, holistic, social and ecological knowledge, practices and beliefs about the relationship of living beings, including people, with one another and with environments" (Indigenous and local knowledge | IPBES secretariat. (n.d.), p.1). The local knowledge component stresses the relationship between the environment and living beings at the local level. The ILK is based on a place and the social context surrounding it; however, it is a hybrid and open form that combines written, oral, tacit, practical, and scientific knowledge collected from multiple sources and validated through different methods, including experimental ones and practical interaction.

A review by Thompson et al. (2020) on Indigenous knowledge and participation in environmental monitoring found that the prevailing literature generally treated participation by Indigenous groups as data collection. They note that, according to the literature, a higher degree of participation from the Indigenous group would have led to different outcomes and indicators than those observed in studies led by external groups. The study suggests that Indigenous knowledge has the power to uncover indicators that might otherwise not get discussed. However, the study also highlighted a few areas that are associated with effective and adequate monitoring using Indigenous knowledge. Based on the authors, "…a key challenge of conducting effective monitoring that leverages both Indigenous knowledge systems and science is the power imbalances that uncouple Indigenous monitoring efforts from management" (p.1).

Given the nature of this study, Indigenous and local knowledge was not further investigated on its own; however, it was expected that using the next approach, citizen science, would capture at least some of it.

b. Citizen science

Citizen science is public engagement and participation in a collaborative effort to advance scientific knowledge. The citizen science method, which involves collecting and validating data, alleviates the limitations imposed by authoritative data.

In recent years, there have been notable success stories, such as the democratization of information through citizen science, which has partially achieved environmental justice. In an environmental justice study, the data collected by citizens was used to validate the need for environmental justice (Dhillon, 2017). In addition, a study by Agyeman and Evans (2003) found that even the "equity and justice" vocabulary was still missing from the practical models of sustainability planning. Equity and justice revolve around how well representation takes place. Representation can be misaligned due to assumptions made by authoritative bodies or to technological mimicry of space, such as the use of Geographic Information Systems (GIS) (ESRI, 2010; ESRI, 2024). This has the potential to create a gap between local knowledge and decisions made at a "high level". The citizen science approach fills in the gap with local knowledge. Although it is still refining its identity (Mahr et al., 2018), it has certainly engaged the public through contributions or collaborations. Overall, the contributory or collaborative process is expected to democratize information from the collection and dissemination points of view. The process assists scientists and organizations in collecting data, supports research through collaboration to generate data that would otherwise be impossible to collect due to the labour required, and then provides communities with access to that scientific information. This study explored citizen science as a proof-of-concept approach to enhance ecological footprint data and local sustainability assessments.

Association of Ecological Footprint with Health and Well-being

As discussed in the previous chapter, sustainability encompasses a broader integration of the three pillars: environmental, social, and economic. They must work in harmony to achieve optimal outcomes, particularly when applying the precautionary principle. The previous chapter examined the key sustainability assessment framework presented by Ness et al. (2007), noting the absence of socio-ecological frameworks, such as the Millennium Ecosystem Assessment (MEA), from those lists. The MEA emphasizes that ecological conditions are closely linked to human health and well-being (Corvalán et al., 2005a). Kassouri and Altintas (2020) further suggest that "positive synergies" between human health, well-being, and environmental quality are desirable. However, their study of 13 Middle Eastern and North African countries reveals a significant "trade-off between the ecological footprint and human well-being" (Kassouri & Altintas, 2020, p. 1), as measured by the Human Development Index. Kassouri and Altintas' (2020) work explored EF data at the national level. In the context of Middle Eastern and North African countries, the study found that human well-being plays a significant role in environmental degradation, contributing to a larger ecological footprint. The authors further elaborate that social welfare policies are contributing to an increase in the human ecological footprint in Middle Eastern and North African countries.

On the other hand, a previous study by Aşıcı and Acar (2009) examined the relationship between per capita income and ecological footprint. Although this differs from the context of human health and well-being, the study found that, initially, as income per capita increases, both the ecological footprint of imports and that of production also increase. Once a certain threshold is reached, the ecological footprint of production tends to decrease. With that, the authors conclude that the initial growth of greater environmental degradation (reflected in a higher ecological footprint) gradually decreases, and the negative environmental impact of production's ecological footprint eventually turns positive. This study included a global sample of 116 countries, comprising high-, middle-, and low-income countries with ecological footprint data from 2004 to 2008. Another study by Uddin et al. (2017) examined the impact of real income on the ecological footprint of consumption (EFC). They ran different models to examine the impact of the world's leading EF contributors, from both developed and developing countries, using data from 1991 to 2012. The results from the dynamic ordinary least squares (DOLS) model showed a positive and significant association between real income and EFC, indicating that a 1% increase in real income is associated with a 0.27% rise in EFC. They found that financial development reduces EF by 0.15% (for every 1% increase in development), and trade openness reduces EF by 0.01%. In another model from the same study, the group mean fully modified ordinary least squares (GM-FMOLS) also showed similar results: every 1% increase in real income was associated with a 0.19% increase in EF. The results from these two studies (Uddin et al., 2017; Aşıcı and Acar, 2009) are similar, indicating that real income or per capita income increases ecological footprint. However, once financial development begins, the increased impact attenuates. Aşıcı and Acar (2009) further explored the ecological footprint and the relationships among income growth, ecological footprint, and human health and well-being.

In the context of Middle Eastern and North African countries, the study by Aşıcı and Acar (2009) shows that there is an ecological cost to pay for ecological degradation, leading to a higher EF if we want to improve our health and well-being. Although the literature is scarce on this topic as it relates to ecological footprint and human health and well-being, it raises the question of whether EFs and human well-being have a broader positive correlation, meaning they tend to increase together. To review this in detail, we must examine the foundation of EF from the regional to the local levels.

Ecological Footprint: Regional versus Local Assessment and Its Connection with Human Well-being

The goal of ecological footprint accounting and understanding is closely tied to aligning sustainable development goals with actual sustainability, which, in turn, has a significant impact on making these goals consistent (Wackernagel et al., 2017). Whether the EF is used for local or global analysis, there have been critics who have questioned its purpose and misinterpret it, a claim others have addressed (see Galli et al., 2016; Goldfinger et al., 2014; Kitzes & Wackernagel, 2009). Critics, such as Mario Giampietro, highlight potential risks in policy implementation that may underrepresent or overrepresent reality (Giampietro & Saltelli, 2014). One of the criticisms of the EF was that the only factor resulting in overcapacity (overshooting) is carbon footprint, given that forest, built-up land, and fishing lands are limited in their growth (Giampietro & Saltelli, 2014). The critics also argued that aggregating multidimensional phenomena into single indices was problematic. Galli et al. (2016) have addressed the criticisms and surrounding concerns, thereby clarifying the purpose of the EF and the need to evaluate it in the context in which it is meant to serve.

The EF account from Global Footprint Network aggregates national data and provides it to users at a national level (Global Footprint Network, 2023). Some researchers have developed a "EF calculation at a regional scale" (Hopton & White, 2012) or a municipal level for local sustainability assessments (Baabou et al., 2017; Galli et al., 2020; Hori et al., 2023; Scotti et al., 2009). However, those studies generally use per capita data from larger systems to downscale to the local level, augmented by commercially available expenditure data estimated at the municipal or regional level rather than at the finer (neighbourhood) scale, using publicly available data.

Whether it is at the local or regional scale, finding data to calculate EF is one of the biggest challenges (Hopton & White, 2012). Hopton and White looked at a regional-scale EF analysis in southern Colorado. As data is often collected and managed at the state or national level, they found it daunting. Other challenges included inconsistent data and varying data-collection intervals. The authors reduced the number of variables so that the national footprint did not need to be scaled to specific regions, such as counties, and so that not all data were available at the regional level. As such, the authors downscaled (disaggregated) the data from state or country levels to county levels when they were not locally available. The downscaling was done based on the per capita rate of the larger systems. For example, per capita food consumption data from the USDA at the national level were used to estimate regional food consumption. In addition, a linear interpolation was used to fill gaps in data that were not reported at regular intervals. The authors analyzed 35 variables from 1980 to 2005 and concluded that the ecological footprint remained steady over this period; however, per capita biocapacity decreased due to population growth. The authors replaced national data with specific local data when available. This simplified method is an example of how national EF accounts have been scaled down or used in conjunction with other local data/variables.

Although there are a few local analyses of the ecological footprint, as well as a substantial number of national and global analyses using time-series data (Global Footprint Network, 2023), relatively few studies have specifically linked the local ecological footprint to human health and well-being. A few recent studies, including the one mentioned above, discuss the links between them (Barbier & Hochard, 2018; Long et al., 2020; Smith et al., 2019; Türe, 2013). They are not necessarily at the local level, but some, such as the study by Long et al. (2020), developed an ecological well-being performance (EWP) model using an improved three-dimensional EF to evaluate sustainable development across four island regions in China, using 2017 data. The study concluded that enhancing the Human Development Index (HDI) while simultaneously reducing EF indicates greater efficiency in the use of ecological resources. This approach is proposed to achieve sustainable urban development. Another study by Kassouri and Altinas (2020) focuses more on multi-national assessments.

The study by Kassouri and Altintas (2020) utilizes data from 1990 to 2016 to examine the association between human development (well-being) and ecological footprint in 13 Middle Eastern and North African (MENA) countries. The authors chose this region because the MENA region has adopted the Sustainable Development Goals (SDGs) framework, committing to achieve them by 2030 (UNDP, 2016). The study explored the interconnectivity between those two sustainability-based indicators. Although geographically located in the same region, the 13 MENA countries exhibit significant differences in their economies, depending on whether they export oil. The study divided the countries into two subsamples: seven as oil exporters and six as non-exporters. They concluded that there was "a strong trade-off" between human well-being, as measured by the human development index, and the ecological footprint across all sectors, both overall and within the subsamples. This highlights that, in the context of the MENA countries, as human well-being improves (increases), so does the EF. In addition, they noticed that the socioeconomic index was negatively correlated with EF per capita. This finding aligns with previous studies and the Environmental Kuznets Curve (EKC) hypothesis, which suggests that developing economies with lower socioeconomic indices tend to have lower per capita ecological footprints (Grossman & Krueger, 1995; Ulucak & Bilgili, 2018). According to a study by Ulucak and Bilgili (2018), the ecological footprint increases at the early stages of economic growth in a country, but tends to decrease as economic growth increases in high-, middle-, or low-income countries, regardless of the level of development. Based on these studies, we can expect that if a growing economy is an indicator of an improving socioeconomic index, an EF is likely to increase at first, along with human well-being, given the positive relationships between them.

Summary

After reviewing multiple sustainability assessment frameworks, this study utilizes EF, an *indicator-based integrated approach*, along with the citizen science method. By utilizing citizen science, we have multiple avenues to gather and refine local information, thereby enhancing and embedding a sustainability assessment at the local level. The study aims to conduct a targeted assessment alongside a broader sustainability assessment that is transparent and open to various uses. It is also a reality that outcomes from a sustainability assessment, whether site-specific or more strategic, depend on the quality of the data input and participation from stakeholders. By formalizing sustainability as a loosely defined yet complex requirement for the modern world, the Brundtland Report of 1987 introduced a new wave of thinking into our day-to-day lives. This has resulted in legislative implementations of sustainability, which is also reflected in corporate practices of sustainability through seven dimensions, or the “7 Ds”. It has guided us through sustainability assessment principles, paving the way for us to become sustainable within our limits. Best of all, we could yearn for human health and well-being while attempting to mitigate the impacts of climate change.

In this chapter, I explored several frameworks, including those outlined in detail by Ness et al. (2007). The frameworks by Ness (2007) are comprehensive; however, they do not include socio-ecological frameworks (such as the planetary boundaries (PB) and Millennium Ecosystem Assessment (MEA)) or other frameworks (such as the Global Reporting Initiative (GRI) as it relates to the Bellagio principles). The current literature also suggests that there is no consistency in describing some of the same components; "approaches" are also described as "tools", "methods", "indices" or "methodologies" by various authors. There is a need for the scientific community to come together to agree on a set of comprehensive sustainability assessment frameworks that encompass different hierarchies for integrated, non-integrated, temporal, and geographic scale-based sustainability assessments.

As the study focuses on ecological footprint, this chapter explored further explored enhachment opportunities for EF and its connection to health and well-being. Measurements at local and regional scales of EF have faced challenges, including inconsistent and outdated data. Nevertheless, these analyses have often relied on national EF data, through methods such as downscaling, to provide a more accurate representation of EF within their respective jurisdictions. On the other hand, studies linking EF to human health and well-being are scarce.

One of the recent studies in MENA countries, done at a national level, concluded that as human well-being improves (increases), so does the EF, whether the country has a relatively better economy (oil-exporting) or not. There have been no local-level (census tract or dissemination area) studies that directly link health and well-being to ecological conditions using the ecological footprint indicator. Generally, the studies closest to connecting EF with human health and well-being have focused on economic growth and prosperity as indicators, using socioeconomic indices such as the HDI.

A few studies have focused on economic growth, socioeconomic improvement, and the tendency of an increased or decreased EF. Those studies use the Environmental Kuznets Curve (EKC) hypothesis, stressing that developing economies with lower socioeconomic indices tend to have lower EF per capita (Grossman & Krueger, 1995; Ulucak & Bilgili, 2018). Although lower EF per capita in this context changes as the economy grows, there is an inverted U-shaped relationship between environmental degradation and economic growth.

Overall, EF assessments are available at varying global and regional scales. However, it is crucial to recognize that the degree of connection between EF assessments and sustainable development indicators varies. Studies examining the relationship between health and well-being and EF are relatively sparse and often focus either on specific niche regions or on local jurisdictions. Chapter 3 covers citizen science in the context of EF.

Chapter Three: Citizen Science

Introduction and Background

Citizen science facilitates public involvement and input across a broad spectrum of topics. It represents a collaborative approach to advancing knowledge and scientific discovery through public contribution, engagement, and participation. This assertive citizen science method, which involves collecting and validating data, mitigates the limitations imposed by authoritative data. The Oxford Dictionary defines assertive as "expressing opinions or desires strongly with confidence, so people take notice" (Oxford Dictionary, 2024). Whereas authoritative data is defined among the data or geographic information system practitioners as the data that is either produced or is approved by certain authorities, such as by a government or professional stamp (such as a surveyor's stamp) that is recognized by authoritative agencies that provide those certifications (ESRI, 2024). On the other hand, citizen science thrives on contributions and collaborations.

Although its identity is still being refined (Mahr et al., 2018), the public has been engaged through contributions or collaborations for a long time. The overall process is expected to democratize information, making it accessible to people, from collection to dissemination. It is a powerful way for the public to contribute scientific information, engaging with and collaborating with researchers to improve the decision-making process for a community or society. The labour required to collect massive amounts of local data by scientists or organizations is sometimes impossible, given the resources and time available, without public collaboration. This process also provides communities with access to that scientific information.

However, experts have argued whether citizen science is an “additional scientific method” or a “true opportunity for empowerment”, while trying to avoid creating “human sensors” (Dickel, 2016; Mahr et al., 2018). Arguments revolve around where our focus should be; the whole idea of empowerment and unbiased local intelligence falls apart if the shift is toward productivity and efficiency. The concept of democratization is left behind if “human sensors” can only “sense or collect” data in a robotic way, without participating in other processes, such as design, collaboration, and analysis. By narrowing citizen science to its policy relevance and a recipe for creating efficiency, we might end up defining it very narrowly (Auerbach et al., 2019). This leaves us with the question of when and how citizen science started.

History and Origins of Citizen Science

Although many citizen science programs commonly trace their origins to the Christmas Bird Count, which began in the 1900s, another volunteer program existed before then, originating in the late 1880s. In this program, lighthouse keepers began collecting data on bird strikes. Those records were used to understand patterns and help understand bird migration at the local level (Droege, 2007). The volunteer effort traversed from the American coasts to the Caribbean Sea. Data quality was uneven: some noted only the type of bird, while others provided a more comprehensive description and correctly identified the bird. The program's validity was questioned regarding data quality, as the same species were sometimes identified incorrectly, for example, by colour-based names such as “yellow bird”. Wells Cook led the lighthouse surveys, which continued past World War II (Droege, 2007); however, the term “citizen science” was not coined until the late 20th century.

Alan Irwin and Richard Bonney are credited with promoting the term “citizen science” in their works in 1995 and 1996, respectively (Strasser et al., 2019). They reflect the participatory ideals and their limitations from the 1970s (Bonney et al., 2009; Irwin, 2002; Strasser et al., 2019). However, Irwin and Bonney differed in their visions for citizen science. According to Bonney, it is a strategic way to build public literacy and trust through a top-down approach that can make ordinary people aware and enthusiastic about the creation of scientific knowledge (Woolley et al., 2016, p. 3). Conversely, Irwin’s definition emphasizes the potential for emancipation, which could foster a more accurate representation through direct, active public involvement. This perspective aligns with the notion of “science for the people and science by the people” (Strasser et al., 2019, p. 53). Irwin and Bonney differ in their visions in such a way that Bonney sees it as an advantageous outcome of scientific knowledge, whereas Irwin sees it as “…emancipatory benefits of active public input on the direction of scientific research agendas” (Woolley et al., 2016, p. 4). This delves into deeper questions about the nature of citizen science. The short answer is that citizen science is used to advance society or promote the greater good. However, societal good can be viewed in various ways. If both visions of citizen science align with the ideal definition of societal good, there is no issue with the interpretation; however, if they do not, diverging visions can emerge. Thus, the risk of creating “citizen sensors” rather than empowering citizens becomes a question when employing citizen science (Catlin-Groves, 2012).

There are various ways those risks can be mitigated by design; however, participation also depends on citizens' willingness to participate. There are several types of citizen science programs in which participants can be expanded or contracted as needed. There are guiding principles for the citizen science framework that can inform the types of citizen science projects. These relate to participants' contributions, engagement and roles in those projects.

Contribution, Participation or Engagement

According to Woolley et al. (2016), people participate in citizen science differently, based on their interests, skill levels, and openness to those who create the skills and to those who create citizen science projects. The different ways to participate in a citizen science project are known as participation, engagement, and involvement (Woolley et al., 2016). If research impacts someone's life directly or indirectly, citizen scientists provide the data for that research. This is participation. This is an intentional role, being aware of their rights and the democratic processes involved in those studies.

The level and type of the public's participation, or their awareness of it, is called engagement. The engagement depends on how frequently and for how long scientific research is communicated to and collaborated with the public. In certain instances, the public plays a crucial role in the design, planning, and research processes, which may encompass defining the scientific questions to address grassroots issues. This level of high engagement, from defining the scientific questions to address grassroots issues, is called involvement. Based on the nature of the roles that citizen scientists assume, citizen science projects are categorized into the following three types (Bonney et al., 2009):

a. Contributory projects
b. Collaborative projects
c. Co-created projects

Professionals or scientists design *contributory projects*. Participants collect information according to guidelines established by professional researchers. One such example is crowdsourcing. Sometimes, citizen participants may conduct data analysis.

Collaborative projects are also planned and created by professionals; however, participants play a range of roles by getting involvedin designing or shaping a particular scientific outcome. Participants in these projects are more engaged than in contributory projects, and, depending on the type of project, some guides for public participation are available (Wiggins et al., 2013). Some environmental and more urban emotion-based projects, such as designing a mural to reflect a locality in an urban area with the active involvement of residents, belong to this category (Gunnell et al., 2021).

Co-created projects, on the other hand, have the highest level of involvementfrom participants. These projects are collaboratively designed, with participants and the scientific community working together as partners. At least a few volunteers participate in most or all steps of the scientific process. Some examples include community-led projects, such as the "Making Sense" project that addresses air quality and noise pollution in Amsterdam, "The Alberta Furbearer Project" for wolverine population and conservation risk assessment, and some other local initiatives against environmental injustice (Gunnell et al., 2021).

Due to the broad nature of citizen science projects, it is very difficult to define citizen science (Dickel, 2016; Mahr et al., 2018). If we define it too narrowly, it defeats the purpose and original vision. If we define it too broadly, it loses its relevance. One way to guide citizen science projects is through guiding principles. Based on the European Citizen Science Association

(ECSA) working group on "sharing best practices and building capacity of citizen scientists - 2015", there are ten principles of citizen science (Robinson et al., 2018):

1. Citizen science projects actively involve citizens in scientific endeavours that generate new knowledge or understanding;
2. Citizen science projects have a genuine science outcome;
3. Both the professional scientists and the citizen scientists benefit from taking part;
4. Citizen scientists may, if they wish, participate in multiple stages of the scientific process;
5. Citizen scientists receive feedback from the project;
6. Citizen science is considered a research approach like any other, with limitations and biases that should be considered and controlled for (democratization of science);
7. Citizen science project data and metadata are made publicly available, and where possible, results are published in an open-access format;
8. Citizen scientists are acknowledged in project results and publications;
9. Citizen science programmes are evaluated for their scientific output, data quality, participant experience and wider societal or policy impact; and
10. The leaders of citizen science projects take into consideration legal and ethical issues surrounding copyright, intellectual property, data-sharing agreements, confidentiality, attribution and the environmental impact of any activities.

The current study is a *contributory* citizen science study, in which 9 of 10 principles were met (Table 1). Among other citizen science benefits, such as capturing details with local variation, this study is different from a generic survey-based study because it adheres to the principles set forth for a citizen science project (Table 1).

Table 1. Citizen science principles (Robinson et al., 2018) applied in this study, along with rationale.

Principle number & keywords	**Applied here**	**Rationale for how this study captures the principles**
1: Active participation	Yes	The study involved citizen scientists from across Canada who contributed their ecological footprint (EF) and health and well-being data. This was to create new knowledge about local variations in these phenomena..
2: Scientific outcome	Yes	The goal was to capture varied EFs from participants so as to create a national benchmark for scientific output at the local level within the study area.
3: Benefits for both parties	Yes	The goal of the study was to benefit both the researcher and the participants by providing them with feedback during the process. The feedback included an overview of their EF as they go through the process.
4: Participation in multiple stages	No	The participation across multiple stages is a weakness in this study, given that it was intended to capture time-stamped data. However, this could be achieved in a subsequent study if a refinement is performed using the current base data.
5: Receive feedback	Yes	Participants received feedback on their EF and health and well-being throughout the data collection process. This was automated to provide participants with information relative to the average participant. The feedback included generalized statements such as "m*oderate ecological footprint – good job! There is still some room to improve"*.
6: Research with limitations considered	Yes	Limitations and biases are considered, such as selection bias, representation issues, and under- or over-reporting of certain patterns. They are discussed in the limitation section of this study.
7: Data available to the public	Yes	The intention of this study is to make aggregated (privacy-compliant) data and results available to the public.
8: Acknowledged	Yes	All citizen scientists from the study are acknowledged throughout the study, in data and result presentations, and in publications.
9: Evaluated for outcome	Yes	The study was evaluated for scientific outcomes, data quality, and potential societal and policy outcomes. The study presents two findings based on these criteria: (a) a raw data approach within the study area, which was only exploratory given considerations of statistically representative samples within the study, and (b) an average-based approach for a larger geographic area that provided a representative sample to apply as a benchmark at the local level. The details are discussed in the methodology and results sections.
10: Legal and ethical considerations	Yes	Legal and ethical considerations for human subject participation were approved by the York University Ethics Committee before the study began.

Role of Citizen Science

Citizen science projects are increasing, especially in the ecology and environmental fields (Ottinger, 2010; Silvertown, 2009). The public has been participating in scientific research for a long time in various ways, such as collecting water-quality data and identifying species of flora and fauna. Bonney et al. (2009) highlight the success of the Cornell Lab of Ornithology (CLO) citizen science projects while identifying the risks, protocols, and costs associated with them.

Citizen science projects stem from a scientific question, with the collected information monitored by a team of evaluators. It is essential to engage citizens and provide them with training; the incoming data must also be evaluated and disseminated back to them for it to be meaningful. With predefined protocols for collecting and conducting quality assurance and control of the data, citizen science has evolved over the past two decades (Bonney et al., 2009; Bonney et al., 2014; Cohn, 2008). Beyond the scientific sector, the impact of citizen science on social, economic, and environmental fields can also be significant, with many targeted approaches. For example, a sea turtle monitoring network called Grupo Tortuguero in northwest Mexico ultimately contributed to the development of sustainable fisheries practices and improved local livelihoods (Bonney et al., 2014). The collaboration created between local agencies, communities, and scientists in that project helped establish marine protected areas and sustainable fisheries practices. Despite the potential and expected social, scientific, and overall positive outcomes, current issues with citizen science remain at the process level. Strategic investments and coordination are necessary for citizen science to reach its full potential, rather than duplicating similar work and reinventing the wheel.

New studies have evaluated current scenarios and envision a path for citizen science that is more collaborative, participatory, and teamwork-focused, employing various partnerships and customized regional data and system “portals.” The eBird project (electronic bird database), which addresses local issues while also addressing global or regional ones, is one such project (Bonney et al., 2014; SciStarter, 2020). A future version of citizen science is expected to have the capacity to make “viral scenarios” through social media and to develop “collective capital” with an accelerated feedback loop, where tracking and successes are more integrated and transparent (Newman et al., 2012). However, volunteers' motivation levels vary significantly based on personal interests and external factors, such as associations and recognition. Therefore, these factors must be identified and integrated during the design phase of citizen science projects to ensure an engaged collaboration among participants and scientists (Rotman et al., 2012).

In recent years, since around 2010, citizen science collaborations have moved to online platforms and universities and schools. In the Season Spotter, where participants were asked to help classify and mark images based on seasonal changes, some multi-scale projects (at local and regional levels) were conducted entirely through online engagement (Crall et al., 2017). Other projects include plans to integrate citizen science into the classroom by facilitating local partnerships between scientists and teachers, as well as on-the-ground learning and student participation (Harlin et al., 2018). These examples demonstrate how we are moving forward to achieve our vision of creating social good and developing approaches that democratize information.

Policy decisions, in general, have been based on authoritative information, such as data provided or approved by government bodies, with little or no input from participants with local knowledge. With these processes, policymakers are at greater risk of failing to represent the space on which the policies are based (Beyer et al., 2010). Everything that has been represented is devalued as a part of the process "in the society of the spectacle" (Crampton & Krygier, 2005). Besides, representation in our society is not necessarily just one thing, whether it is a "representation of space" as a physical or material entity or a "space of representation" where meanings, emotions, and lived experiences are included, as Harvey (2008) clarifies in Lefebvre's characterization of space.

The study presented in this dissertation examines the representation of ecological footprint data and human health and well-being in a local context, utilizing a Geographic Information System (GIS) and a citizen science approach. The representation is a model built from a combination of available metrics and citizen-collected data. In the context of representing space solely using GIS, authoritative mapping may not include assertive representations of local collective knowledge, and thus may not provide a just framework. "Space-based" social or environmental injustice, as represented by minority and marginalized communities, adds a new dimension to the already existing social challenges. To represent space, whether for ecological footprint analysis, waste management, or Indigenous land mapping, there is a strong possibility that the "politics of knowledge" occurs without people's direct representation. The "politics of knowledge" is critiqued "…not to say that our knowledge is not true, but that the truth of knowledge is established under conditions that have a lot to do with power" (Crampton &Krygier, 2005, p.14). In terms of mapping, it is not because the "scientification" of mapping was inaccurate; rather, the complexity of the "value" of space is sometimes difficult to put into coordinates and extents. Without the context of social relations, it is hard to map represented space, particularly through the authoritative approach. Representation, therefore, is a flawed concept if we think that we can replicate x on earth with y in perceived "reality" without involving the *represented* in the first place. There are other ways to represent reality via local and Indigenous knowledge.

The value of Indigenous and local knowledge has frequently been highlighted in citizen science (Danielsen et al., 2018; Wall, 2020). Even though we use the *represented*, or the citizens, there may not be an objective truth. However, the collaborative process of representation can deliver agreed-upon justice within a society, providing better-quality data or information than authoritative sources. In these types of scenarios, a post-normal science approach can be used to address complex problems (Funtowicz & Ravetz, 2003; Kay et al., 1999; Turnpenny et al., 2011). Post-normal science has greater tolerance for uncertainty than normal science (Funtowicz & Ravetz, 2003; Kay et al., 1999; Turnpenny et al., 2011). The science that emerged to address those complex challenges primarily stemmed from the practicality of the 'use-inspired' implementations with solution-oriented practices (Kates, 2011).

GIS, a mode of representation, has been criticized for providing a single point of view and an authoritative, power-based imposition of the truth about space, which is inherent in the information it represents (Bunch et al., 2012; ESRI, 2010; Schuurman, 2000). Citizen science plays a crucial role in compiling and validating georeferenced representations in space. Wikimapia and OpenStreetMap are examples of Volunteered Geographic Information (VGI), reflecting a trend of growing citizen participation in which assertive methods of collecting geospatial information are preferred over authoritative methods (ESRI, 2010). In a conversation with ESRI, Michael Goodchild, a prominent thought leader in GIS, highlighted that GIS is criticized for empowering only those who can afford the price tag, leaving out the less fortunate. Goodchild reiterates that engaging citizens in the process of collecting and participating in geographic data collection has a big potential to change the landscape, particularly with VGIS (ESRI, 2010, p. 20).

The debates around “critical GIS” in the 1990s (Schuurman, 2000) have given rise to a “socially aware type of GIS” that distributes the power and legitimacy of local or Indigenous spatial knowledge in various names, such as Participatory GIS (PGIS), Public Participation GIS (PPGIS) and Community Integrated GIS (Dunn, 2007). The objective of a PGIS is to integrate local and Indigenous knowledge with “expert” level data for the “democratization of GIS”; however, this does not guarantee the “…power [given] to those involved in, and affected by, the decision-making” (Aitken & Michal, 1995, p. 17). There is also the likelihood that conflict may emerge between participants with different stakes, and that participants' skills can impact the quality of the data. While various factors may influence the use of citizen-focused GIS or other participatory approaches, the overall outcome typically integrates a comprehensive range of representation aspects, such as ecological processes and local knowledge, into the decision-making process. GIS can play a role in the spatial interpretation and representation of space in the context of local information.

Ecological Footprint, Health and Well-being and Citizen Science

Singh et al. (2009) summarize the descriptive nature of existing sustainability assessment methods from a “normal science” perspective, which assumes the linearity of processes within the scientific community. Normal science is based on the premises of normal conditions, where all the complexities of interconnectedness and interdependence are not always accounted for. Post-normal science is more open to uncertainty than normal science (Funtowicz & Ravetz, 2003; Kay et al., 1999). If we want to address the complexities of interconnectedness and interdependence, we need a “solution-oriented discipline” that opens the door to a holistic approach (Kay et al., 1999). Local and Indigenous knowledge cannot be captured by numerical modelling at a global level. For example, instead of creating a national map of butterfly species distribution based on secondary data and modelling of potential habitats, field-collected or locally collected information from citizen science projects, such as a ‘Butterfly Blitz’, would yield higher-quality data and a more accurate representation of species distribution. Quality assessments of assumptions about citizen involvement at the local level can help provide comprehensive data. Citizen science has the potential to fill the gap in environmental management and sustainability assessment, and to analyze and improve health and well-being.

Given their holistic approaches, citizen science and post-normal science have the potential to enhance data quality, including EF data, and to contribute to the development of an integrated policy framework at the local level. The EF data have been criticized for their policy relevance due to a misunderstanding regarding the purpose and structure of the EF accounting (Van Den Bergh & Grazi, 2014; Fiala, 2008; Galli et al., 2016; Goldfinger et al., 2014). Although there have been several studies to define purposes and use the EF structures to help local policy makers, such as one in the 19 Mediterranean cities (Baabou et al., 2017), Portugal's six municipalities (Galli et al., 2020), prefectures in Japan (Tsuchiya et al., 2021), and by scaling down national EF data to regional or municipal levels using multi-regional input-output analysis (MRIO), they focus on the complicated models with data-heavy approaches to address them at those scales. There were no studies to directly review and evaluate whether we can employ citizen science to improve the quality of ecological footprint data at the local level, thereby enhancing policy relevance at the neighbourhood scale. Although citizen science is a more comprehensive and holistic approach to gathering information, it still faces challenges of under-or overrepresentation of certain voices. This study presents a proof-of-concept for using a participatory citizen science approach to supplement local EF calculations. This is an innovative approach; however, it has limitations, which are discussed in the limitations section of the subsequent chapter.

Citizen science is an effective way to monitor health and well-being related to the Sustainable Development Goals (SDGs) and the WHO's Triple Billion Targets (Fraisl et al., 2023). Fraisl et al. (2023) highlight that the power of citizen science to increase the accessibility, quality, granularity, and timeliness of health and well-being data is unparalleled. Their study reviewed citizen science portals, such as SciStarter and Zooniverse, as well as other community-based monitoring and crowdsourcing tools. Based on the study, 48 out of 58 health and well-being-related indicators, which relate to 83% of the SDGs and the WHO's Triple Billion Targets, have either already benefited from citizen science or have the potential for a direct or indirect citizen science contribution.

Summary

Citizen science has the potential to enhance the data quality of ecological footprint analyses and explore their relationships with human health and well-being. In the context of EF assessments, where data quality could be enhanced or calibrated to reflect local reality, citizen science could contribute by validating data at local and regional scales and by increasing accessibility and relevance for local stakeholders. The study presented in this dissertation is a *contributory* citizen science project. Despite its potential to address gaps in local EF data enhancement and improve information on human health and well-being, there remains a risk of both over- and under-representation of citizen voices. Chapter 4 delves into the methodologies used in this study.

Chapter Four: Methodology

Introduction and Study Area

In this chapter, I present the comprehensive methodology used in this study. This methodology employs an ecological footprint (EF) disaggregation approach to estimate the EF of consumption at a localized scale (the Region of Peel), utilizing national-level data, along with a ratio adjustment to align with contemporary data. Additionally, I examine the EF of consumption at the Dissemination Area (DA) level, illuminating the disparities between established Canadians and recent immigrants. The methodological approaches are further explored using citizen-science-collected data. Finally, the chapter also dives into the methodological approach used to analyze community health and well-being, utilizing existing data and comparing it with citizen-collected data.

The Region of Peel, the study area in this study, represents a substantial portion of the EF of Canadians within the province of Ontario, which has a population of 1,499,917 out of 14,223,942, or 10.55%, of the total population of Ontario (Statistics Canada, 2021). The GTA has also been the subject of several studies examining the relationship between environmental factors and human health and well-being (e.g., Awuor & Melles, 2019; Campbell et al., 2014; Macfarlane et al., 2015; Perrotta, 1999). The methodological approaches are presented in the subsequent sections in detail.

Background for Methodology

Others have estimated the ecological footprint (EF) at local levels (city or municipal) for use in an attempt primarily to raise awareness or inform policy-based decisions (Aall & Thorsen

Norland, 2005; Kovács et al., 2020; Kuzyk, 2011). The argument for local estimation of EF from national averages is that the national averages do not provide sufficient guidance from the indicators to inform policy-based decisions at a local level, despite offering a broader international benchmark (Aall & Thorsen Norland, 2005). In these studies, the complexity of converting national EF averages to local levels is highlighted, as seen in one study in which a lack of local data in Oslo led to accounting for only 20% of Oslo's total ecological footprint. The authors of the study then had to use proxies and estimations from the national averages (Aall & Thorsen Norland, 2005).

Many other studies have employed income and expenditure-based models to examine the relationship with EF (Cranston et al., 2010; Kovács et al., 2020; Kuzyk, 2011, 2023; Muñiz & Galindo, 2005; Rees, 2006; Wackernagel & Rees, 1996; Wackernagel et al., 2006). Based on those studies, income is highly correlated with consumption (Cranston et al., 2010; Muñiz and Galindo, 2005; Wackernagel & Rees, 1996), suggesting that the same pattern may hold at the local level. Other studies, such as those by Barrett et al. (2006), have also supported a strong positive relationship between income and expenditure. The Stockholm Environment Institute is a leader in EF calculations, using comprehensive resource flow models, and also highlights that variation in EFs is rooted in income (Haq & Owen, 2009). The income and expenditure-based local EF estimations, such as those by Kuzyk (2011), have been derived from studies that highlight these relationships. Kuzyk (2011) employed this estimation method after comparing subnational data using the income-based deciles from Mackenzie et al. (2008). This study offers a Canadian perspective, utilizing similarly available local data from across the country, and employing their methodology. An overall structure and summary of the methodology (Figure 10) and detailed methodological steps (Figure 11) applied in this study are summarized in the flowchart below:

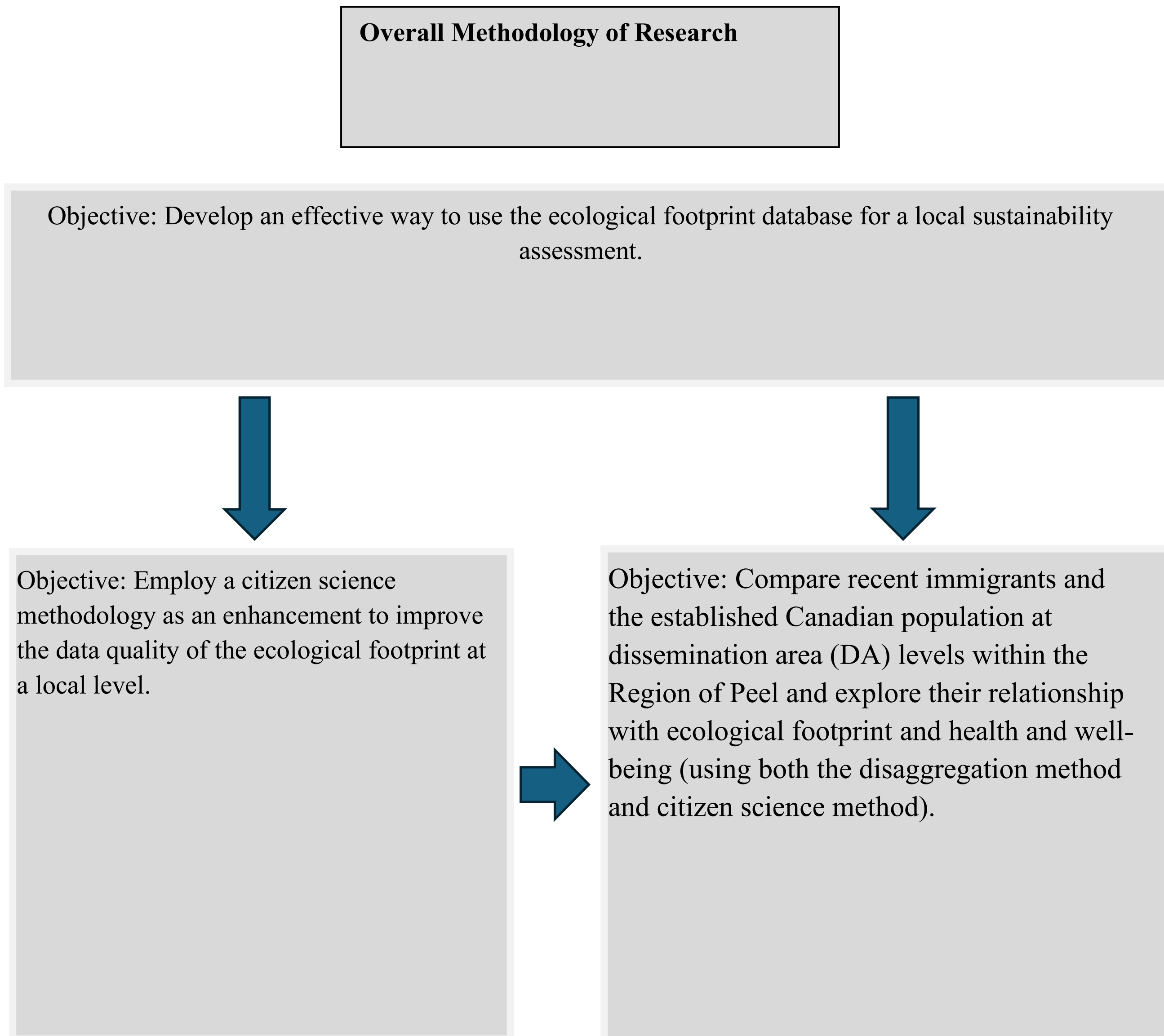


Figure 10. Overall methodology of research in this study.

Detailed Methodology per Objective

Objective 1: Develop an effective way to use the ecological footprint data for a local sustainability assessment

Selected an existing methodology in the context of the study area.
(Kuzyk (2011)) methodology was selected

Compared after-tax median household income to average expenditure.
Mackenzie (2008) data was used as a ratio

Created Local Income Ratio (LIR) for the Region of Peel (ROP).
Canadian EF of consumption was 7.42 gha/cap, and ROP became 10.20 gha/cap.

LIR was assigned to all EF of consumption categories.

Income-decile-based EF was applied and converted to local DAs, as per Mackenzie's (2008) ratio with the actual data from 2021.

Created household income decile vs EF of consumption categories and assigned to each EF land use of consumption categories.

Applied EF of consumption at the DA level based on the income decile algorithm (using Python scripts) within the ROP.

Objective: Employ a citizen science methodology as an enhancement to improve the data quality of the ecological footprint at a local level

Objective: Compare recent immigrants and the established Canadian population at dissemination area (DA) levels within the Region of Peel and explore their relationship with ecological footprint and health and well-being (using both the disaggregation method and citizen science method)

Objective 2: Employ a citizen science methodology as an enhancement to improve the data quality of the ecological footprint at a local level

Data: collected 407 submissions, out of 385 required from all of Canada, as a benchmark. Health and well-being components have 403 submissions.

Canadian average EF of consumption (7.42 gha/cap) was used as a basis for the average citizen science (CS) consumption as a starting point. Applied average Canadian consumption category percentage as a ratio to citizen science data (for example, if food-related EF was 2.13 Gha/cap, the ratio out of 7.42 gha/cap was applied to food-related EF values on CS data.

Assigned ratio-based values on CS data in all 5 consumption categories.

Assigned income-decile-based EF of consumption values if there were no data in some DAs.

Compared the results from the disaggregation method with the citizen science method using *t*-test and examined correlations.

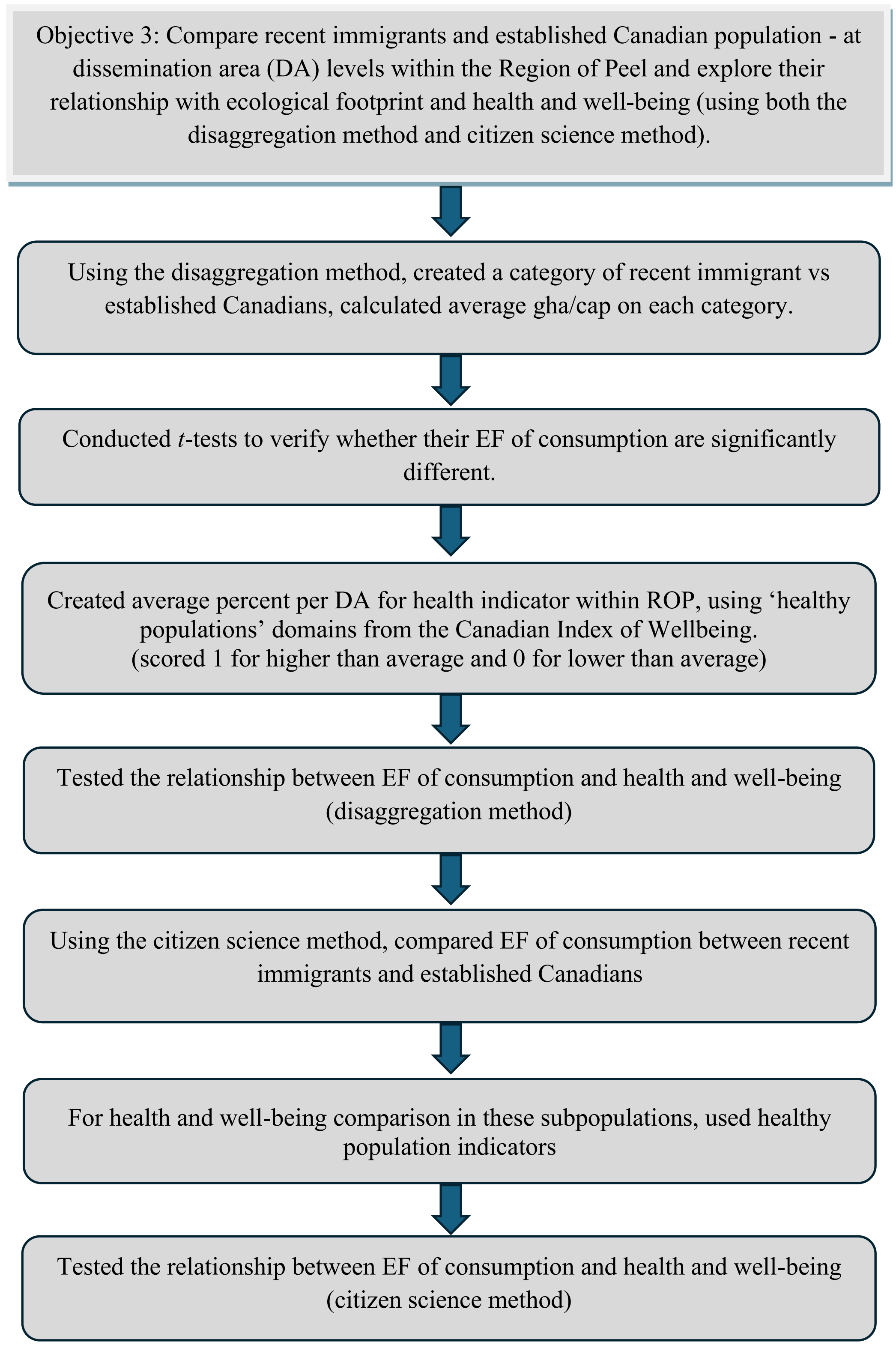


Figure 11. Summary of overall methodology with detailed steps taken per objective.

The detailed steps used in this study are discussed in the subsequent sections. A legend (in the form of a flowchart) was created for each objective to guide readers through the steps for the methodologies discussed in detail in the subsequent sections.

Methodology for Disaggregation of EF of Consumption

I assessed the local EF in this proof-of-concept study using a mixed-methods approach, combining a *top-down disaggregation* of national EF data to the local level with a *bottom-up citizen science* method to calibrate and validate the results. Dissemination Areas (DAs) were chosen as the unit of analysis for local EF; DAs (defined by Statistics Canada) are small geographic units of roughly 400–700 people, which Kuzyk (2023) suggests may be an optimal scale for fine-grained EF analysis (sometimes referred to as a “census village unit”).

The strategy in this study was as follows: first, apply an *income-based disaggregation method* to estimate the EF of consumption within the Region of Peel and its constituent DAs using national data; second, refine or compare these estimates with data collected directly from local participants via a citizen-science approach (a new methodology introduced in this study for local calibration).

Income-based EF Disaggregation Method

Kuzyk's (2011) methodology is grounded in a Canadian context, using national EF data to estimate local-level EFs in the province of Alberta. It was selected for this study to draw parallels in the Canadian context within the study area and to explore alternative ways to compare and, if possible, enhance the local EF measurement.

Rationale for Using an Income-Based Approach: Although other methods focusing on input-output approaches exist (e.g. Baabou et al., 2017; Galli et al., 2020; Lenzen & Murray, 2001; Lenzen & Murray, 2003; Tscuchiya et al., 2021; Wiedmann et al., 2006), they have complex methodologies and a complexity of input requirements in those approaches. This, in turn, poses a potential obstacle to local estimation of EF, which can support decision-making at the community level where data, time, and resources may be limited. Although an input-output method is a well-recognized approach, it has some limitations, including the complexity of the models. Multi-regional or international input-output models, which are very labour-intensive, would need to be developed to minimize assumptions, such as the assumption that all imported goods are produced at the world-average carbon dioxide intensity, which does not account for regional variations (Wiedmann et al., 2006). In addition, Wiedmann et al. (2006) also point out that the monetary weight of imported commodities is assigned as domestic products due to a lack of data, which is not always the case. Another challenge with this method is the lack of up-to-date supply-based data, which is a common issue in the industry. Such complexities can be obstacles for community-level or local-level analysis, where data, time, and resources are limited. Another issue with the disaggregation is that the reported results are aggregated at the national level. This could result in an *ecological fallacy*. The ecological fallacy is the incorrect assumption that a group-level variable applies at the individual level (Schwartz, 1994). It is possible that the aggregated variable might measure a distinct construct from that at the individual level. If we downscale national-level EF reporting to the individual level, there is a risk of a larger ecological fallacy.

Moreover, even these sophisticated models have shown that EF correlates strongly with expenditure; for example, Wiedmann et al. (2006) found a strong positive correlation between per capita EF and per capita expenditure. Given that consumption (spending) drives EF (Rees, 2008; Wiedmann et al., 2006) and is itself driven by income, a more straightforward income/expenditure-based method appears justified and practical for local EF estimation. Many other researchers have successfully used income or expenditure as proxies for consumption in EF studies (Cranston et al., 2010; Graymore et al., 2010; Klinsky et al., 2010; Muniz & Galindo, 2005; Wilson & Grant, 2009), lending credence to this approach. Although these models have limitations, the income-based disaggregation approach used in this study has a lower ecological fallacy compared to the national models (e.g., assuming everyone in a neighbourhood has the same EF as nationally reported gha/cap) because we are capturing local income data at the DA level, which should help mitigate some of those concerns.

Overview of Kuzyk's Method: Using those studies about EF's correlation with income and expenditure as a basis, Kuzyk's method (2011) was found to be a strong approach to disaggregating national EF data in Canada into a local EF. A simpler approach was used in Kuzyk's method (2011), which utilized readily available data in Alberta, Canada, and could potentially benefit local policymakers. Thus, Kuzyk's method (2011) served as the basis for estimating local-level EF within the study area, with some modifications made to reflect more current data.

The core assumption in Kuzyk's method is that communities with higher income (and expenditure) have proportionally higher ecological footprints. The steps involve establishing the correlation between income and spending, calculating a local income ratio, and scaling the national average EF by this ratio to obtain a local EF estimate. Additional refinements include distributing that EF across consumption categories (e.g., food, housing, mobility, goods, services) and across income groups, using ratios derived from earlier research (Mackenzie et al., 2008). Kuzyk's methodology, which uses median household income and average spending to estimate local-level EF, was applied in this study, with any data gaps filled using ratios from Kuzyk's (2011) results or those of Mackenzie et al. (2008).

Application of Kuzyk's Method in this Study: Statistics Canada does not report EF directly; however, it conducts annual surveys of household expenditure. Since 2017, these data have been available only at the provincial or higher level (not for metro areas). Previous studies (Wilson & Anielski, 2004; Kuzyk, 2011) have used Census Metropolitan Area (CMA) expenditure data to scale down to neighbourhoods, but such CMA-level data were not available for the current period. Therefore, I began with provincial-level expenditure data (for 2021) as a basis and assumed that the relationship between income and expenditure observed at that level remains applicable to smaller geographies, such as DAs.

Correlation of Income and Expenditure: Given that income is correlated with spending, spending is consumption, and that consumption is the basis for the EF calculation (Rees, 2008; Wiedmann et al., 2006), this study uses Kuzyk's (2011) method to scale down the national EF to the local level. The methodology uses median household income and household expenditure as a foundation for estimating EF at the local level, a similar approach to that employed by Kuzyk

(2011). It then calibrates the methodology using current data by applying ratios. Although various other approaches exist, such as the ones by Haq and Owen (2009) that combine Statistics Canada data with approaches for sustainability assessment, many other researchers (Graymore et al., 2010; Klinsky et al., 2010; Wilson & Grant, 2009) have used a similar approach to this study based on income and expenditure. Baabou et al. (2017) use a ratio of city-to-national-level per capita household expenditures, derived from Oxford Economics, as a scaling factor to estimate households' EF of consumption for each city in the host country. The approach was not within the scope of this study due to the data's accessibility, which was hindered by its commercial nature. Instead, national and provincial averages of expenditure data from Canada were used as a baseline to establish a foundation for national-level, comparable citizen-science-based gha/cap.

The variables used in this methodology are easily accessible; however, the methodology becomes complex as we investigate decile-based income and corresponding EF contributions. This study reviews how those consumption categories and land use result in the EF of the consumption land use matrix, commonly known as CLUM (Isman et al., 2018; Wackernagel et al., 2006). Those details are explained in the subsequent sections; however, we need to start with the basis of how national-level EF corresponds to national median household income versus average spending.

As a first step, total median after-tax income from Statistics Canada (2021) and average household expenditure from 2021 were used, as per Kuzyk's (2011) methodology for reviewing the correlation. It is important to note that the 2021 income data includes the full year of 2020 income data due to the reporting structure. Table 2 below shows the distribution of income and expenditure by provinces.

Table 2. Total median after-tax income and average spending, based on published data from 2021 (Statistics Canada, 2021).

Provinces	Total median after-tax income $2020	Average spending on goods and services ($)
New Brunswick	$62,000	$57,582
Nova Scotia	$62,400	$60,132
Newfoundland and Labrador	$63,200	$60,275
Quebec	$63,200	$57,889
Prince Edward Island	$64,000	$58,594
Manitoba	$69,000	$64,311
Saskatchewan	$73,000	$68,494
British Columbia	$76,000	$75,028
Ontario	$79,500	$69,608
Alberta	$83,000	$75,003

Kuzyk (2011) found a very high correlation between household income and expenditure, with an R^2 value of 0.94. I used a similar approach to test recent data from this current study. The data in the current study showed a similar pattern, with a correlation coefficient (r) of 0.95 and a coefficient of determination (R^2) of 0.89 (See Figure 12, $R^2 = 0.89$). The correlation coefficient (r) indicates a strong linear relationship between the total median after-tax income and average spending on goods and services. The R^2 value of 0.89 shows how much variance in the relationship this model explains. A strong relationship between after-tax income and average household spending suggests that as after-tax income increases, average household spending rises. A graph illustrating the strong correlation between household income and average spending by province (2021) is shown below.

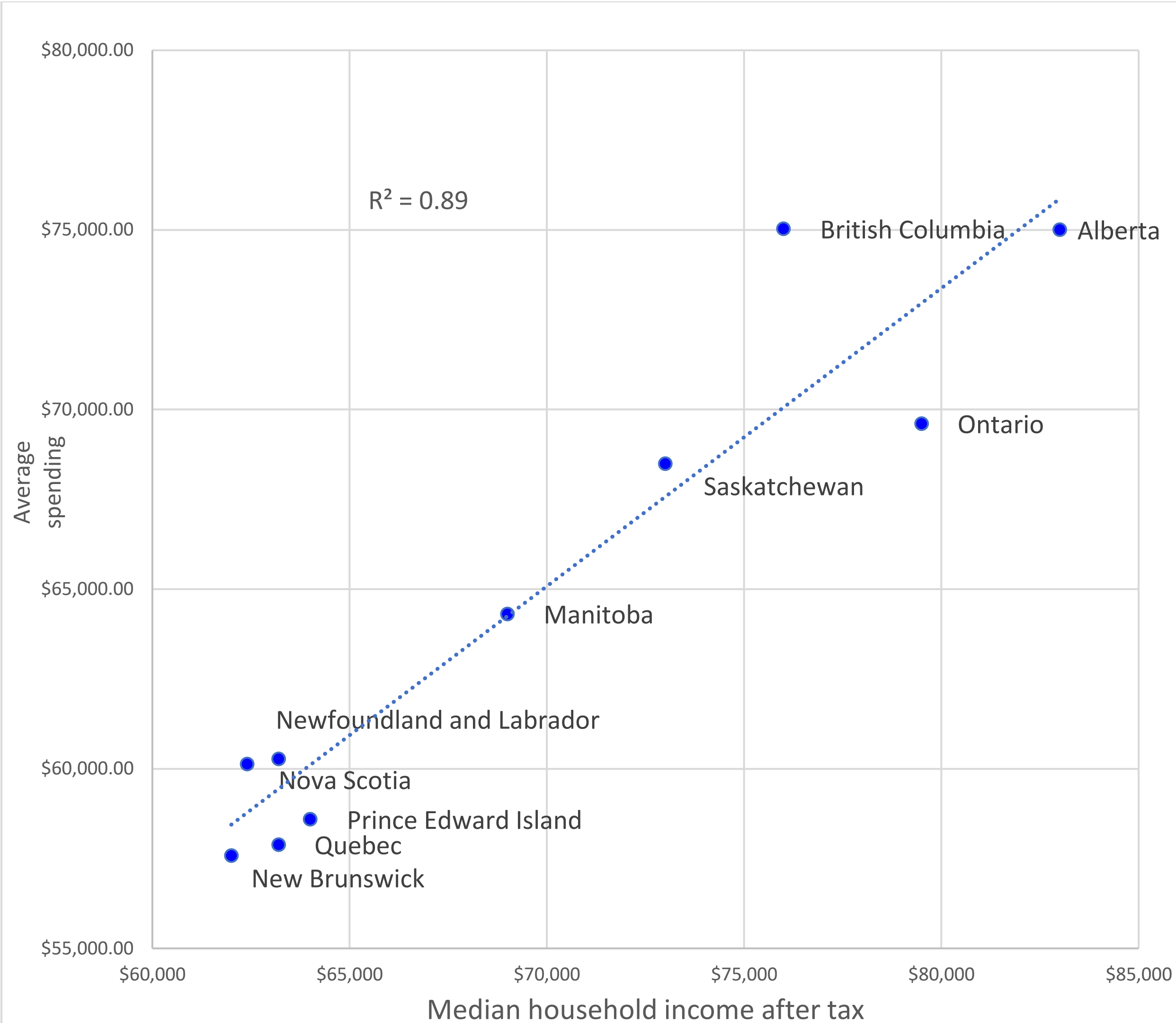


Figure 12. A strong correlation (r =0.95) between household income and spending in 2021.

Local Income Ratio (LIR) and Scaling EF: To measure the local EF, this study used a method similar to Kuzyk's (2011), in which the Local Income Ratio (LIR) was calculated from national data. The median household after-tax income in the Region of Peel was $94,000, and the median household after-tax income in Canada was $68,400 (Statistics Canada, 2021). The LIR for the Region of Peel is 1.37 based on the Canadian national EF, which is 7.42 global hectares per capita (gha/cap) as of 2021 (York University Ecological Footprint Initiative & Global Footprint Network, 2023) (see Equation (1) below).

$$LIR = \frac{N}{P} * EF \qquad \ldots(1)$$

Where LIR means Local Income Ratio;

N means median after-tax household income nationally in Canada (2021);

P means median after-tax household income, Region of Peel (2021); and

EF means Ecological Footprint (gha/cap).

Please note that the previous literature refers to this ratio as LIR (Kuzyk, 2011); however, it reflects not only the local income ratio, but also includes the multiplication of the national average gha/cap. The term was left as is (LIR) in this current study to avoid confusion. Based on the calculations, the Region of Peel's EF is 10.20 gha/cap, and the EF per capita was translated based on the LIR factor to reflect different consumption categories (Table 3):

Table 3. Region of Peel-based consumption categories using the LIR factor, 2021.

Consumption Categories	**Total gha/cap based using LIR factor**
Cropland Footprint	1.73
Grazing Footprint	0.39
Forest Product Footprint	1.51
Carbon Footprint	6.35
Fish Footprint	0.17
Built-up land Footprint	0.06
Peel Total Ecological Footprint (gha/cap) (Consumption)	**10.20**

The EF for Canada (7.42 gha/cap) was retained from 2022, as it was the closest estimate available at the time of the analysis (York University Ecological Footprint Initiative & Global Footprint Network, 2023).

The next step was to distribute this per capita EF into more detailed components to understand its composition and prepare for comparison with local data. This involved two levels of disaggregation using ratios from prior studies:

1. **By Income Decile**: A ratio from published data by Mackenzie et al. (2008) was used to calculate the income decile-based EF. Mackenzie et al. (2008) provided estimates of the proportion of the total national EF attributable to each income decile. From those estimates, I extracted proportional "EF contribution ratios" for each income decile. These ratios essentially inform us, for example, what fraction of the total EF is attributable to the lowest (poorest) 10 % income category of households versus the highest 10% income category, etc. (Table 4 shows the conversion of Mackenzie's decile EF data into ratio values and the resultant gha/cap in this study's context.)
   In other words, out of the average Canadian national EF (gha/cap), a ratio (as per published data) was created to identify which decile (i.e., lowest (poorest) 10% to top 10% income earners) contributed which amount of EF in five different consumption categories: food, housing, mobility, goods and services (Table 4).
2. **Consumption Category and Land Use**: I further disaggregated the EF of consumption by consumption categories (food, housing, mobility, goods, services) and by the type of land use or resource area (Consumption Land Use Matrix (CLUM), categories such as energy land, cropland, forest products land, built-up

land, fishing grounds, etc.). Mackenzie et al. (2008) also provided breakdowns of EF by these categories. From their data, I obtained:

i. The proportion of the total EF attributable to each consumption category (food, housing, mobility, goods, services) for each income decile.
ii. The proportion of the total EF attributable to each land use type for each consumption category.

The percentage/ratio was obtained from the Mackenzie et al. (2008) study (Table 5) for this purpose and applied in the income-decile-based method for the land-use type, similar to step #1 (by income decile) (Table 6). Subsequently, the land-use matrix (CLUM) data were created for the study area, the Region of Peel (Table 7).

The ratio obtained from the published data in Table 5 (Mackenzie et al., 2008) was applied to Canadian national data and subsequently to the Region of Peel data from 2021. Please note that the Region of Peel median household income (after tax) data is based on official statistics from 2021; however, to reflect the reality at the time of the analysis, projected data for the analysis year of 2023 (current year) from Envionics Analysis was used within the Region of Peel (Envionics Analytics, 2023). The income data is referred to as 2021 in the subsequent chapters, given that it is the official release date from Statistics Canada. Using the ratios for income deciles and EF consumption land use, as presented in Mackenzie et al. (2008) (Table 5), the final table for the Region of Peel was derived (Table 6).

Table 4. Conversion of EF deciles from Mackenzie et al. (2008) into a ratio value and gha/cap for this study, 2021.

Categories	Poorest 10%	D1Ratio	Decile 2	D2_Ratio	Decile 3	D3_Ratio	Decile 4	D4_Ratio	Decile 5	D5_Ratio	Decile 6	D6_Ratio	Decile 7	D7_Ratio	Decile 8	D8_Ratio	Decile-9	D9_Ratio	Decile 10	D10_Ratio	Total consumption
Food	2.1	1.0	2.2	1.0	2.1	1.0	2.1	1.0	2.1	1.0	2.2	1.0	2.2	1.0	2.2	1.0	2.1	1.0	2.2	1.1	2.1
Housing	1.5	0.7	1.8	0.8	1.8	0.8	1.7	0.8	1.9	0.9	2.0	0.9	2.1	1.0	2.2	1.0	2.3	1.1	3.4	1.6	2.2
Mobility	0.4	0.3	0.6	0.4	0.9	0.6	1.0	0.7	1.2	0.8	1.4	1.0	1.6	1.1	1.7	1.2	2.2	1.5	3.2	2.3	1.4
Goods	0.6	0.6	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.4	2.1	2.2	1.0
Services	0.6	0.7	0.7	0.9	0.7	1.0	0.7	1.0	0.8	1.1	0.8	1.1	0.8	1.1	0.9	1.2	1.0	1.3	1.5	2.0	0.7
Total																					**7.4**

Note: Deciles refer to the income deciles, and D1, D2, D3… refer to the deciles 1 to 10 in chronological order.

Table 5. A conversion of Mackenzie et al. (2008) values into percentages to use as a ratio for this study, 2021.

Categories	Energy land (carbon land)	% of total carbon	cropland	Pct of total cropland	Pasture land (grazing land)	Pct of total grazing land	Forest land	Pct of total forest land	Built Area	Pct of total built area	Fishing grounds	Pct of total fishing ground	Total
Food	0.60	0.13	1.04	0.98	0.34	0.89	0.02	0.02	0.00	0.00	0.12	1.00	2.13
Housing	1.35	0.29	0.00	0.00	0.00	0.00	0.81	0.64	0.01	0.25	0.00	0.00	2.18
Mobility	1.42	0.31	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.25	0.00	0.00	1.45
Goods	0.54	0.12	0.01	0.01	0.02	0.05	0.40	0.31	0.01	0.25	0.00	0.00	0.99
Services	0.68	0.15	0.00	0.00	0.00	0.00	0.04	0.03	0.01	0.25	0.00	0.00	0.73
Unidentifed	0.00	0.00	0.00	0.00	0.02	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Total	**4.59**		**1.06**		**0.38**		**1.27**		**0.04**		**0.12**		**7.50**

Table 6. Income decile-based categorical EFs as per Mackenzie et al. (2008) ratio from the published data. Note: For the Region of Peel, the lowest income decile was <$20,000 (representing the poorest 10%) and the highest income decile was≥ $180,000, as reported by Statistics Canada in 2021.

Categories	**Lowest income decile**	**Decile 2**	**Decile 3**	**Decile 4**	**Decile 5**	**Decile 6**	**Decile 7**	**Decile 8**	**Decile 9**	**Highest income decile**	
Income	**<$20,000**	**<$40,0-00**	**<$60,0-00**	**<$80,0-00**	**<$100,-000**	**<$120,-000**	**<$140,-000**	**<$16-0,000**	**<$180-,000**	**$180,00-0 or more**	**Total consumption**
Food	2.96	3.09	3.08	3.08	3.08	3.11	3.09	3.11	3.07	3.22	3.07
Housing	1.99	2.40	2.36	2.28	2.47	2.61	2.71	2.88	3.04	4.48	2.84
Mobility	0.50	0.86	1.23	1.45	1.67	1.99	2.16	2.43	3.03	4.50	1.99
Goods	0.73	0.97	1.08	1.12	1.22	1.31	1.43	1.52	1.74	2.77	1.27
Services	0.74	0.92	0.96	1.00	1.07	1.11	1.12	1.21	1.29	2.00	1.00
Unidentified											0.02
Total											**10.20**

The graph below shows the relationship between income deciles and different consumption categories (Figure 13).

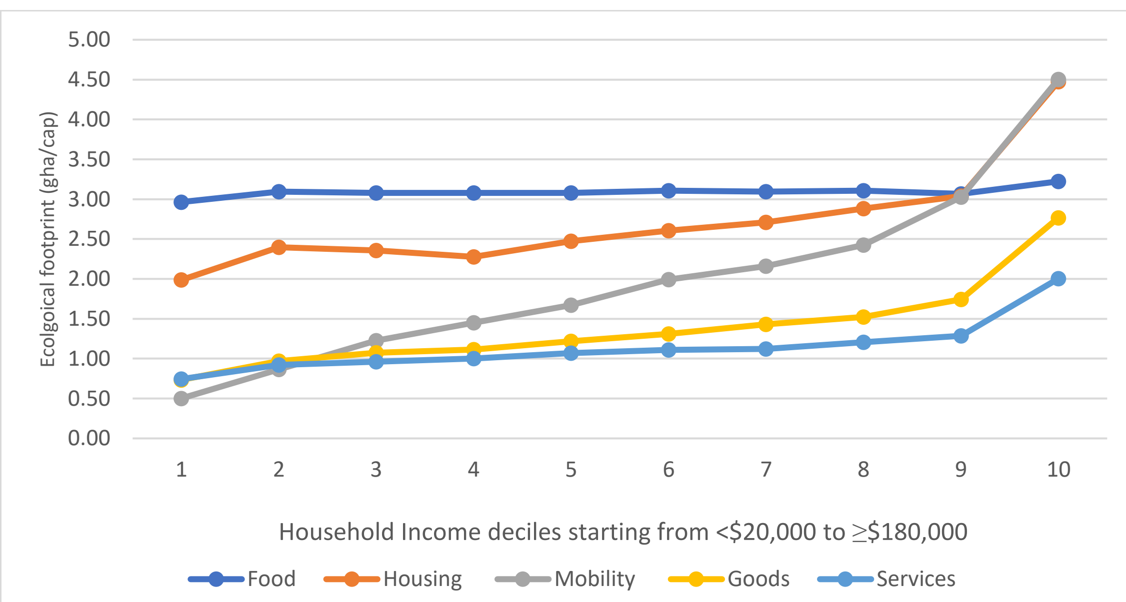


Figure 13. Household income deciles based on EF of consumption in the Region of Peel, 2021.

The expenditure categories were then converted to the EF land use consumption categories. The EF land use consumption categories have the following pattern (Table 7):

Table 7. Ecological land use-based consumption pattern within the Region of Peel as per the ratio from Mackenzie et al. (2008).

Categories	Energy land (carbon land)	Cropland	Pasture land (grazing land)	Forest land	Built Area	Fishing grounds	Total
Food	0.83	1.70	0.35	0.02	0.00	0.17	3.07
Housing	1.87	0.00	0.00	0.96	0.01	0.00	2.84
Mobility	1.96	0.02	0.00	0.00	0.01	0.00	1.99
Goods	0.75	0.02	0.02	0.48	0.01	0.00	1.27
Services	0.94	0.00	0.00	0.05	0.01	0.00	1.00
Unidentified	0.00	0.00	0.02	0.00	0.00	0.00	0.02
Total	**6.35**	**1.73**	**0.39**	**1.51**	**0.06**	**0.17**	**10.20**

Ratio Adjustments to Reflect Current Data

While Mackenzie et al. (2008) were an important resource for developing the ratios for income-decile-based, category-based, and land-use-based EF consumption, their published data reflect the 2008 scenario. For example, in 2008, published data showed that food spending accounted for a very high percentage of 29%. According to 2021 data, spending on shelter is the highest at 31.4% of the total spending, while spending on food accounts for 15% (Statistics Canada, 2021). To be consistent within the income-deciles, 2021 income data was used with the Mackenzie (2008) ratio, noting that there is a need to update Mackenzie's income-decile-based model. The adjustment process was as follows:

- **I retained the income-decile-based EF proportions (ratio) from Mackenzie et al. (2008) with the latest data**. Although the ratio is from Mackenzie et al. (2008) (Table 5), as no newer publication is available, the actual data used for adjustment are from 2021, which reflects the current reality. For the categorical EF consumptions, the latest data from Canada (national consumption by category) was used, with the final adjusted number for the study.

- **I updated the consumption category split for landuse matrix using 2021 national data**. The latest data (2021) from Statistics Canada do not distinguish between consumption categories for goods and services (reporting them as one category); therefore, the ratio from Mackenzie et al. (2008) was applied to separate them proportionately. Of which, the 2008 ratio was 57% goods and 43% services. Those ratios were applied to the recent (2021) data.

The consumption ratio, based on 2021 data, was as follows: food (15.4%), housing (31.4%), mobility (15%), goods (21.7%), and services (16.5%). Table 8 refers to the EF categories adjusted for the Region of Peel. The adjusted EF categories were ready for use at the DA levels.

Table 8. Region of Peel Adjusted EF categories (gha/cap) based on 2021 spending data.

Categories	Energy land (carbon land)	% of total consumption	Cropl-and	% of total consumption	Pasture land (grazng land)	% of total consumption	Forest land	% of total consumption	Built Area	% of total consumption	Fishing grounds	% of total consumption	Total	Out of total consumption % as per 2021 Stats. Can Canada
Food	1.0	0.2	0.3	0.2	0.1	0.2	0.2	0.2	0.0	0.2	0.0	0.2	1.6	0.2
Housing	2.0	0.3	0.5	0.3	0.1	0.3	0.5	0.3	0.0	0.3	0.1	0.3	3.2	0.3
Mobility	1.0	0.2	0.3	0.2	0.1	0.2	0.2	0.2	0.0	0.2	0.0	0.2	1.5	0.2
Goods	1.4	0.2	0.4	0.2	0.1	0.2	0.3	0.2	0.0	0.2	0.0	0.2	2.2	0.2
Services	1.0	0.2	0.3	0.2	0.1	0.2	0.2	0.2	0.0	0.2	0.0	0.2	1.7	0.2
Unident-ified	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**6.3**		**1.7**		**0.4**		**1.5**		**0.1**		**0.2**		**10.2**	

Applying Region of Peel-based EF Consumption Data at the Dissemination Area within the Region of Peel

Once these categorical ratios were calculated in the Region of Peel, the EF was applied based on the income of the dissemination areas (DAs). To reflect the latest population and other demographic information, industry-leading Environics Analytics' projection data for 2023 were used (Environics Analytics, 2023). The data used official 2021 demographic data from Statistics Canada and projected it to 2023. The data from Environics Analytics was licensed for this study.

Calculating EF per DA: For each DA, I applied the income-based EF calculation model in the following way:

1. Determine the DA's income decile category. Using the DA's median household income, identify which income decile (1 through 10, from lowest to highest) it falls into (based on national income distribution).
2. Assign the corresponding per capita EF for that income decile, broken down by consumption category. (This uses the Table 6 values; for example, if a DA's income level is equivalent to the seventh decile, then use the EF breakdown proportions for the seventh decile.)
3. DAs within a decile were assigned the same per capita EF of that decile group.
4. Sum the EF contributions of all categories to get the total EF of consumption per capita for that DA.

Table 9 below shows a sample of the median household income (2023) per DA and their corresponding categories of EF of consumption.

Table 9. Sample data showing EF categories (gha/cap) by DA within the Region of Peel.

DAUID	Total Population	Median Household Income (current year 2023)	EF of Food	EF of Housing	EF of Mobility	EF of Goods	EF of Servi-ces	Total EF of Consumption Per Capita	Total EF of Consumption by DA
35210001	1248	$197,412	3.22	4.48	4.50	2.77	2.00	16.97	21178.56
35210002	539	$211,306	3.22	4.48	4.50	2.77	2.00	16.97	9146.83
35210003	1052	$190,614	3.22	4.48	4.50	2.77	2.00	16.97	17852.44
35210004	749	$204,210	3.22	4.48	4.50	2.77	2.00	16.97	12710.53
35210011	492	$115,970	3.11	2.61	1.99	1.31	1.11	10.13	4983.96
35210013	756	$169,461	3.07	3.04	3.03	1.74	1.29	12.17	9200.52
35210014	414	$152,370	3.11	2.88	2.43	1.52	1.21	11.15	4616.10
35210015	985	$132,896	3.09	2.71	2.16	1.43	1.12	10.51	10352.35
35210017	965	$144,028	3.11	2.88	2.43	1.52	1.21	11.15	10759.75
35210018	918	$138,045	3.09	2.71	2.16	1.43	1.12	10.51	9648.18
35210019	584	$138,903	3.09	2.71	2.16	1.43	1.12	10.51	6137.84

The ratio from Table 6 was used in an equation to calculate for the entire jurisdiction. For example, the following script was used to calculate the EF of food using ArcGIS Pro and Python:

```
def reclass(ECYHNIMED):
    if (ECYHNIMED ≥ 180000):
        return 3.22
    elif (ECYHNIMED   ≥ 160000 and  ECYHNIMED < 180000):
        return 3.07
    elif (ECYHNIMED   ≥140000 and  ECYHNIMED < 160000):
        return 3.11
    elif (ECYHNIMED   ≥ 120000 and  ECYHNIMED < 140000):
        return 3.09
    elif (ECYHNIMED   ≥ 100000 and  ECYHNIMED < 120000):
        return 3.11
    elif  (ECYHNIMED   ≥ 80000 and  ECYHNIMED < 100000):
        return 3.08
    elif (ECYHNIMED   ≥ 60000 and  ECYHNIMED < 80000):
        return 3.08
    elif (ECYHNIMED   ≥ 40000 and  ECYHNIMED < 60000):
        return 3.08
    elif (ECYHNIMED   ≥ 20000 and  ECYHNIMED < 40000):
        return 3.09
    elif (ECYHNIMED   < 20000):
        return 2.96
```

Once the calculations for the EF categories were completed, the following equation (2) was used to calculate the total EF per capita (gha/cap):

$$Total \text{ EF per capita (gha/cap)} = EF_f + EF_n + EF_m + EF_g + EF_s \quad \ldots(2)$$

Where,

f means food;

h means housing;

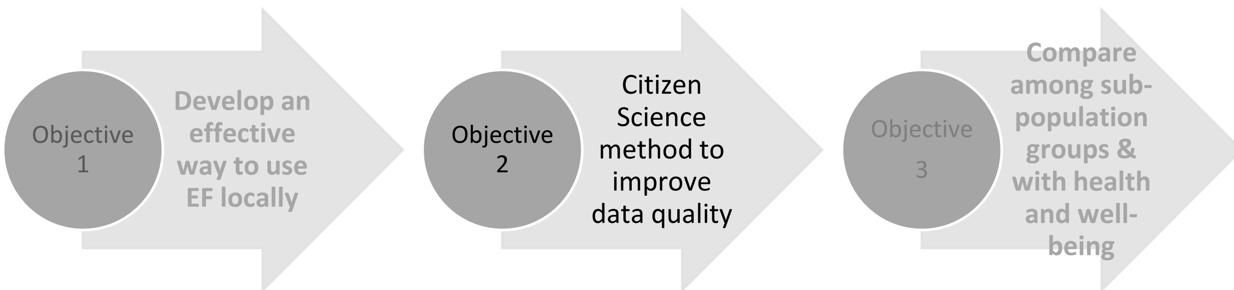
m means mobility;

g means goods; and

s means services.

The total EF of consumption per capita was multiplied by the total population per DA to calculate the total EF per DA (Table 9). Figures 17 and 18 show the results in the subsequent chapter.

Citizen Science Data Collection and Analysis Methodology



To improve the above data-driven approaches and to ground the research in actual community experiences, I implemented a citizen science data-collection effort to capture local realities. The aim was to gather primary data on individuals' consumption patterns (to estimate their personal EF) and well-being, and then use these data to perform calculations.

Data collection Period and Purpose: The citizen science data collection took place between October 10, 2022 and March 15, 2024. The data was collected to explore relationships between EF and health and well-being at the local level. By collecting data nationally, the intention was to first establish a baseline that reflects the average Canadian's EF (so it could be compared to official national EF values), and then zoom in on the subset of data from participants in the Region of Peel to compare with the disaggregated results, especially noting differences between recent immigrants and established Canadians, if possible.

Sample Size Considerations: I determined that a minimum of 385 completed responses would be needed to achieve a 95% confidence level with a 5% margin of error for national-level estimates (Figure 14)[1]. The population proportion (Figure 14) is the percentage of values likely to be associated with a survey. For example, if there is a known value, such as the fact that 40% of Canadians are homeowners, that could be used as a reference. However, given that there is an equal probability that the values we get from these survey results or submissions can be higher or lower than the *actual* value, the 50% standard (recommended and default value) is used.

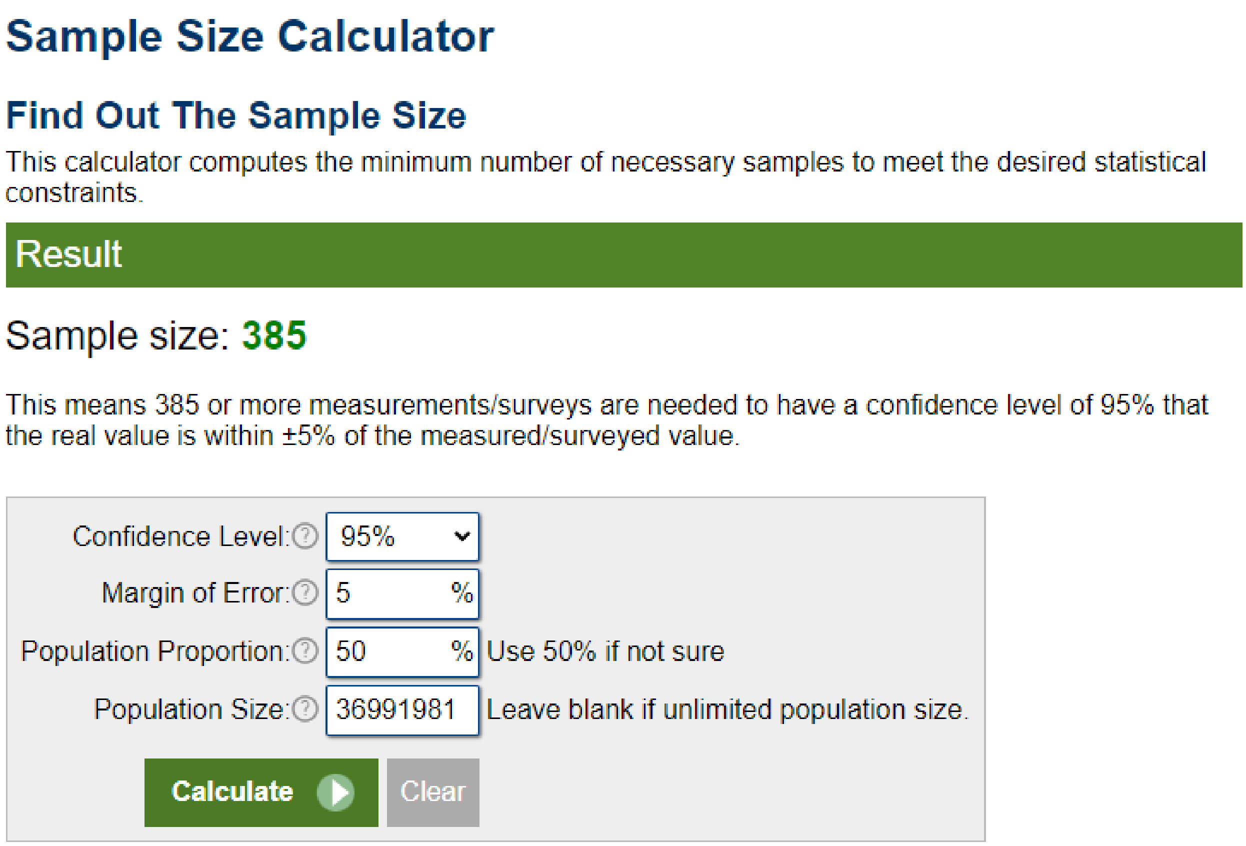


Figure 14. Sample size required for the study, using Canada's population as per census records from 2021[1]

[1] The following website was used to calculate the sample size: (https://www.calculator.net/[1]sample-size-calculator.html).

Recruitment and Participation: After obtaining ethics approval from York University for human participant research, citizen science data were collected across Canada. This method was used to create a foundational gha/cap at the national level, allowing the data to be applied to explore gha/cap in the Region of Peel study area. The foundational benchmark data was needed to review local differences. Please refer to the subsequent sections for more details. Given that the total population (unlimited or Canadian total population) for the sample size has no impact as long as 385 data points (submissions) are received, this number was used as a threshold.

This approach with the foundational data was necessary to coincide with the average reported EF of consumption (based on NFA) from Canadians to compare against the equivalent base citizen science data (e.g., the average gha/cap of all participants in this research from across the country should reflect the average gha/cap of all Canadians from across the country). This was done to match the spatial distribution of the average gha/cap from the citizen science project with that reported in the national ecological footprint database. The objective was to narrow it down to the local level once the base is established.

First, it was necessary to calculate the citizen-science-based global hectares per capita (gha/cap) for Canada. This calculation served as a foundation and point of comparison for the national average of gha/cap before proceeding with comparisons at the local level. This approach was required because there was no official local comparator for the EF of consumption within the Region of Peel. The participation was encouraged through multiple channels:

- **Social media:** I promoted the participation via social media such as Facebook, Instagram, etc. The surveys were promoted through boosted posts (or paid advertisements) and content-sharing options.

- **Community outreach:** I reached out to a few community events to promote participation.
- **Professional network:** I used professional networks such as LinkedIn and university networks (e. g., email distribution list (available), reaching out to others) to distribute surveys/questions.
- **Feedback loop:** The survey itself was designed to be engaging. As participants answered questions, they received immediate, personalized feedback on their consumption patterns. For example, upon completing the section about food consumption, a message might pop up saying *"Moderate ecological footprint – good job! There is still some room to improve."* or if very high, *"High ecological footprint. We think you can do better next year!"*. These gamified elements aimed to make the survey more interactive and enjoyable (Harms et al., 2015), in the hope of increasing completion rates and encouraging word-of-mouth sharing.
- **Incentives:** To further boost participation, two Apple™ watches were offered via a raffle draw as prizes for those who completed the survey.

Survey Design: The citizen science questions were carefully structured to collect data corresponding to the five EF consumption categories and the health and well-being indicators:

- For the **EF of consumption component**, participants answered questions related to *Food, Shelter (housing and energy use), Mobility (transportation), Goods and Services.* These questions were inspired by existing EF calculators and surveys (Bagliani et al., 2008; Kuzyk, 2011; Wackernagel, 1994) and included both qualitative and quantitative items. For example, questions related to food asked how often per week the person eats meat or fish, questions about shelter covered housing types and energy consumption, etc. (the complete list of questions and their sources are provided in Appendix B; sources included Carragher & Peters, 2018; Dal Grande et al., 2000; Evangelical Alliance, 2015; Meyer, 2004; World Wildlife Fund, 2024).

- For the **health and well-being component**, the questionnaire included questions corresponding to the *Healthy Populations indicators* discussed earlier (Canadian Index of Wellbeing, 2024; Smale & Margo, 2024). For instance, participants were asked to rate their own health and mental health, among other aspects (also listed in Appendix B).

The survey clearly separated sections on consumption (for EF calculation) from those on personal health/well-being to avoid confusion. Participants were informed about the purpose of the research and how their data would be used, and consent was obtained in accordance with the ethics protocol.

Collected Data and Data Cleaning: Citizen science data was collected at a national level and then analyzed to explore the patterns in the Region of Peel. Of the required 385 citizen science contributions/submissions, 439 submissions were collected during the data collection periods, exceeding the minimum requirements (Figure 15).

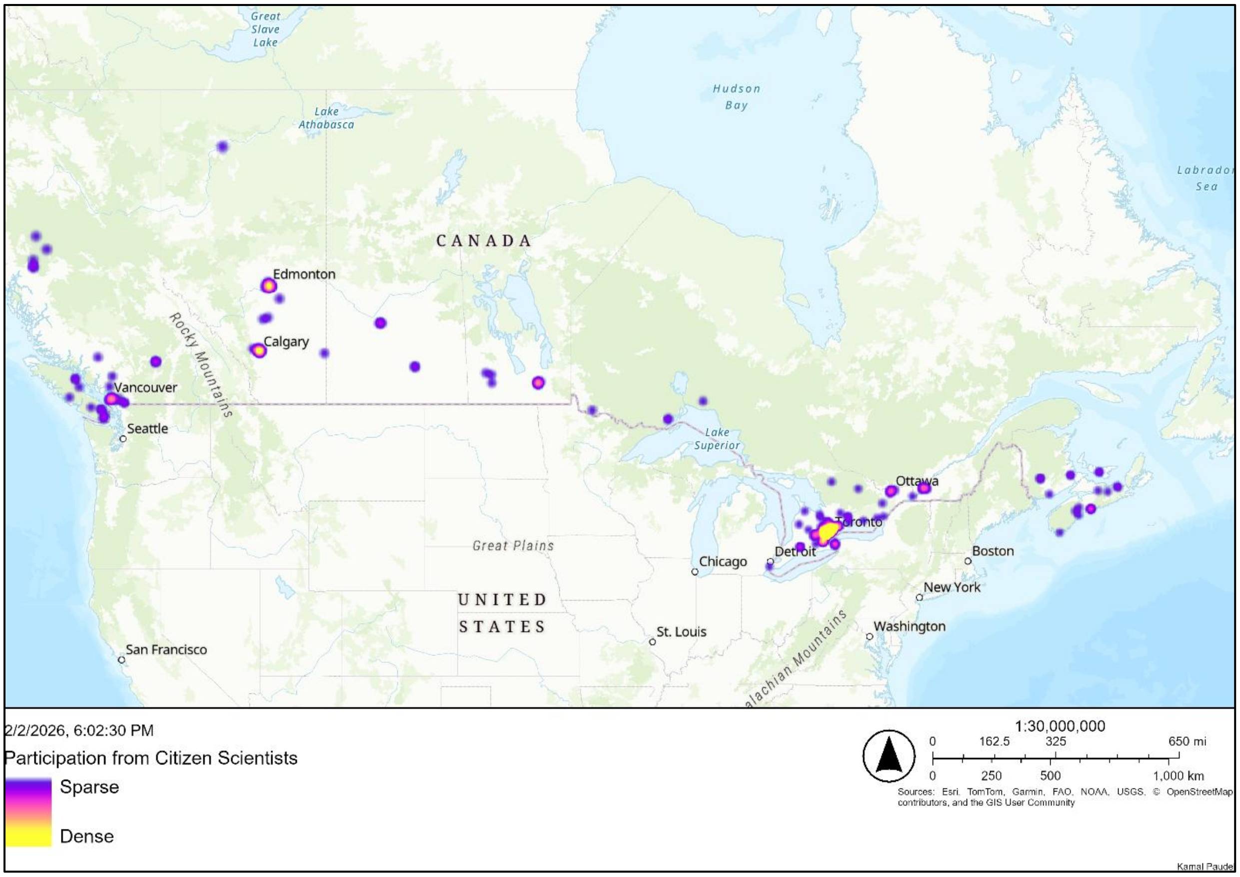


Figure 15. Total submissions from the citizen science project for the study from all over Canada.

Out of 439, 10 data points were 'test data' with no inherent values; therefore, they were removed from the analysis. A total of 429 data points were used as the foundation for the analysis.

After reviewing and analyzing the citizen science data, it was noted that out of 429 submissions, only 407 had complete data. The remaining 22 submissions were removed from the next stage of analysis. Out of 407 submissions, four additional submissions had incomplete data for the health and well-being components. Therefore, the health and well-being component has a total of 403 submissions for analysis, whereas the EF calculation and analysis have 407 submissions. Table 10 shows the gender distribution of citizen participants.

Table 10. Gender-based distribution of participants in the citizen science-based data collection.

Participants By Gender	Total Count
Female	184
Male	218
I do not want to disclose	3
Non-binary	2
Total	**407**

Conversion of Citizen Science Consumption Information into EF of Consumption gha/cap Equivalent

One of the novel aspects of this study is the conversion of qualitative and quantitative self-reported data from the citizen science project into an estimated EF (gha/cap) for each participant. This is not straightforward, since participants did not directly provide values in hectares. I developed a novel modelling approach to translate survey answers into an EF estimate. The approach was essentially to benchmark survey responses against the known national average EF and assign weights to responses so that the average survey result of the total collected data matched the national average footprint of 7.42 gha/cap. In other words, an average Canadian should have the same gha/cap no matter what method we use, given that they are based on official statistics and sources. We aim to identify the local difference in this study and calibrate it at the local level to better reflect the realities. In other words, I established a linear mapping from the "survey score units" to actual global hectares. To convert them into a quantitative model, the following approach was used:

Step 1: Establish Baseline (using national data)

Using Canadian EF as a foundation (assuming the average EF for the country is what is reported in the Canadian national EF database), I used the Canadian average as a starting point for the survey participants. For example, given that the Canadian average EF of consumption is 7.42

gha/cap, out of which the EF of food (consumption) was 2.13 gha/cap, the average food-related EF from the participants was assigned 2.13 gha/cap. Because the participants did not report their food consumption in the gha/cap unit, the results from these participants were coded to reflect this based on the ratio value within the category (see steps 2 and 3 below for more details on the processes; the actual numbers are located in Appendix C).

Step 2: Assign Category Weights to Survey Questions

I broke down the footprints by the five consumption categories based on the national averages from 2021 (Statistics Canada, 2021):

- Food =15% of total EF
- Shelter (housing) =31%
- Mobility =15%
- Goods = 22%
- Services =17%

Assigned all 5 consumption categories (food, shelter, mobility, goods and services) the same ratio as per the official national statistics (as per Appendix C, i.e., shelter is 31% of the total weight of the EF of consumption, etc.).

Step 3: Assign Subcategory Weights to Survey Questions

For the subcategories within each of the five broad categories (such as food), the survey included multiple other questions (subsections). A standard rule was applied in those subcategories for consistency, except for the apartment-versus-house category and energy-efficient products (see Appendix C notes section for details and reasoning).

- For example, within **Food** (15% of total EF), one key question was "How often do you eat meat or fish per week?" (following these references: Carragher & Peters, 2018; Dal Grande et al., 2000; Evangelical Alliance, 2015; Meyer, 2004; World Wildlife Fund, 2024). This is one of the major drivers of the food footprint. It was assigned a 0.05 ratio out of 0.15 of the total EF of the food consumption category in Appendix C.
- In the **Shelter** category: questions about home size/type (apartment vs. house), energy efficiency, and electricity usage were included. A larger share of the shelter footprint might be tied to home heating and cooling/cooking, and electricity (for example, a house versus an apartment could be a significant factor). This would collectively account for 31% of the EF.
- For **Mobility**: questions captured driving frequency, use of public transit, etc. These would collectively account for that 15% weight.
- The **Goods and Services** category was combined (a total of 39%) into a bigger group during the data collection. It was later divided using the ratio in Canada, as used in the previous section of the study related to disaggregation method (22% goods and 17% services) (Statistics Canada, 2021).

Step 4: Create a Scoring System for Submissions/Responses

A rule was created to distribute the weight of subcategories within each category, such as grouping food-related and shelter-related questions into separate categories. The following rules were applied to convert each category to a 0-1 scale (0-100%).

- The standard rule was applied to reflect the percentile numerical value in the order of 25% (0%, 25%, 50% or 75 % up to 100 % as needed) based on responses related to that EF sub-category (Appendix C). For example, if a food sub-category had a question that contained 10 total points to be assigned towards the total EF of consumption, each response within the sub-category would be valued between 0 and 10 (for example, consuming more than 5 meat/fish meals every week would be 10, whereas 0 per week would be 0).

- The standard rule was to make sure that the highest EF of consumption (from the categorical data/response) within the sub-category gets 100% of the value towards the contribution of the EF of consumption, the second highest gets the 75th percentile and so on.

Step 5: Calculate Each Participant's Total "EF Consumption Score"

After scoring all responses, I summed the contributions from all categories for each participant. This yielded a raw score (in dimensionless units) representing the relative magnitude of that person's footprint as measured by the survey. For the next stage of the EF analysis, the *average EF of consumption*, as per Appendix C, for Canadian participants was 0.4733, which translates to an equivalent average EF for Canadians in a global hectare unit of 7.42 gha/cap.

Step 6: Converting the EF Consumption Score to gha/cap

Using the raw average score of 0.4733 from Step 5, the estimated gha/cap per submission/survey was calculated. Given that the average person in Canada has 7.42 gha/cap of EF of consumption (based on the published EF data, Global Footprint Network, 2023), the study assumes that the average of the citizen science participants represents the average Canadian (because the participants are from all over Canada). Based on the average value, 7.42 gha/cap of EF of consumption (national average) represents 0.4733 units (calculated based on the collected data-based ratios, see Appendix C and explanation in the previous section). That's how a linear mapping from the "survey score units" to actual global hectares was created. In summary, this represents:

- Average score of respondents (0.4733) should equate to 7.42 gha/cap (the known Canadian average EF).
- A score of 0 would correspond to 0 gha/cap (if someone somehow answered in a way that implies virtually no footprint).

Thus, 1 unit of EF gha/cap is equivalent to 0.0638 units in the citizen science data (0.4733 divided by 7.42). It is essential to note that the average and unit values were calculated to four decimal places to capture finer details; however, they are reported in this study using a rounding method with two decimal places, e.g., 0.0638 is rounded to 0.06 for reporting/display purposes. In summary, a 0.06 unit increase in citizen science-based EF of consumption from the survey contribution represents 1 additional gha/cap of EF of consumption. This formula was used to estimate self-reported citizen science-based consumption in terms of the equivalent EF of consumption in gha/cap. Citizen science-based EF unit values were divided by 0.06 to calculate the self-reported EF from citizen science-based data. Based on this method, the citizen-collected data at the national level shows a minimum of 3.53 gha/cap, whereas the maximum citizen-reported EF of consumption is 11.87 gha/cap (Table 11). Table 11 indicates that the data distribution is uniform with a few outliers. The distribution of participant EF was normal (bell-shaped), with a slight skew. Specifically, it exhibited slightly negative skewness (left-skewed), meaning that a few individuals had particularly low footprints, pulling the tail to the left. The kurtosis is low (thin-tailed), indicating that there were few extreme outliers, and the values tail off relatively gently. *Skewness* is a measurement that describes how symmetrical or asymmetrical a distribution based on its mean is, whereas *kurtosis* refers to the shape of the distribution, particularly the "tailedness" of a distribution (Michelucci, 2025). A leptokurtic distribution appears with a longer tail due to outliers (Kallner, 2018). Kurtosis is generally used as a practical method to identify outliers (Kallner, 2018). These characteristics in Table 11 indicate that while most people cluster around the middle, there are some lower-end consumers in the sample, but not an excessive number of them beyond what a normal distribution would predict. Table 11 provides summary statistics of these results.

Table 11. EF of consumption in gha/cap from the citizen science-based data collection within Canada.

Description	Value
Average Gha/cap	7.42
Min Gha/cap	3.53
Max Gha/cap	11.87
Standard Deviation	1.49
Skewness	-0.10
Kurtosis	-0.02

This range is plausible (Table 11): very low footprints might refer to individuals who live sustainably or have lower-than-average consumption (perhaps no car, a vegetarian diet, small housing, etc.), while very high footprints could correspond to those with large homes, long commutes, or meat-rich diets.

Comparison of EF and health and well-being between Recent Immigrants and Established Canadians

Community Health and Well-being Methodology

In the last section, with each participant's EF in hand, I compared the citizen science-based EF for the Region of Peel residents to the EF estimated via the disaggregation method, and examined patterns to explore whether recent immigrants in the sample have different EFs than those of established Canadians. This section dicusses health and well-being aspects.

Community well-being encompasses a multitude of domains and indicators (Smale & Margo, 2024). In the context of Canada, the domains of well-being are listed below (Canadian Index of Wellbeing, 2024; Smale & Margo, 2024):

1. Community vitality;
2. Democratic engagement;
3. Education;
4. Environment;
5. Healthy populations;

6. Leisure and culture;
7. Living standards; and
8. Time use.

According to the Canadian Index of Wellbeing (CIW), each domain comprises eight indicators. For this study, the *healthy populations* domain was chosen as a representative of the health and well-being of the population within the Region of Peel. This was done to align it with the health and well-being components of the targeted survey/research questions administered in this investigation. Within the *healthy populations* domain, the following eight indicators are identified as the key eight indicators:

1. Percentage of self-rated health as excellent or very good;
2. Percentage who rate their mental health as very good or excellent;
3. Percentage with self-reported diabetes;
4. Life expectancy at birth, in years. Due to a local data limitation, the Canadian average of 81.3 years (2022) was used (Government of Canada, 2023)**;**
5. The percentage of daily or occasional smokers among teens aged 12-19 years (note: instead of this variable, the percentage of daily or occasional smokers 12+ was used due to data limitation);
6. Percentage of Canadians with a regular medical doctor;
7. Percentage of population getting influenza immunization; and
8. Percentage of population with an absence of health limitations (note: this indicator reports the percentage of Canadians who do not have any activity limitations because of

physical or mental health problems. Due to data limitations, an average of indicators 1 and 2 from above was used.

For this analysis, the 2018 Canadian Community Health Survey was retrieved as a foundational data source from the Environics Analytics (2023) database. The steps for compiling the well-being index were:

1. **Data extraction:** First, the DA-level data, which is collected as part of the Canadian Community Health Survey and managed by Environics Analytics (2023), was extracted. The relevant columns were extracted and combined in an Excel file. For example, for self-rated health, the data provides an estimate of how many individuals (or what percentage) in each DA rate their health as excellent or very good.
2. **DA Percent Calculation:** Once they were organized by the DA IDs, the eight indicators listed above were calculated. The calculation was a simple tabulation: the total value of an indicator was divided by the total population aged 12 years and above to obtain the ratio. The Excel data was then joined to the DA boundary files using ArcGIS Pro.
3. **Average Calculation:** The average from each of those indicators was extracted by the DA. Table 12 shows the averages for the Region of Peel (DA-based) for each indicator. Out of eight, life expectancy was not included in the formula, as it had no impact given the Canadian average lifespan of 81.3 years. Using key variables from the Environics Analytics (2023) data, the average percent per DA of the health indicator was calculated. The population-based response per DA per indicator was used to calculate the percentage of x indicator on average per DA within the Region of Peel (e.g., different DAs have on

average 80-99 percent of people with access to a medical doctor. However, overall in the Region of Peel, 88% is the average per DA in this indicator) (see Table 12).

Table 12. Health and well-being indicators and their averages within the Region of Peel.

Indicators		Mean % by DA
1.	Health indicator	59%
2.	Mental health indicator	67%
3.	Diabetes indicator	7%
4.	Smoker indicator	11%
5.	Access to regular medical doctor indicator	88%
6.	Influenza immunization indicator	54%
7.	No health limit indicator	63%

4. Scoring DAs on the Health Indicators: To calculate scores per DA, the following approach was taken. Using the averages from Table 12, out of the seven indicators, all of them were treated equally, with the following condition:

1. If the percentage of health indicators is *higher* than the average from all of Peel DA, it gets a score of 1; otherwise, it gets a score of 0;
2. If the percentage of mental health indicators is *higher* than the average from all of Peel DA, it gets a score of 1; otherwise, it gets a score of 0;
3. If the percentage of the diabetes indicator is *lower* than the average from all of Peel DA, it gets a score of 1; otherwise, it gets a score of 0;
4. If the percentage of smokers 12 years or older indicator is *lower* than the average from all of Peel DA, it gets a score of 1; otherwise, it gets a score of 0;
5. If the percentage of a regular medical doctor indicator is *higher* than the average from all of Peel DA, it gets a score of 1; otherwise, it gets a score of 0;

6. If the percentage of the population getting influenza immunization indicator is *higher* than the average from all of Peel DA, it gets a score of 1; otherwise, it gets a score of 0; and
7. If the percentage of the population getting no health limits indicator is *higher* than the averages from all of Peel DA, it gets a score of 1; otherwise, it gets a score of 0.

Those scores were then added together, and a 50% rule was applied. If a DA has a score greater than 3.5 (half of the seven indicators examined, given that the life expectancy has no impact), the DA was coded as "higher health and well-being within the Region of Peel"; otherwise, it was coded as "lower health and well-being within the Region of Peel". Figure 16 shows the distribution of health and well-being indicator scores by DAs.

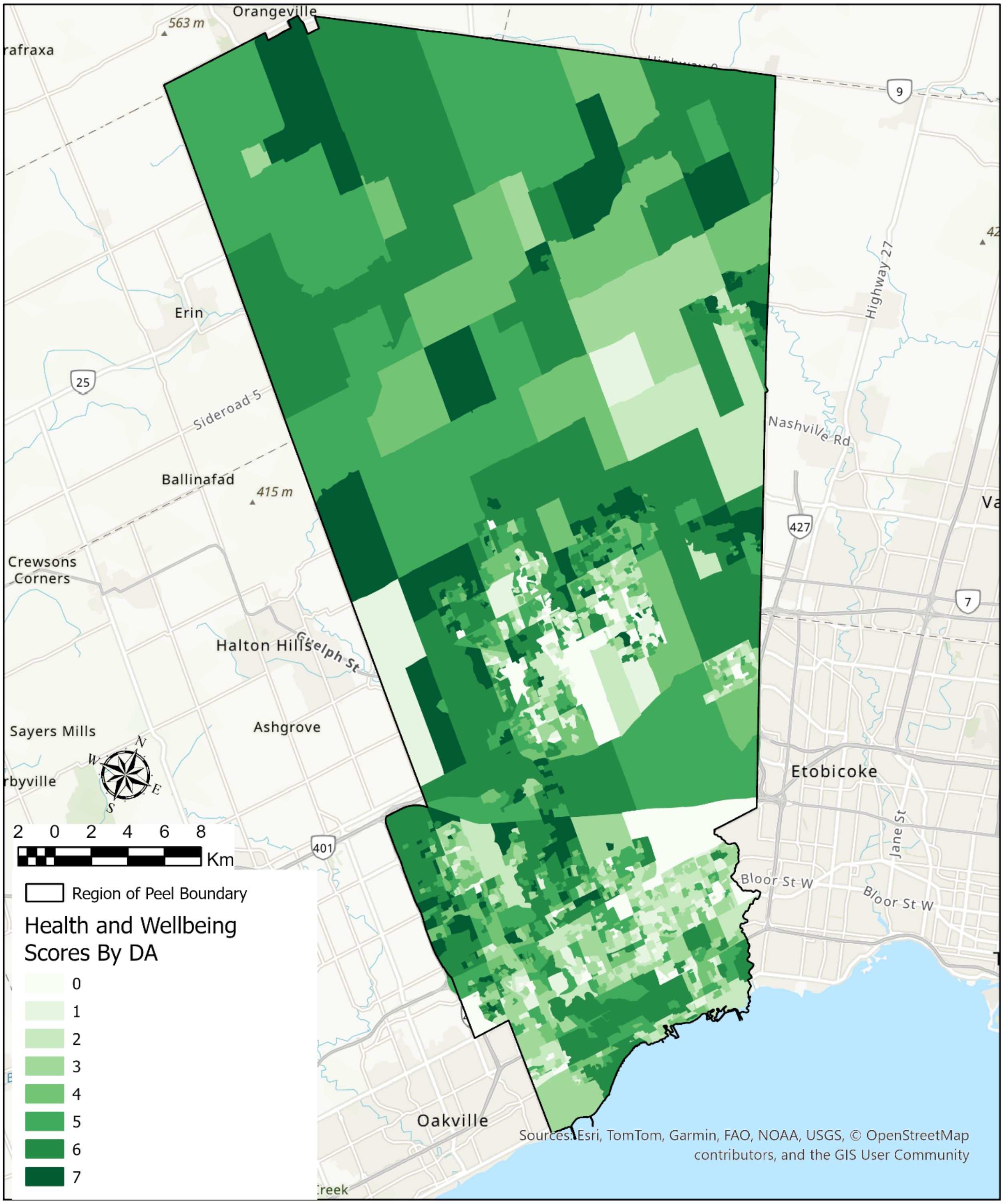


Figure 16. Health and well-being indicators by dissemination area (DA) within the Region of Peel, 2021.

Data Analysis Methods

To this point, I have detailed the data preparation and characteristics of the data sets used in this research. Once the data was collected and prepared, the hypotheses of this study were tested using a number of standard statistical techniques. These included F-tests, Welch's t-test, Pearson's product-moment correlation test, simple linear regression, and Cohen's *d* tests. For the *t*-test, the "two-sample unequal variance" type was used[2]. This *t*-test, accounts for unequal variance, based on Welch's *t*-test. Welch's t-test is recommended for normal data as a standard when variances are unequal (Welch, 1947). Variance was explored by running F-tests. The F-test results (Table 17) show that there are significant differences ($p \leq 0.05$) between those variances; therefore, data having unequal variances were used for the *t*-test.

Cohen's *d* test measures the size of the standardized difference between two distributions with confidence intervals (CI), which is useful to understand both magnitude and precision (Cohen, 1998). Cohen's *d* test provides benchmarks for small effect size (0.2), medium effect size (0.5), and large effect size (0.8 or higher). Correlation analyses and simple linear regressions were used to examine relationship strength and to quantify the variance explained by the observed data. Those analyses are discussed in the Results chapter (Chapter 5).

Summary

This chapter outlined the multifaceted methodology used in this study. I employed a disaggregation method to estimate local EF from national EF, updating an existing model (Kuzyk, 2011) with current data. This produced a detailed view of the Region of Peel's EF of

[2] It was a Type 3 in a Microsoft Excel-based formula.

consumption and its distribution across different communities (DAs). I also introduced a novel citizen science approach to capture individual consumption and health and well-being data, which not only serves as a potential calibration for the local EF estimates but also stands on its own as a means to directly measure personal footprints. This approach required developing a conversion model to translate survey responses into gha/cap values, a process that was described step-by-step in this chapter.

Additionally, I outlined the methodology for assessing health and well-being using a set of indicators. I explained how each DA was evaluated based on its health and well-being outcomes. This provides an independent, but parallel, dataset that can be linked to sustainability metrics. Together, these methodologies enable a comprehensive analysis in the next chapter (Chapter 5), where I explore the results: comparing the EF of consumption between recent immigrants and established Canadians, examining geographic patterns of EF and health and well-being in the Region of Peel, and identifying any relationships between a community's EF and the health and well-being of its residents. The subsequent chapter presents the results and insights derived from the collected data and applied methods.

Chapter Five: Results, Analysis and Discussion

Introduction

This chapter presents the findings of analyses conducted in the Region of Peel and explains their implications in the context of ecological footprint (EF) for established Canadians and recent immigrants. The primary research questions addressed in this proof-of-concept study are: *(1) How can we better estimate the EF at the local level in the study area, using data produced at a national level?*, and (2) *What type of differences, if any, exist between the EF of the recent immigrant communities and the established Canadian communities, and how do these differences relate to their health and well-being?*

- **$H0_1$:** There is no difference between the EF calculated using citizen science at the local level compared to nationally reported EF disaggregated for the local level.
- **$H0_2$:** There is no difference in EF of the recent immigrants versus the established Canadian communities in the study area.

Both null hypotheses were rejected based on the study's results. In other words, the EF estimations done at the local level are significantly different from the disaggregated national-based estimates, and the EF of the recent immigrants differs significantly from that of the established Canadians in the Region of Peel ($p < 0.05$ in each case). The discussion then extends to the potential of citizen science data to refine local EF estimates of consumption. Furthermore, this chapter examines the correlations between health and well-being, and the EF of consumption, within these sub-populations. The following sections are organized to first present *results,* including the EF calculations at the local level, comparisons between sub-populations and methods, and additional analyses (correlations with health and well-being), and then the discussions, which interpret these findings. A brief *Conclusion* summarizes the key outcomes.

Results and Key Findings

Disaggregation Method: Local EF Estimates at the Dissemination Area Level

As discussed in the methodology chapter, Kuzyk's (2011) approach was employed as a starting point to disaggregate the national EF of consumption to a local level using median household income and expenditure data. The income-based decile ratio published in 2008 (Mackenzie et al., 2008) was used in this study (Table 6). For consumption based on EF categories and EF land-use categories, the 2021 ratio was used to estimate EFs in the Region of Peel. The consumption ratio, based on 2021 data, was as follows: food (15.4%), housing (31.4%), mobility (15%), goods (21.7%), and services (16.5%). Table 8 (Chapter 5) refers to the land use-based EF categories adjusted for the study area

Within DAs, the income-decile-based EF was calculated using the income-decile-based categorical EF from Table 6. Table 9 (in the previous chapter) shows a sample of median household income (2023) per DA and their corresponding EF consumption categories. The total EF of consumption per capita was multiplied by the total population per DA to calculate the total EF per DA (Table 9).

Population Coverage

There were a total of 1,746 DAs within the Region of Peel boundary. Of these, three of themhad no population. Those DAs were treated as if they had no population or household income. It was re-examined because one of the DAs was either erroneous or depicted a reality in which a fully commercial area had a population of 2. After reviewing an aerial photo, I determined that people likely lived in the DA. Therefore, it was left as is (included). The rest of the DAs had population vaules. The results show that the EF of consumption ranges from 6.9 to 17 gha/cap, which differs from the national average of 7.42 gha/cap (Figure 17).

There are some outliers showing higher consumption EFs in some DAs within the study area. The outliers show that approximately 150 DAs have very high EFs compared to the rest of the average DAs. Within the Region of Peel, there are a few DAs with very high median household incomes over $150,000 per year. Given that high income is correlated with high expenditure, a higher EF of consumption results in a very high per capita EF of consumption in those DAs (Figure 17).

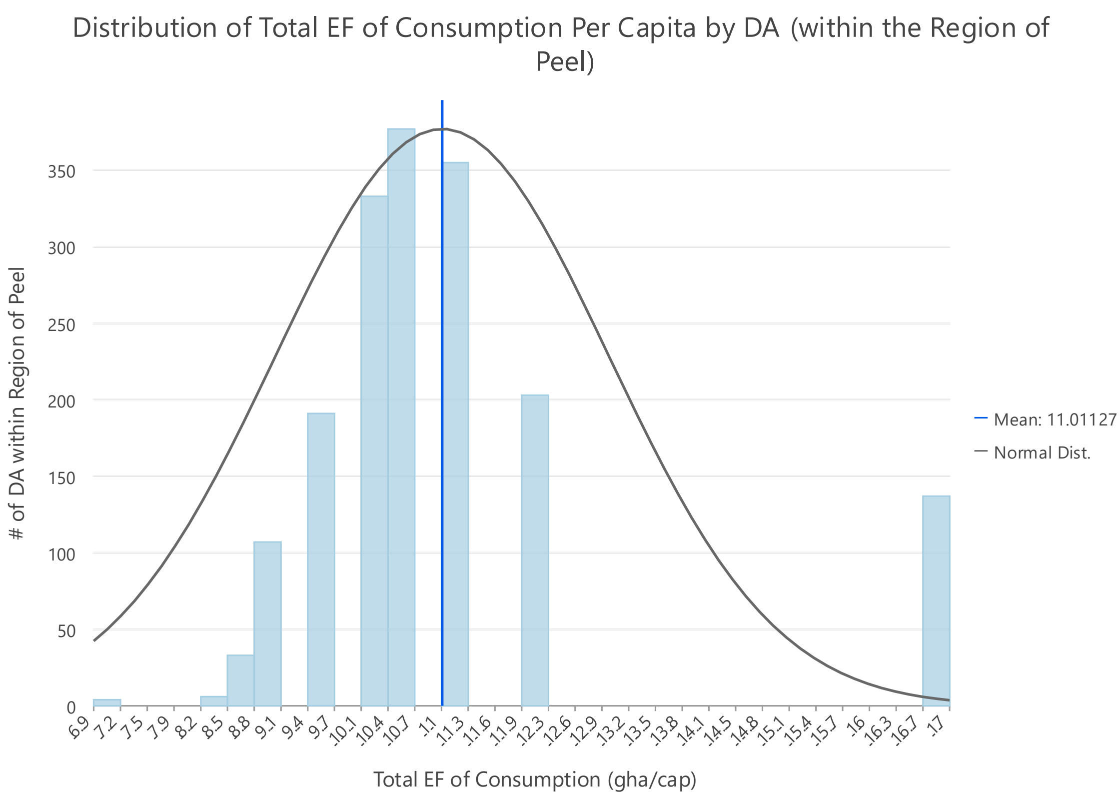


Figure 17. Distribution of EF of consumption by DA within the Region of Peel, 2021.

Although slightly positively skewed, the data shows a skewness of 2.04 and a leptokurtic kurtosis of 4.01 (see Figure 18). After reviewing the data, it was found that there is a group of DAs that have different consumption patterns (see the explanation for the reasons above) and that the transformation of the data using the logarithmic method did not impact the overall distribution of the data (for example, the complete data after logarithmic transformation (log10) had a similar skewness (1.54) and similar kurtosis (2.75) to that of the original data (skewness 2.04 and kutosis, 4.01)). Research shows that kurtosis transformations make the data more difficult to explain, yield no improvement, and that there are no simple transformations for kurtosis (Rindskopf and Shiyko, 2010). The authors highlight that skewness properties are more important than kurtosis for selecting appropriate statistical tests. I proceeded with the analysis using the existing data without performing any data transformations.

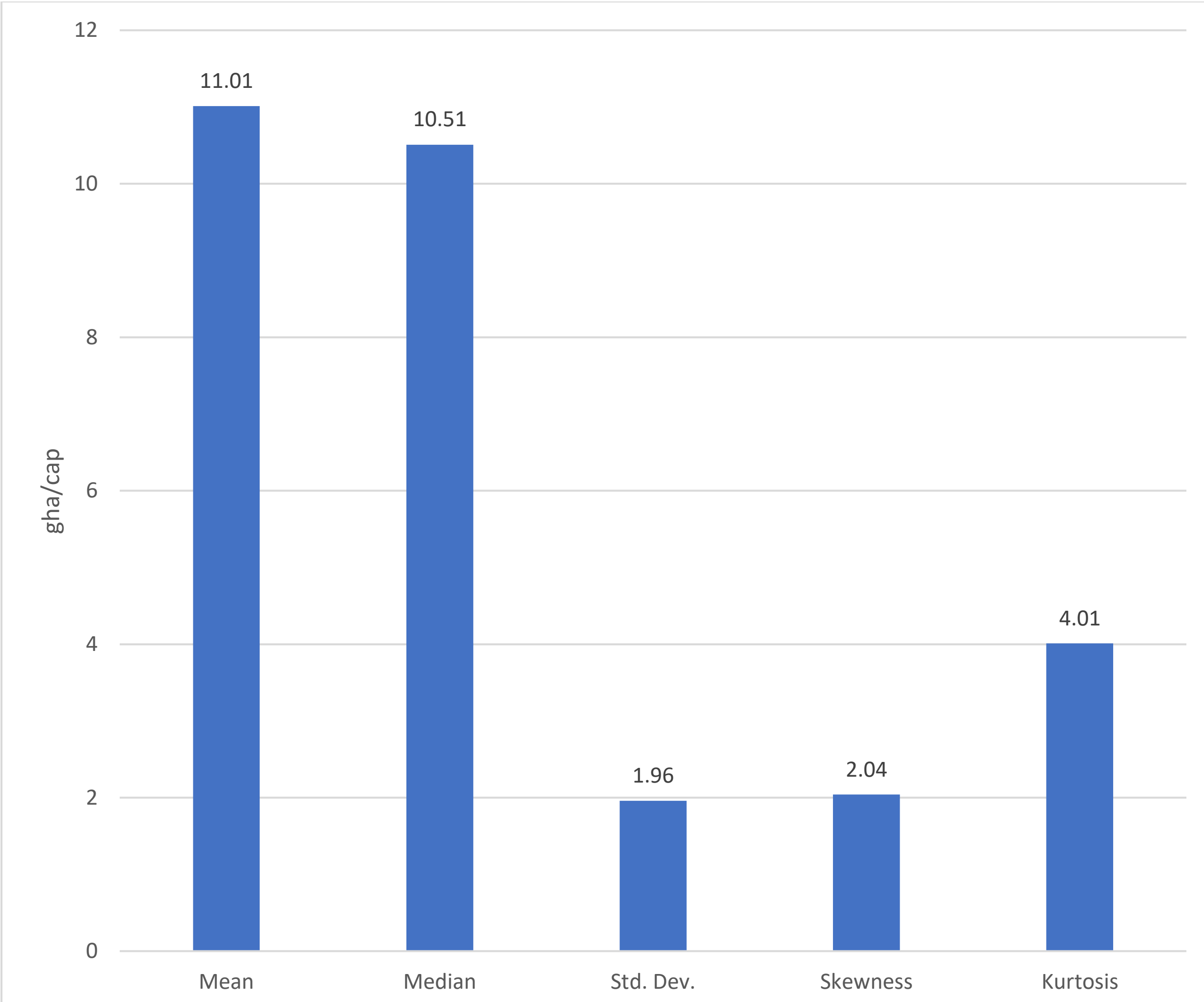


Figure 18. Distribution of EF by DA within the Region of Peel, 2021.

The distribution of the EF of consumption was mapped to review the pattern within the Region of Peel. It is shown in Figure 19.

Figure 19 shows a higher concentration of EFs within the DAs located in southwest Mississauga and parts of north-east Brampton and north-east Caledon. The median after-tax income in those areas is also generally higher than the rest of the Region of Peel.

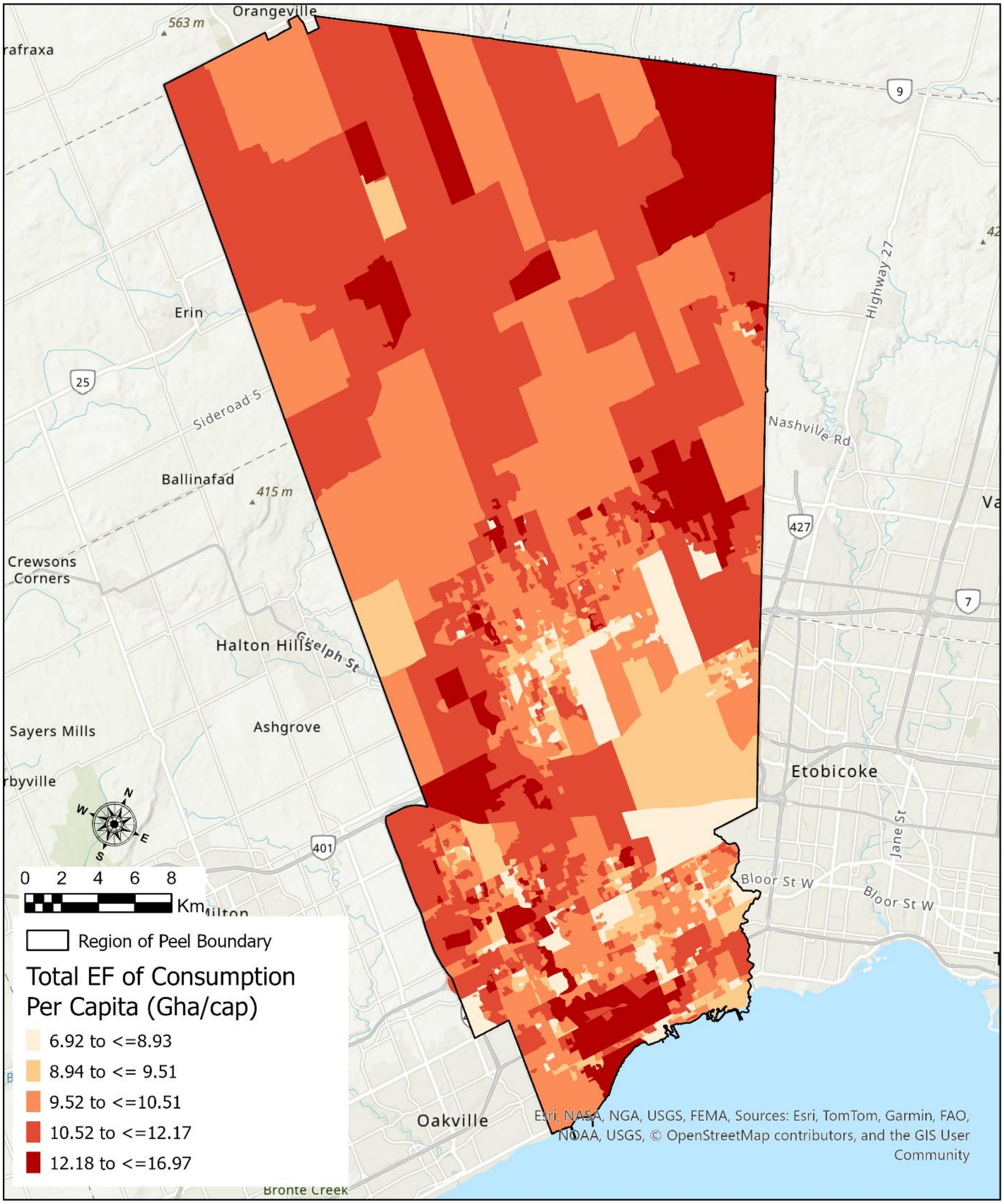


Figure 19. EF of consumption distribution by DA within the Region of Peel, 2021.

Exploration of Differences in EF by Immigration Status

To understand the difference in EF of consumption between the DA with a majority of immigrants versus non-immigrants, the total immigrants (by place of birth) were divided by the total population within the DA. The average immigrant ratio in the Region of Peel was 52%. Because of its proximity to the 50% mark, this analysis used a 50% cut-off to differentiate whether a DA was *immigrant-centric* or *non-immigrant-centric* to explore the pattern of EF of consumption. This method is also known as the 50th percentile rule. The 50th percentile is the value at which 50% of measurements fall below it and 50% above it; this statistical measure is used in several industries (Louden, n.d.; SpeedCurve, 2024; Ziegler & Nelson, 2012).

In this study, among 1,746 DAs, 1,060 had an immigrant percentage of 50% or higher. The immigrant-centric DA (Figure 20) had a very similar average (10.92 versus 11.16) gha/cap to that of the non-immigrants (Figure 21). The pattern indicated a similar ratio to the overall Canadian data.

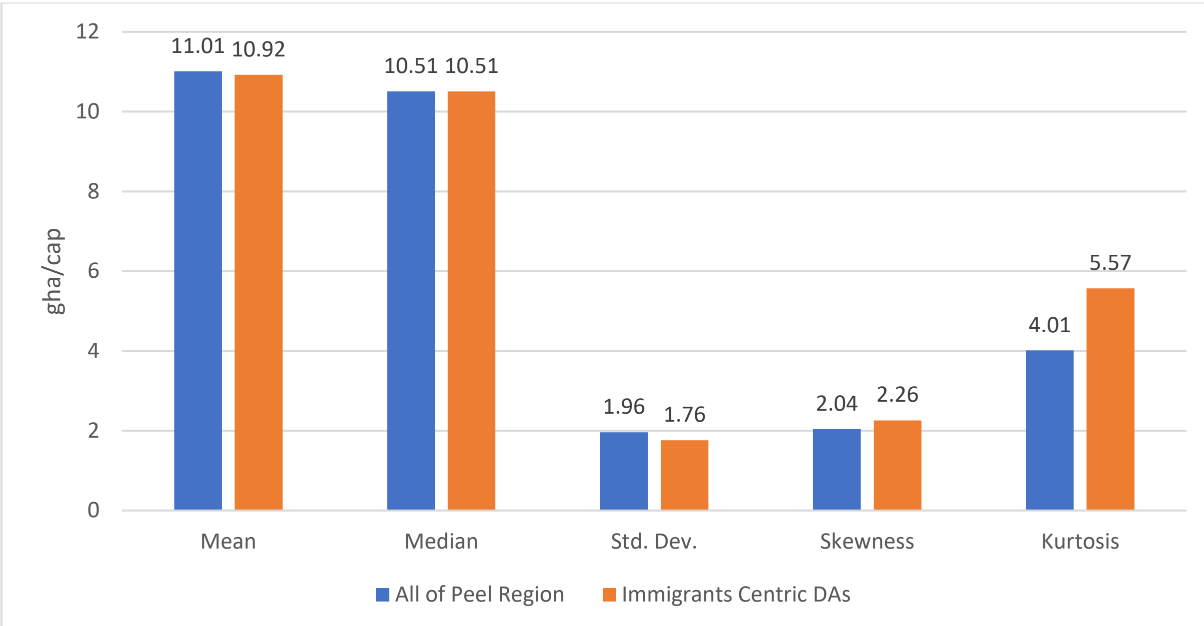


Figure 20. EF of consumption from the immigrant-centric DAs, Region of Peel, 2021.

The non-immigrant DAs show a similar pattern (Figure 21) to that of the immigrants from Figure 20.

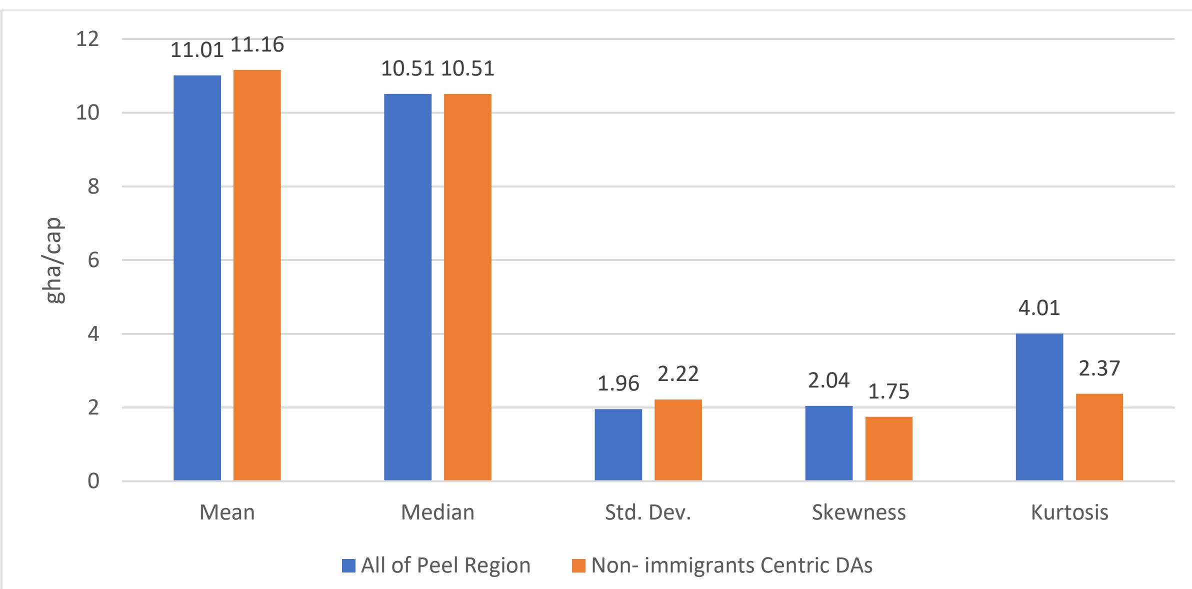


Figure 21. EF of consumption from the non-immigrant-centric DAs, Region of Peel, 2021.

Analyzing EF of Recent Immigrants versus Established Canadians in the Region of Peel

Recent immigrants are defined in this study as individuals who have immigrated to Canada within the 20 years preceding the commencement of this study in 2021 (i.e., since 2001). Therefore, this study considered immigrants who moved to Canada after 2001 as recent immigrants. Using ArcGIS Pro, the following calculation was applied to identify recent immigrants based on the census-reported fields:

Recent Immigrants = Immigrant Household Population 2001 to 2005 **+** Immigrant Household Population 2006 to 2010 **+** Immigrant Household Population 2011 to 2016 **+** Immigrant Household Population 2017 to 2021 **+** Non-Permanent Residents

Note: Non-permanent residents were included in this category as they do not belong to the established Canadian category, given their general lifestyle. Their general lifestyle is closer to that of recent immigrants.

The remaining population within the study area was considered to be established Canadians. The following calculation was used to identify established Canadians.

Established Canadians = all other household populations that do not belong to Recent Immigrants (non-immigrants + immigrants from before 2001).

As a next step, the ratio of established Canadians to the total population was calculated. Another field was created in ArcGIS Pro so that proper values could be assigned per DA as Recent Immigrants or Established Canadians, based on the 75th percentile rule. The 75th percentile is the value at which 75% of measurements fall below it and 25% fall above it (SpeedCurve, 2024). It is a statistical measure frequently used to reduce the potential influence of outliers to make data representative of the conditions in the study area (CTC Source Protection Committee, 2019; Ministry of Ontario Environment and Energy, 2021; Singh et al., 2022). Given the ratio of *recent immigrants*, not all immigrants, this percentile was selected to support the sub-population-based comparisons. For example, if an established Canadian ratio was found to exceed 75%, the DA was coded as established Canadians; otherwise, it was coded as recent immigrants. If we were to use the 50th percentile rule, as in comparing immigrants versus Canadians, the majority of the DAs (1,743 out of 1,746) would belong to established Canadians, negating the original intention of comparing with recent immigrants. Figure 22 shows the distribution of EFs across the two communities.

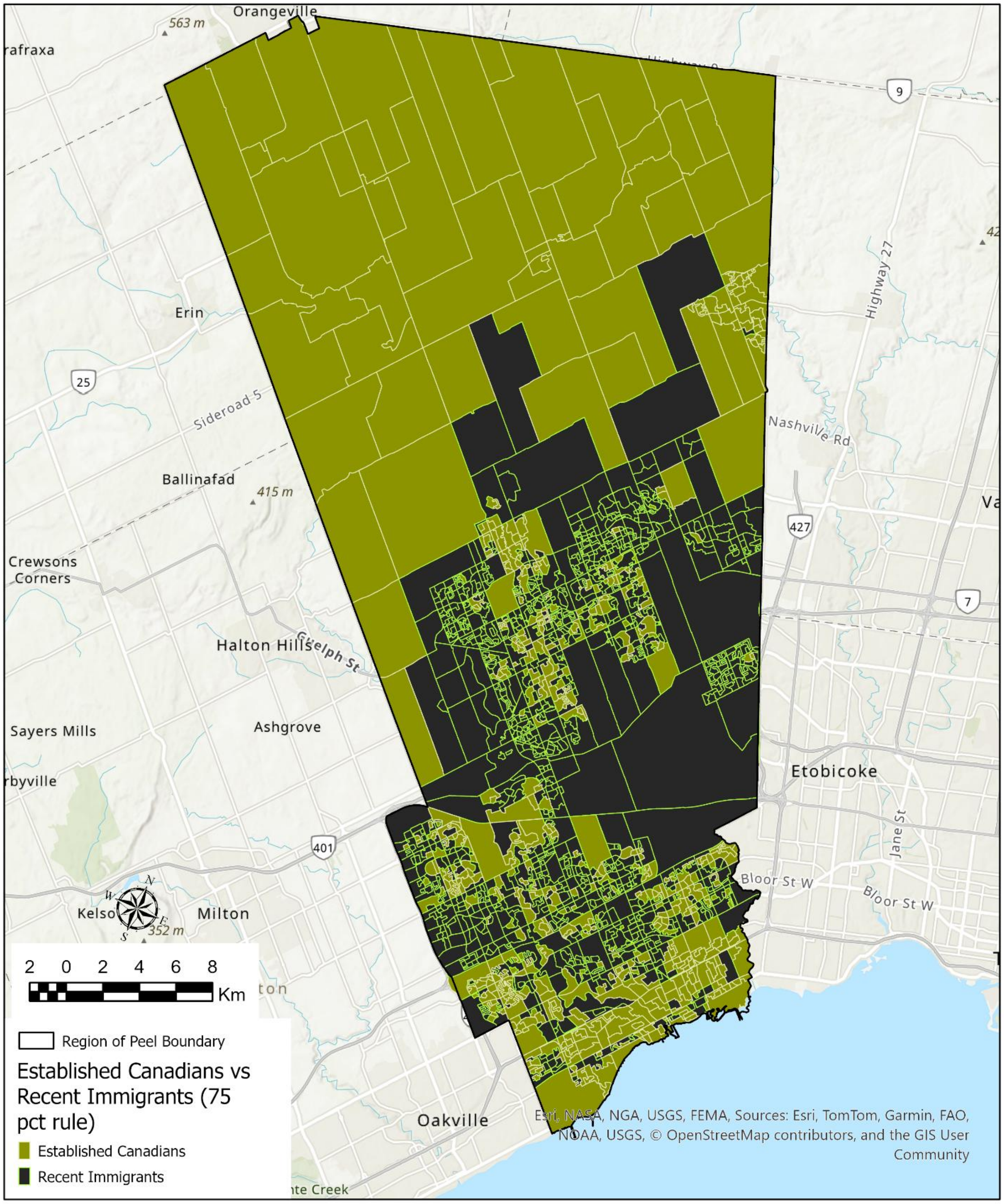


Figure 22. Distribution of established Canadians versus Recent Immigrants, based on the 75th percentile rule within the Region of Peel, in 2021.

The chart below shows that established Canadians have an EF of consumption of 11.51 gha/cap at the DA level (Figure 23), compared to recent immigrants, who have 10.8 gha/cap (Figure 24).

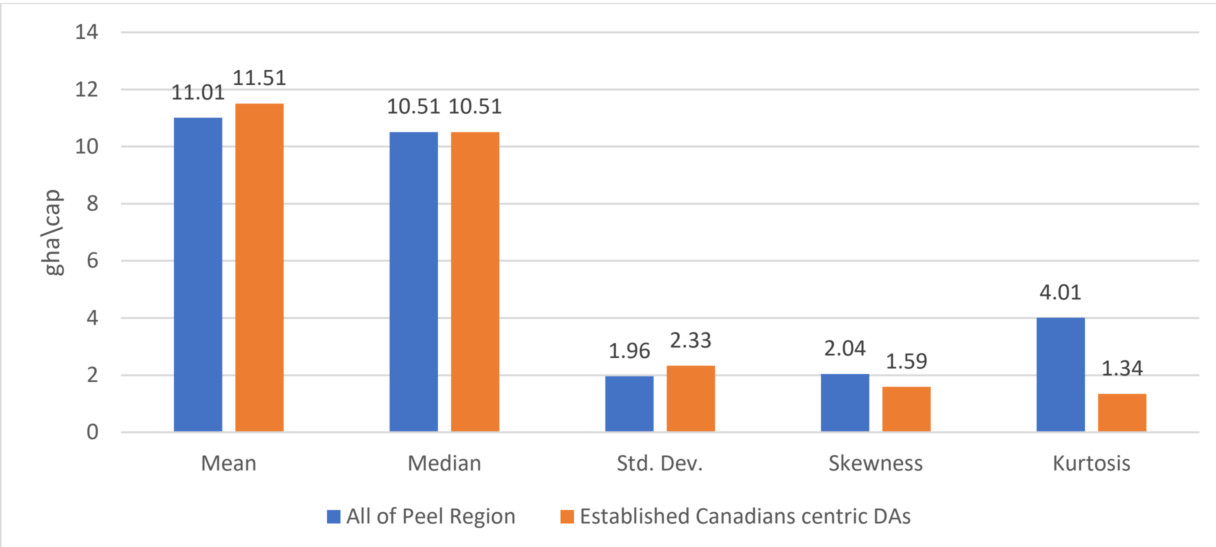


Figure 23. EF of consumption by the established Canadians (distribution by DA within the Region of Peel, 2021).

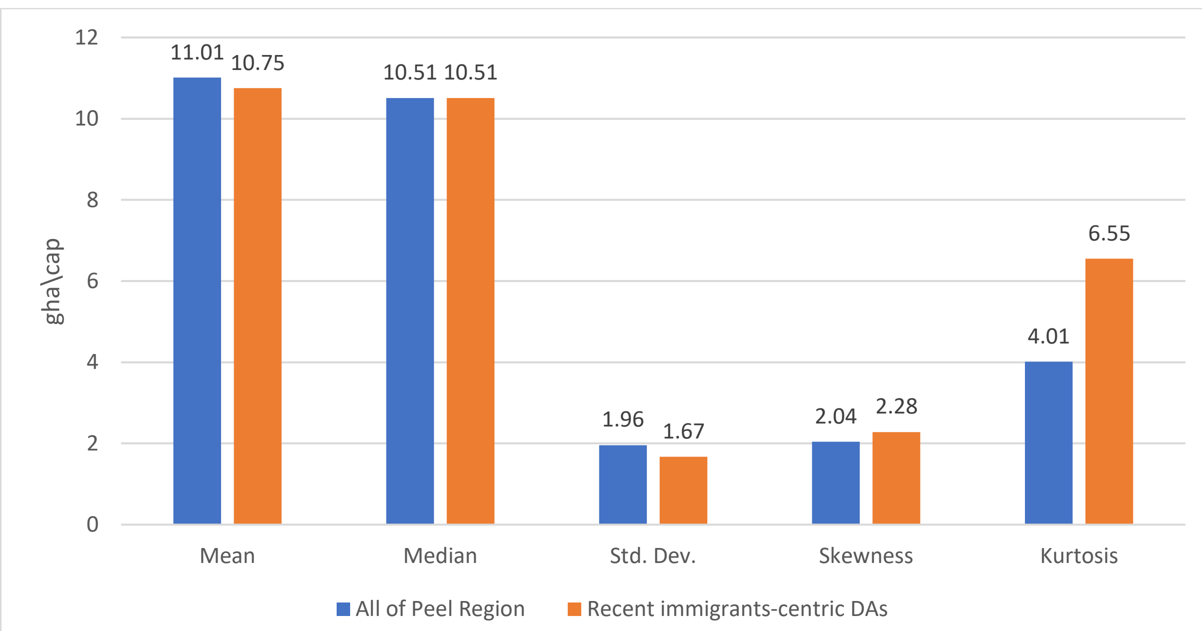


Figure 24. EF of consumption by the recent immigrants (distribution by DA within the Region of Peel, 2021).

Statistical Test of Significance

A *t*-test and Cohen's *d* were used to determine whether there was a significant difference in EF of consumption between established Canadians and recent immigrants, and to estimate the magnitude of the difference using the disaggregation method. A two-sample *t*-test was performed to compare the EF of consumption between established Canadians and recent immigrants. There was a significant difference in EF of consumption between established Canadians (M=11.51, SD=2.33) and recent immigrants (M=10.75, SD=1.67); t(df)=597,p =4.7E-12 (Table 13, 14). The results from Cohen's *d* test show that they are *significantly different (p ≤ 0.05), with a small effect size (d = 0.39, 95% CI [0.29, 0.49])* (Table 13). In other words, *I reject* $H0_2$ *and conclude that the recent immigrant communities EF are different from those of established Canadians.*

Cohen's d of 0.39 (95% CI [0.29, 0.49]) indicates a small effect size in EF between established Canadians and recent immigrants (Table 13). Cohen's *d* test provides benchmarks for small effect size (0.2), medium effect size (0.5), and large effect size (0.8 or higher) (Cohen, 1998). Established Canadians exhibited a 0.39 standard deviation higher EF using the disaggregation method. The communities differ statistically, but the effect is small. The results from the 95% confidence interval show that 95% of those studies would produce an effect size between 0.29 and 0.49, indicating that we are 95% confident that the true difference between the groups lies within the range. In practice, because both upper and lower bounds are positive, we can confidently say that there is a positive difference between the two groups and that it is statistically significant.

Table 13. Results of Cohen's *d* test and *t*-test using the disaggregation method (comparing recent immigrants versus established Canadians).

Cohen's *d* test		***t*-test**	
Pooled SD (unequal n)	1.92	T-test results (2-tailed) P value	4.7E-12
Cohen's d	0.39	Variance (recent immigrants)	2.80
Standard Error of d	0.05	Variance (established Canadians)	5.44
95% Confidence Interval (L)	0.29		
95% Confidence internal (U)	0.49		
Effect size	Small		

The unequal variance was determined by running an F-test. The F-test results (Table 14) indicate significant differences in variances ($p \leq 0.05$); therefore, data with unequal variances were used for the *t*-test.

Table 14. Results of the F-test on recent immigrants versus established Canadians data using the disaggregation method.

Description	**Established Canadians: Total EF of Consumption Per Capita**	**Recent Immigrants: Total EF of Consumption Per Capita**
Mean	11.51	10.7536
Variance	5.44	2.7987
Observations	598.00	1148.00
df	597.00	1147.00
F	1.94	
P(F<=f) one-tail	5.8E-22	
F Critical one-tail	1.12	

In practical terms, the significance likely stems from several variables. Recent immigrant DAs, often found in urban, apartment-dominated areas, tend to have slightly lower consumption (possibly due to lower average incomes initially or culturally different spending patterns), whereas established suburban areas may have larger homes and more cars, which raises their EF. Nonetheless, the lower EF in recent immigrant communities is not a large difference, and other studies suggest that, after some time in the region, consumption patterns may converge, a point we return to in the discussion.

Citizen Science Data Analysis and Results: Conversion of Citizen Science Consumption Information into EF of Consumption Gha/cap Equivalent

The citizen science data comprised both qualitative and quantitative data submissions. To date, no previous studies have collected citizen science-based consumption data and translated it into the equivalent EF of consumption. Consequently, a new method was developed to convert the citizen science-based consumption data into EF of consumption in this study, adapted for application at the local level within the study area.

This study established that 1 unit of EF of consumption in global hectares per capita (gha/cap) corresponds to 0.06 units in the citizen science data (equation 3), *based on the ratio of 0.4733 divided by 7.42 (0.0638, rounded to 0.06).*

$$EF\left(\frac{gha}{cap}\right)CS = \frac{0.4733}{7.42\ (average\ Canadian\,\frac{gha}{cap})} \qquad \ldots(3)$$

Where,

EF (gha/cap) CS means 1 unit of EF of consumption (gha/cap) from the citizen science method.

The value of 0.4733 means the calculated average EF of consumption (gha/ca) from the citizen science method

The value of 7.42 gha/cap meansaverage Canadian EF of consumption

Thus, a 0.06 unit increase in citizen science-based EF of consumption from survey contributions equates to an additional 1 gha/cap in EF of consumption. This formula was applied to estimate the equivalent EF of consumption (in gha/cap) from self-reported citizen science-based data.

Specifically, citizen science-based EF values were divided by 0.06 to calculate the self-reported EF.

Using this method, citizen-collected data at the national level revealed a minimum EF of 3.53 gha/cap in some areas and a maximum of 11.87 gha/cap in others (Table 11, Chapter 5). The data followed a normal distribution with slightly negative skewness (right-skewed) and exhibited low kurtosis (thin-tailed, -0.021), indicating a relatively uniform distribution with minimal outliers.

A major component of this study was a *citizen science approach*where individuals self-reported aspects of their consumption. This data was converted into EF estimates and compared against the conventional income-based disaggregation method (Kuzyk, 2011).

I present here two sets of analyses: one using raw data collected through citizen science in the Region of Peel alone, and the second using values averaged from the GGHA as a benchmark. The former had a primary fault; the number of citizen science responses does not support it. The latter is intended as an alternative that improves data representativeness by aggregating values for the local area containing the Region of Peel. I present both approaches to retain an example of how they may be done under different citizen science-based data availability. The following two analysis options were explored:

- **Region of Peel Raw Data Only Approach: Raw Region of Peel Submissions** – Using only citizen data from within the Region of Peel. Due to data limitations, it is not the primary analysis (see subsequent sections below). It was an exploratory analysis.
- **Greater Golden Horseshoe Area Average-based Approach: GGHA Average (Primary Analysis)** – Using the Greater Golden Horseshoe Area (GGHA) average as a basis for Peel.

The subsequent sections highlight two sets of results based on the citizen-science data on EF (*Region of Peel Raw Data Only Approach and Greater Golden Horseshoe Area Average-based Approach).* The first option is based on the raw data from the Region of Peel's DAs, and the second option uses the average from the Greater Golden Horseshoe Area (GGHA) to apply within the Region of Peel.

Region of Peel Raw Data Only Approach: *Results using raw data* within the Region of Peel: Transfer of Citizen Science Collected EF of Consumption Data to DAs within the Region of Peel

The citizen science data (Figure 15)were collected at the national level (Figure 15) to provide comparative foundational data (because the official EF of consumption exists only at the national level). However, the main objective was to explore patterns in-depth in the Region of Peel. The collected data were joined to the spatial boundaries of DAs within the Region of Peel using ArcGIS Pro. After joining the data per DAs within the Region of Peel, it was discovered that 156 random submissions were from within the Region of Peel. These submissions represent 38.33% of the total citizen science data. Out of this, 48 unique DAs within the Region of Peel had at least one or more submission.

Within the Region of Peel, the average EF of consumption was found to be 7.73 (gha/cap) based on citizen-science-contributed data (Table 15). The data exhibit a distribution characterized by slightly negative skewness and moderate (medium-tailed) kurtosis. This indicates that the data distribution is normal, with outliers neither frequent nor rare. Note that ArcGIS Pro reports Pearson kurtosis (3 for a normal distribution), while software like Excel reports excess (Fisher) kurtosis (0 for a normal distribution). *Excess kurtosis* intuitively measures the kurtosis above that of a normal distribution (Michelucci, 2025). Given that software packages differ in how they report kurtosis for a normal distribution, the kurtosis values generated in ArcGIS Pro were adjusted by subtracting 3. This standardization ensured consistency across all statistical outputs in the current study.

Table 15. EF of consumption within the Region of Peel from the citizen-collected data, showing the summary of the raw data from within the Region of Peel (156 submissions), calculated using ArcGIS Pro 2.9 (ESRI, 2024). [3]

Description	Value
Average Gha/cap	7.73
Min Gha/cap	4.04
Max Gha/cap	11.87
Standard Deviation	1.41
Skewness	-0.01
Kurtosis	0.28

EF of Consumption using Citizen Science Data vs Disaggregation Method within the Region of Peel using the Raw Data Approach

Based on the results from the study, citizen science-based data indicate that the self-reported local EF (Table 15: mean = 7.73 gha/cap) is lower than that of the disaggregation method (Figure 18: mean =11.01 gha/cap) for the Region of Peel. The results are significantly different, although a correlation exists between the DA's EF of consumption between those two approaches. The results show that citizen science-based data result in approximately 70% lower reporting of the EF of consumption compared to the disaggregation method used in the analysis within the Region of Peel. This translates to every 1 gha/cap in citizen science-based results; the direct comparison showed that 1.42 gha/cap (11.01 divided by 7.73) is estimated from the disaggregation method. Given that it is based on people's consumption patterns, it is expected to

[3] Please note that ArcGIS Pro software produces a kurtosis value of 3 for normally distributed data (source: ESRI, 2024). To compare with other software, such as Microsoft Excel (which produces 0 for normally distributed data and thus measures *excess* kurtosis), the value of 3 was subtracted from the kurtosis value calculated using ArcGIS Pro software.

reflect these patterns more accurately at the local level; however, more data and comparisons would enhance the results (discussed in Chapter 6). In the subsequent sections, the DAs assigned a citizen-science-based ratio (augmented by income deciles) was used for further analysis.

EF of Consumption using income-decile augmented Citizen Science Data for all DAs vs Disaggregation Method within the Region of Peel

The citizen-collected data was limited to a few DAs within the Peel Region. The remaining data (or DAs with no data) were assigned a *ratio of the EF* of consumption (gha/cap) based on the income-decile-based EF method used for the disaggregation method discussed in the previous section of this study, similar to Table 6 (Kuzyk, 2011).

Not all DAs in the Region of Peel submitted data to this project. If DAs had citizen science data, the average value from that data was used. If citizen science data were not collected within a DA, the income-based decile from Table 6 for the Region of Peel, with the ratio (using the average 7.73 gha/cap within the Region of Peel) from the citizen-collected data, was assigned. The following script was used to assign the gha/cap to the DAs that did not have EF of consumption (where ECYHNIMED refers to the median household income of the current year):

```
def reclass(ECYHNIMED):
    if (ECYHNIMED ≥ 180000):
        return 13.94
    elif (ECYHNIMED  ≥ 160000 and  ECYHNIMED < 180000):
        return 9.50
    elif (ECYHNIMED  ≥ 140000 and  ECYHNIMED < 160000):
        return 8.63
    elif (ECYHNIMED  ≥ 120000 and  ECYHNIMED < 140000):
        return 8.10
    elif (ECYHNIMED  ≥ 100000 and  ECYHNIMED < 120000):
        return 7.74
    elif  (ECYHNIMED  ≥ 80000 and  ECYHNIMED < 100000):
        return 7.26
    elif (ECYHNIMED  ≥ 60000 and  ECYHNIMED < 80000):
```

```
        return 6.73
    elif (ECYHNIMED   ≥ 40000 and  ECYHNIMED < 60000):
        return 6.56
    elif (ECYHNIMED   ≥ 20000 and  ECYHNIMED < 40000):
        return 6.20
    elif (ECYHNIMED   < 20000):
        return 5.05
```

Based on the script and the methodology discussed above, the results show the distribution of EF across income deciles by DAs within the Region of Peel (Figure 25). After *applying the income-decile-based parameters*, the EF of consumption is, on average, 8.52 gha/cap for the DAs within the Region of Peel.

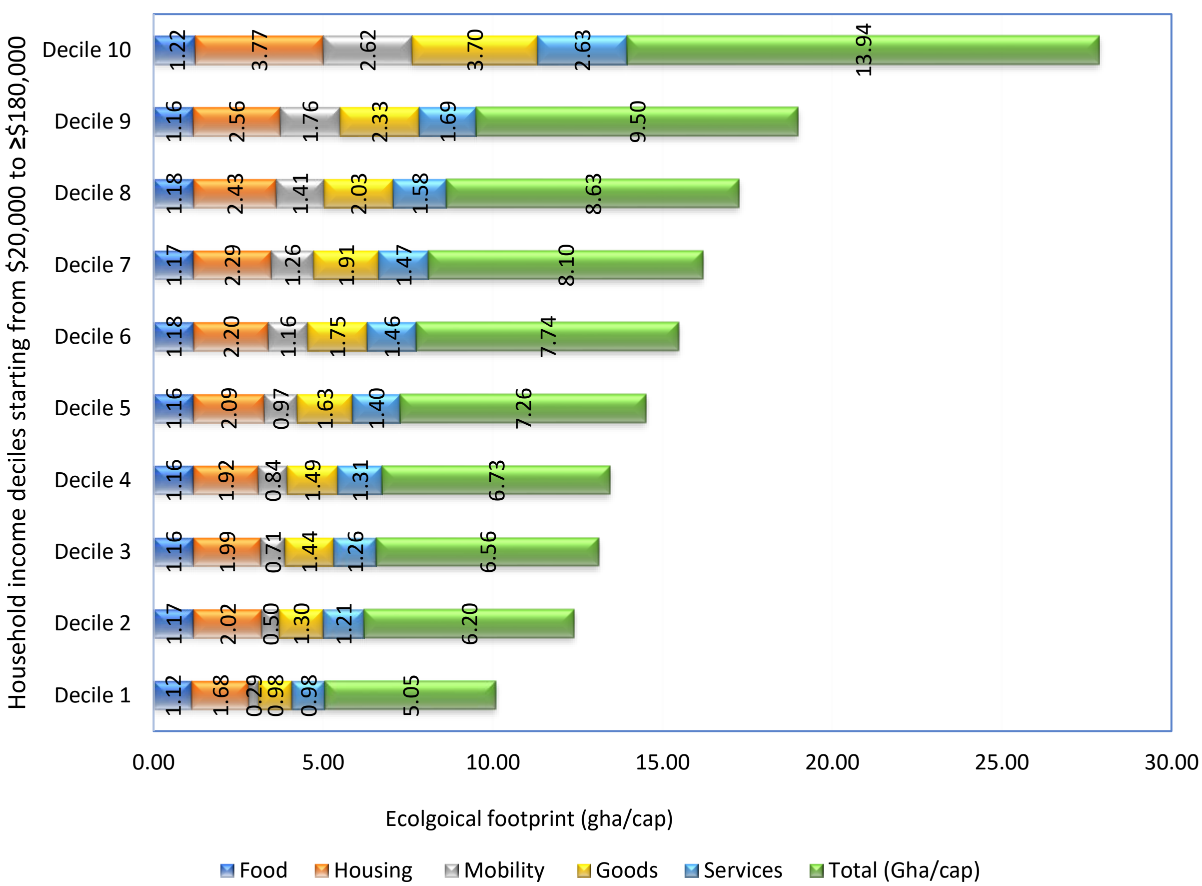


Figure 25. Distribution of EF of consumption from citizen science data augmented using the income-decile ratio within the area in the Region of Peel, 2021.

The analysis results show higher gha/cap in south-central Mississauga and northeast Caledon, as expected, given higher incomes, larger mansions, etc. (Figure 26). It is important to note that the citizen science data in this project includes people's self-reporting of their consumption patterns. This type of self-reporting about themselves can be different from the reporting of external incidents, such as butterfly sightings.

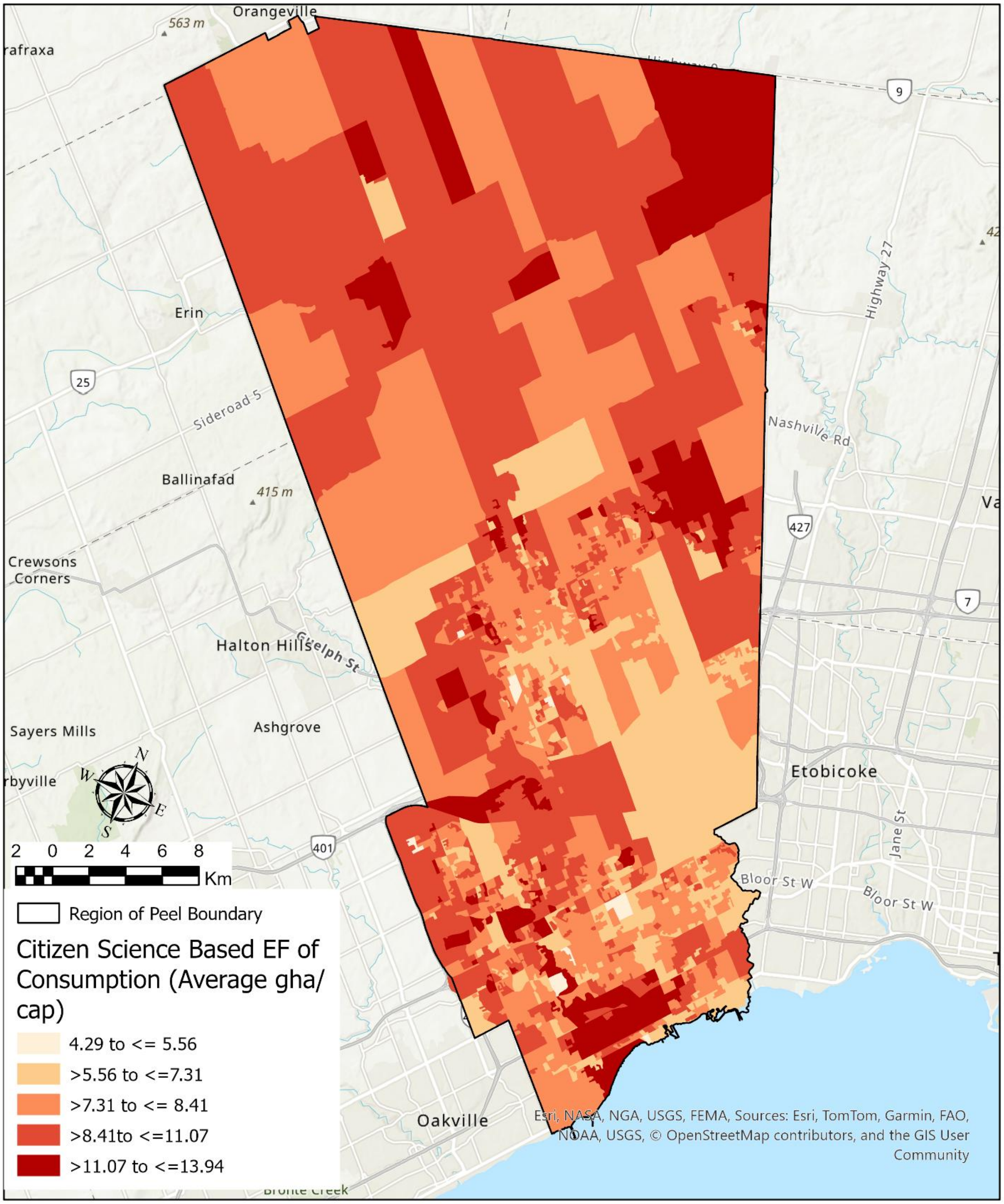


Figure 26. Citizen science-based EF distribution in the Region of Peel, using raw submissions within the boundary, augmented by income deciles, 2021.

Comparing the Disaggregation Method and Citizen Science Method

The disaggregation method, as per Kuzyk (2011) and the citizen science-based data augmented by Mackenzie et al.'s (2008) income-decile ratio representing DAs within the Region of Peel (Figure 27), have a similar pattern; however, there are some differences (see Figure 17). The outliers are from the DAs with the highest median household income within the study area.

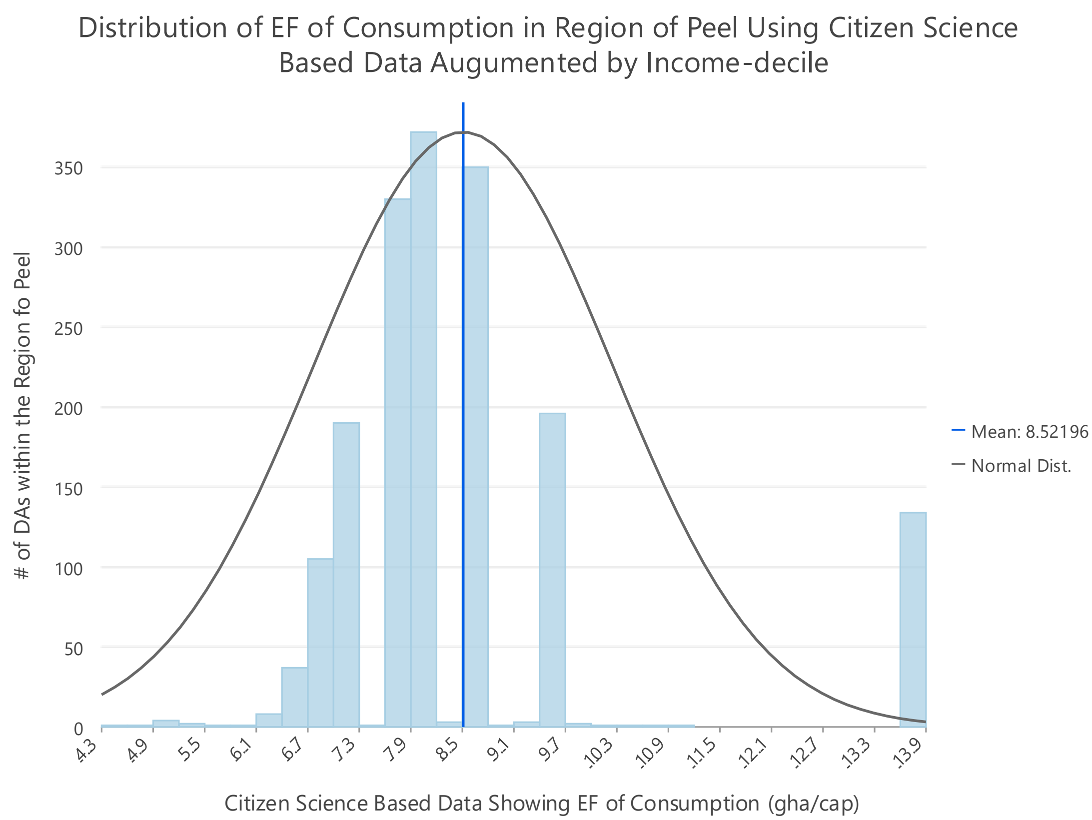


Figure 27. Distribution of EF of consumption by DA in the Region of Peel based on citizen science-based data augmented by income deciles, 2021.

A *t*-test was used to calculate whether there was any significant difference between the two results (Kuzyk, 2011) and the citizen science-based results. A *t*-test was also performed by removing the outlier DAs (values of 10.3 or higher gha/cap from the citizen science data) to examine whether there was a difference in results between the original values and those without the outliers. No differences were found in the results after removing outliers. Therefore, the study proceeded with all data without removing outliers.

A two-sample *t*-test was performed to compare the EF of consumption between the disaggregation and citizen science methods. There was a significant difference in EF of consumption between disaggregation method (M=11.01, SD=1.96) and citizen science method (M=8.52, SD=1.75); t(df)=1745, p =4.78E-283 (Tables 16 and 17).

This *t*-testaccounts for unequal variance, based on Welch's *t*-test. The F-test results (Table 17) show that there are significant differences ($p \leq 0.05$) between those variances; therefore, data having unequal variances were used for the *t*-test. The test results, excluding the outliers (outliers removed version), also showed similar results with $p \leq 0.05$. A total of 137 DAs fell within the outliers group in this data. Given the higher number of DAs and no significant difference between the results (with or without those DAs), those DAs with higher gha/cap were included in the further analyses.

Table 16. Results of the t-test between data produced using Kuzyk's method versus citizen science-based data.

Description	Value
T-test results (2-tailed) P value	4.8E-283
Variance (Disaggregation Method)	3.83
Variance (Citizen Science)	3.07

Table 17. F-test results showing unequal variances.

Description	Disaggregation Method	Citizen Science Data
Mean	11.01	8.52
Variance	3.83	3.07
Observations	1746.00	1746.00
df	1745.00	1745.00
F	1.25	
P(F<=f) one-tail	2.2E-06	
F Critical one-tail	1.1E+00	

Based on the results from the two methods, Table 17 shows the EF of consumption averages in DAs within the Region of Peel. The direct average comparison with income-decile augmented data within the Region of Peel shows that for every 1 gha/cap EF of consumption from the citizen science-based data, there is 1.29 gha/cap (Table 17; 11.01 divided by 8.52) EF of consumption from the disaggregation method (Kuzyk, 2011).

Correlation Test and Linear Regression Test

A correlation test was conducted to investigate the relationship between the data patterns from the disaggregation method and citizen-science methods. Pearson's correlation results showed that both datasets are strongly positively correlated ($r = 0.98$). The R^2 value of 0.96 for those two variables indicates that it accounts for 96% of the variability in estimating the EF of consumption per capita (Figure 28). The linear regression results, with a strong R^2 (0.96), showed that for every 1 gha/cap increase in citizen science-based results, a1.10 gha/cap increase occurs based on the disaggregation method (see Figure 28; $y = 1.095x + 1.68$, $R^2 = 0.96$). Among the direct average comparison and linear regression, the linear regression-based results are recommended for use due to their statistical rigour.

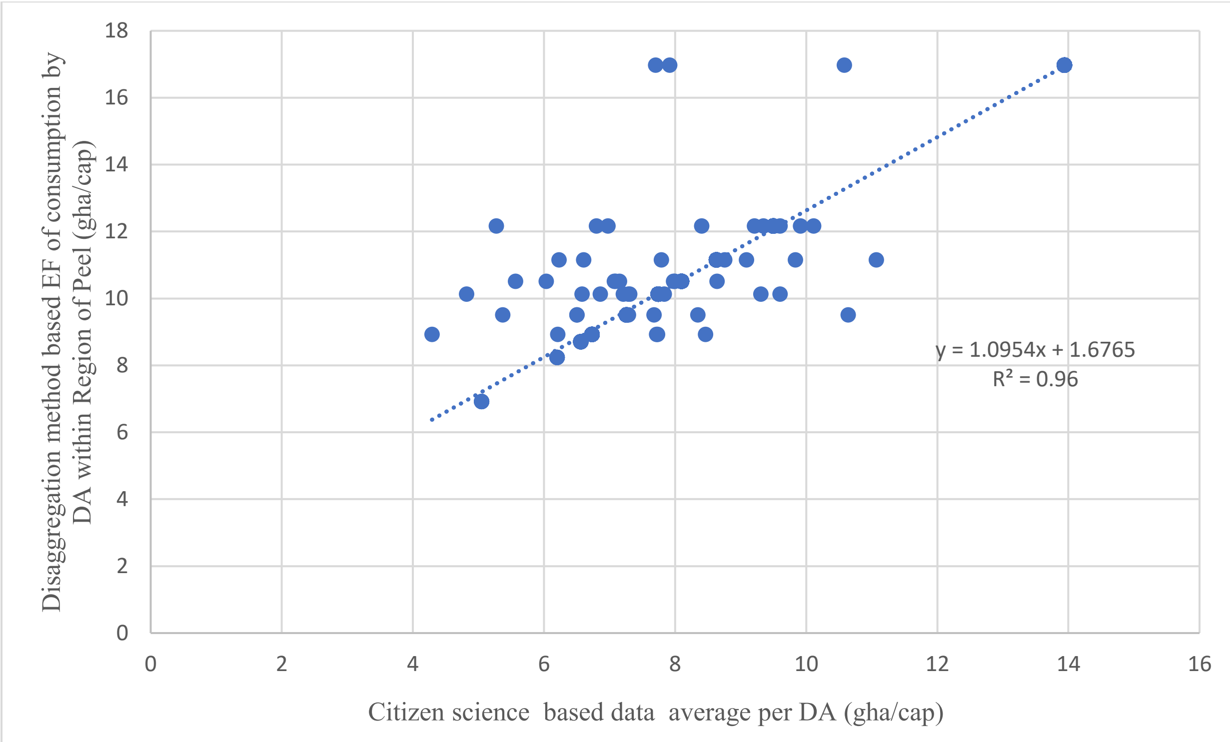


Figure 28. Correlation (r = 0.98) and R^2 results between the disaggregation method versus citizen-science-based data (augmented by income-deciles), Region of Peel, 2021.

The results from the *t*-test and correlation analysis show a strong positive correlation in the patterns of the methods; however, the results from these two methods are significantly different. It is essential to note that the citizen science approach and the disaggregation methods (Kuzyk, 2011) yield two distinct results when compared using average comparison and linear regression tests. For example, using the Region of Peel average augmented by income-deciles, for every 1 gha/cap in citizen science-based results, the direct comparison showed that 1.29 gha/cap (Table 17; 11.01 divided by 8.52) is estimated from the disaggregation method (Table 17), whereas the linear regression method showed that for every 1 gha/cap increase in citizen science-based results, a 1.10 gha/cap increase occurs based on the disaggregation method (Figure 28).

EF of Consumption for Established Canadians versus Recent Immigrants in the Region of Peel

To find out the differences between established Canadians versus recent immigrants, the original rule (used earlier in the study)[4] was applied to identify which DA referred to established Canadians versus recent immigrants. Of the 598 DAs within the Region of Peel attributed to established Canadians, the average EF of consumption based on citizen science data was 8.96 gha/cap, and recent immigrants had a slightly lower EF of consumption at 8.30 gha/cap. Using the disaggregation method (Table 14), a similar pattern is observed in the data, with 11.51 gha/cap for established Canadians and 10.75 gha/cap for recent immigrants.

Health and Well-being Analysis Using Citizen Science Data

Of the eight domains of Canadian Health and Wellbeing, the healthy populations domain was used for the citizen data analysis; this is the same domain used in previous sections of this study, based on the Community Health Survey (Canadian Index of Wellbeing, 2024; Smale & Margo, 2024). Although the *healthy populations* domain encompasses eight indicators, this exploratory study focused on only two indicators due to data-collection limitations and privacy concerns associated with postal-code geolocation data. The two indicators are:

1. Percentage of self-rated health as excellent or very good; and
2. Percentage who rate their mental health as very good or excellent.

[4] Recent immigrants are considered to be those who immigrated to Canada within 20 years from the beginning of this study (2021), whereas established Canadians refer to the rest of the Canadians.

Of the 407 submissions used in the EF of consumption, 4 lacked complete health- and well-being-related data. Therefore, a total of 403 submissions served as the basis for the national data for this component. As per previous analysis, there were 48 DAs in the Region of Peel with the submissions. Given that some DAs had multiple inputs, an average score per DA was used in the analysis.

Given that only 48 DAs had health and well-being-related indicators, the data from the selected 48 DAs within the Region of Peel were compared with the Community Health Survey-based data used in the previous section to explore patterns (Table 18). Table 18 presents detailed information on the number of DAs examined and the findings within those DAs related to health and well-being data.

Table 18. Comparison of the citizen science-based health and well-being data with community health survey-based data used in the previous section of this study (within the Region of Peel).

Description	Total Number	Percentage
Higher Health and Well-being - Community Health Survey-based data	33	68.75%
Higher Health and Well-being - Citizen Science data	38	79.17%
Overlap of Higher Health and Well-being between two methods	31	64.58%
Total DA Examined	**48**	**100.00%**

The pattern from Table 18 illustrates that the citizen science-based data showed better health and well-being at 79.17%, whereas the Community Health Survey-based data (a primary source of data available in this domain in Canada) shows 68.75% reporting better health and well-being, a 10% difference. However, when considering the combined metrics, 65% of the DAs reported better health and well-being in this study (Table 18). The results indicate that the citizen science-based approach tends to show higher/better health and well-being, or an overestimation of it, compared to the national community health survey. It is essential to acknowledge that the citizen science method has limitations in this analysis, primarily due to its significantly smaller sample size, data limitations resulting from resource constraints and scoping, and the fact that only two variables were analyzed using this method, compared to the eight variables analyzed in the previous section using Community Health Survey-based data.

Due to the limitations in the indicators that were available in the citizen-science data and the limited numbers of submissions within the study area due to privacy concerns and other factors (see explanation at the beginning of this section), this analysis is considered an exploratory analysis. It was done to review the citizen science submissions. This study suggests a trend which can support a hypothesis for future research.

Although the citizen science-based results presented in this section include data only from within the Region of Peel submissions as a base, an additional approach (*Greater Golden Horseshoe Area Average-based Approach)* with an average base from citizen science was applied as a final step to strengthen the analysis with a larger sample size. The other approach contains the Greater Golden Horseshoe Area (GGHA) average as a base for citizen science EF of consumption for the study area (Region of Peel). This is discussed in detail in the subsequent sections as the *Greater Golden Horseshoe Area Average-based Approach*. Before exploring the *Greater Golden Horseshoe Area Average-based Approach*, the relationship between EF and health and well-being using the disaggregation method (primary analysis of this component) is discussed in the subsequent section to have a better comparative understanding of the citizen science-based results discussed in this section.

Relationship between EF of Consumption (based on Disaggregation method) and Health and Well-being based on Community Health Survey-based Data

A correlation test was performed on the data to examine if there is a relationship between health and well-being and the EF of consumption. The results show a moderate positive relationship between those variables ($r = 0.47$, $p \leq 0.05$) (Figure 29). The results indicate that the model does not account for all random or other variables related to health and well-being outcomes; however, a slightly positive trend is observed. The outcomes suggest a correlation between higher health quality (encompassing health and well-being) and greater EF in consumption. This is in line with the studies from Middle Eastern and North African (MENA) countries (see Kassouri & Altıntaş, 2020).

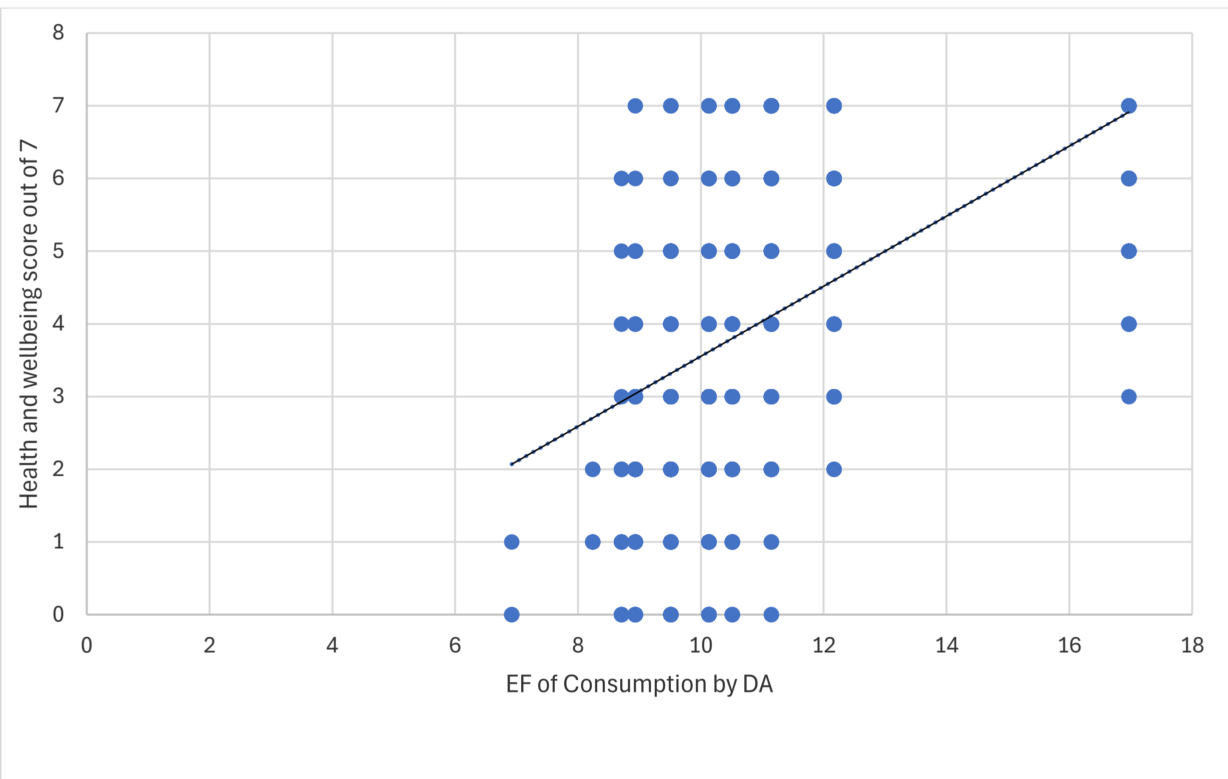


Figure 29. Correlation (r = 0.47) between health and well-being with EF of consumption, Region of Peel, 2021.

Relationship between EF of Consumption and Health and Well-being among Established Canadians versus Recent Immigrants

A correlation test was performed on data comparing established Canadians and recent immigrants to explore whether there is a relationship between health and well-being and the EF of consumption among these subpopulations.

The results show a moderate positive relationship between those variables (Figures 30 and 31). All random (or otherwise) variables related to health and well-being outcomes were not included in the model; however, a slight positive trend is evident.

Recent immigrants are likely to have higher health and well-being, with an increased EF of consumption among their peers, and the positive relationship between health and well-being and EF of consumption is stronger (r value of 0.47; Figure 31) than that of established Canadians (r value of 0.50; Figure 30). It is important to note that the data representativeness within the Region of Peel for health and well-being exploration suggests a trend, but it is a potential area for future study with more data. There are a few outlier DAs with higher EF of consumption; however, the health and well-being outcomes remain consistent with those of the other DAs.

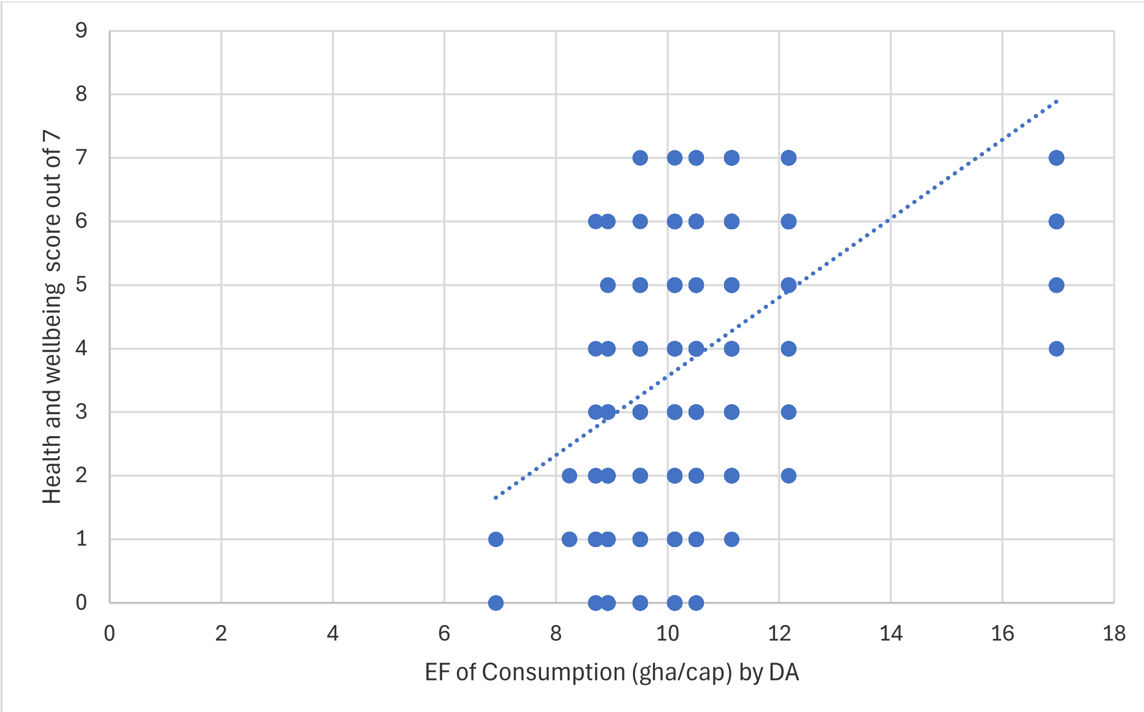


Figure 30. Correlation (r =0.50) between health and well-being and EF of consumption among recent immigrants, Region of Peel, 2021.

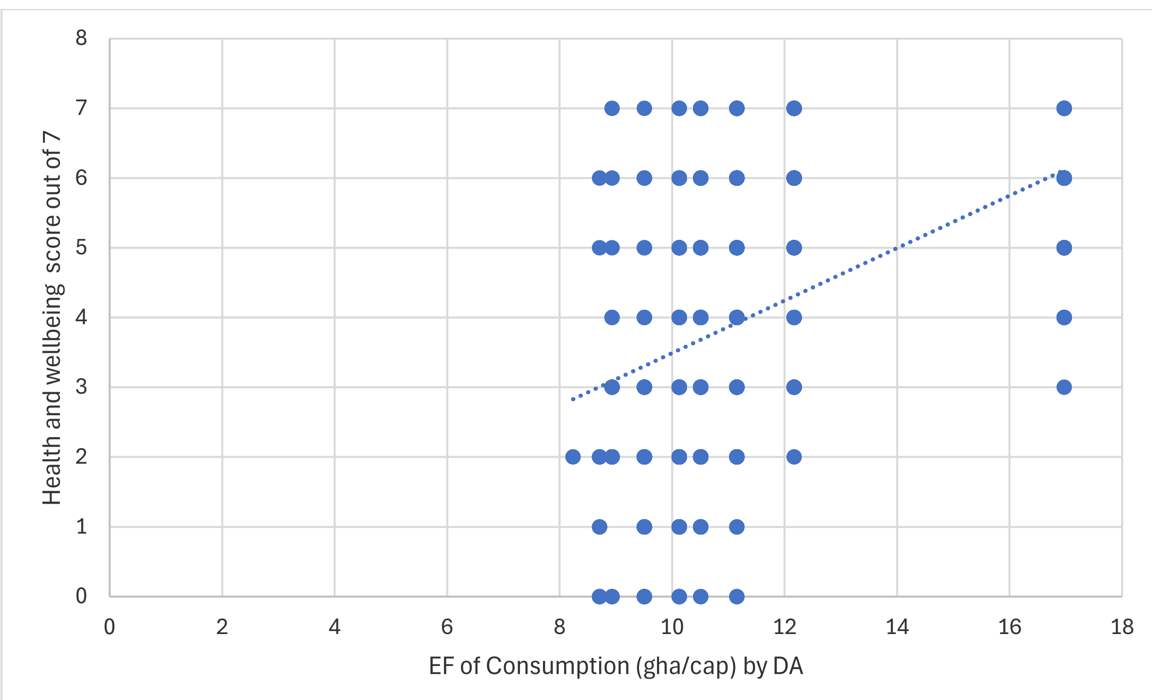


Figure 31. Correlation (r =0.47) between health and well-being and EF of consumption among established Canadians, Region of Peel, 2021.

In summary, the results show a moderate but significant ($r = 0.50$, $p \leq 0.05$, Figure 30) and $r = 0.47$, $p \leq 0.05$, Figure 31) positive relationship between the EF of consumption and health and well-being. The results reveal the relationships between health and well-being, as well as the EF of consumption, among these subpopulations. The relationship observed in this study is noteworthy, as it rather than an extreme relationship. This may be attributable to the research context, which was conducted in a developed country where substantial increases in ecological footprint (EF) from consumption are not necessarily required to achieve better health and well-being outcomes.

The next section presents the primary analysis using citizen-science data (*Greater Golden Horseshoe Area Average-based Approach*), which features a larger sample size to enhance the analysis. The other approach contains the Greater Golden Horseshoe Area (GGHA) average as a base for citizen science EF of consumption for the study area (Region of Peel).

Greater Golden Horseshoe Area Average-based Approach: *Primary results* using the Averages from the Greater Golden Horseshoe Area (GGHA) within the DAs in the Region of Peel

The previous section discusses an in-depth pattern in the Region of Peel using a raw-data approach. Although the raw data is useful, it provides a much weaker representation of the entire DA when there is only one submission for the DA. Therefore, the following analysis uses an average-based approach, using the Greater Golden Horseshoe Area (GGHA) as a base to evaluate the patterns.

GGHA was chosen as the base average for the Region of Peel due to its coverage, which includes the Region of Peel and the surrounding municipalities of generally similar characteristics. The GGHA covers approximately 32,000 km^2 and includes 109 municipalities (Hess et al., 2007). Given its expansive coverage, including semi-rural (e.g., Caledon, Erin) and urban settings (such as Mississauga and Toronto), the region's averages were used as a base for this result, with the goal of improving data representation (Figure 32).

From the statistical sampling requirements perspective, the GGHA has a total of 282 submissions, which exceeds the required minimum for a 95% confidence level with a 6% margin of error for an unlimited population (calculator used at https://www.calculator.net/sample-size-calculator.html) (Figure 33).

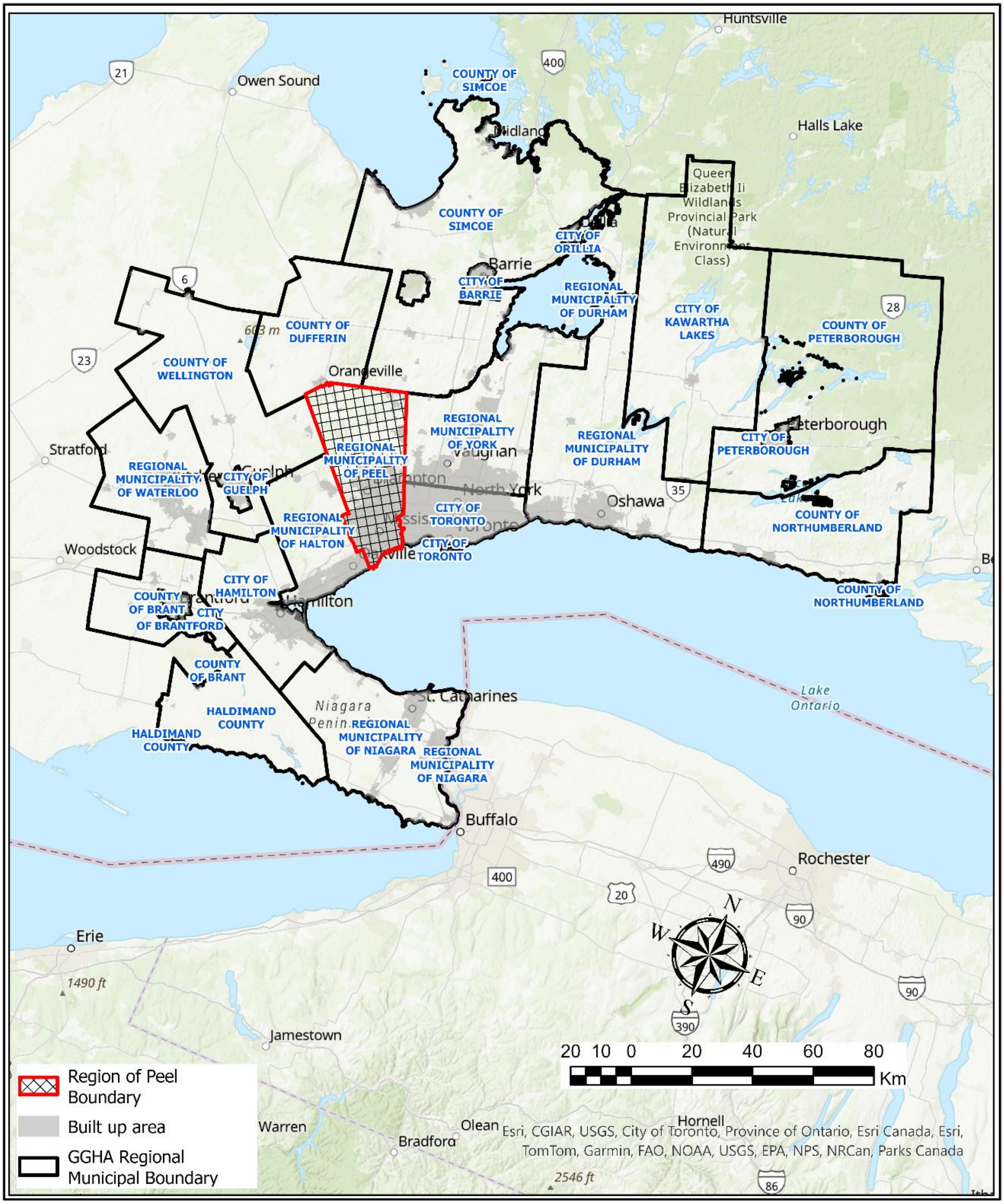


Figure 32. Greater Golden Horseshoe Area in the context of the Region of Peel.

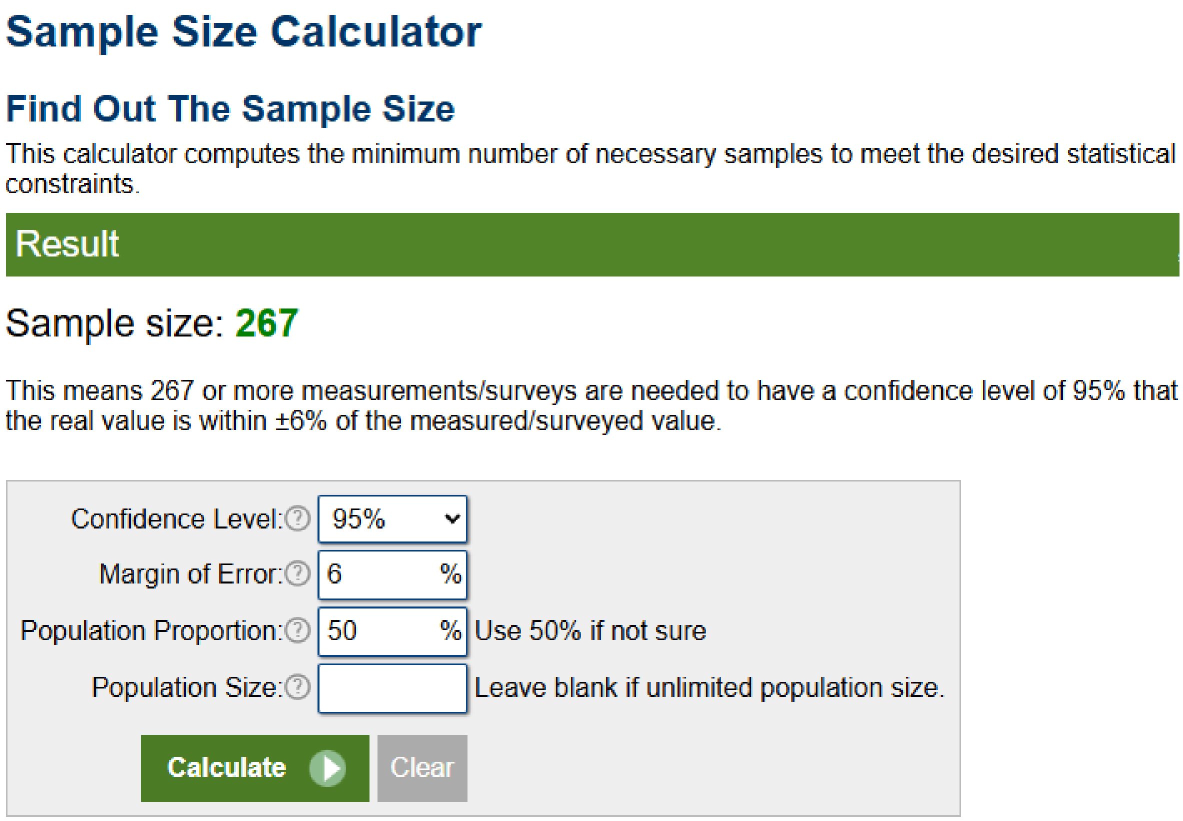


Figure 33. Sample size required for the GGHA area.

Based on the data from GGHA, the average EF of consumption was 7.51 gha/cap based on the citizen science contributed data (Table 19). The data exhibit a normal distribution, characterized by slightly negative skewness and moderate (medium-tailed) kurtosis. This indicates that the data distribution is normal, with outliers neither frequent nor rare.

Table 19. EF of consumption within the GGAH from the citizen-collected data, showing the summary of the raw data (282 submissions) calculated using ArcGIS Pro 2.9 (ESRI, 2024).

Description	Value
Average gha/cap	7.51
Min gha/cap	3.53
Max gha/cap	11.87
Standard Deviation	1.49
Skewness	-0.13
Kurtosis	-0.09

Using the average from GGHA, the income decile-based algorithm (similar to the previous DA section) was used in all DAs within the Region of Peel to translate the gha/cap EF of consumption. The following script was used to assign the gha/cap to the DAs based on income-deciles using the GGHA-based model (where ECYHNIMED refers to a median household income of the current year):

```
def reclass(ECYHNIMED):
    if (ECYHNIMED ≥ 180000):
        return 13.54
    elif (ECYHNIMED  ≥ 160000 and  ECYHNIMED < 180000):
        return 9.23
    elif (ECYHNIMED  ≥140000 and  ECYHNIMED < 160000):
        return 8.38
    elif (ECYHNIMED  ≥ 120000 and  ECYHNIMED < 140000):
        return 7.87
    elif (ECYHNIMED  ≥ 100000 and  ECYHNIMED < 120000):
        return 7.52
    elif  (ECYHNIMED  ≥ 80000 and  ECYHNIMED < 100000):
        return 7.05
    elif (ECYHNIMED  ≥ 60000 and  ECYHNIMED < 80000):
        return 6.54
    elif (ECYHNIMED  ≥ 40000 and  ECYHNIMED < 60000):
        return 6.38
    elif (ECYHNIMED  ≥ 20000 and  ECYHNIMED < 40000):
        return 6.02
    elif (ECYHNIMED  < 20000):
        return 4.90
```

Based on the script and the methodology discussed above, the results show a distribution of EF in different income deciles by DAs within the Region of Peel, created based on the GGHA average of 7.51 gha/cap (Figure 34). For example, the base average gha/cap (7.51 from GGHA) was used to estimate 15% of food-related EF of consumption within the Region of Peel (i.e.1.13 gha/cap out of 7.51 average). This 1.13 gha/cap food-related EF of consumption was applied in individual income deciles using Mackenzie's (2008) ratio. The same approach was repeated for all other categories of EF of consumption (food, shelter (housing), mobility, goods and services). After applying the income-decile-based parameters, on average, the EF of consumption is 8.30 gha/cap of the DAs within the Region of Peel.

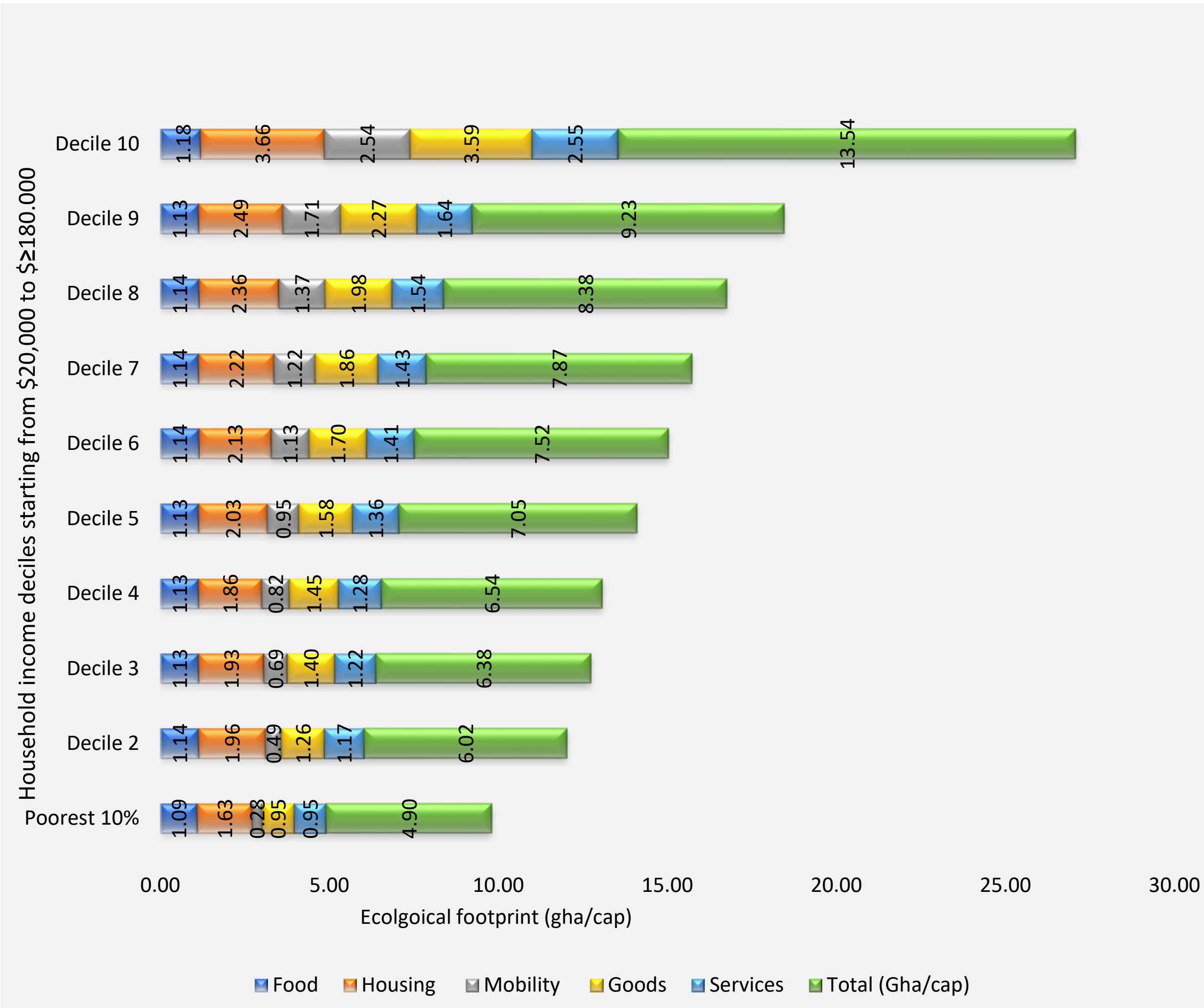


Figure 34. Distribution of EF of consumption from citizen science data augmented with the income-decile ratio within the Region of Peel, based on the GGHA average and 2021 data.

The results show a similar pattern to the previous section, that there is a higher gha/cap in south-central Mississauga and northeast Caledon, as expected, given higher incomes, bigger residences, and so forth (Figure 35).

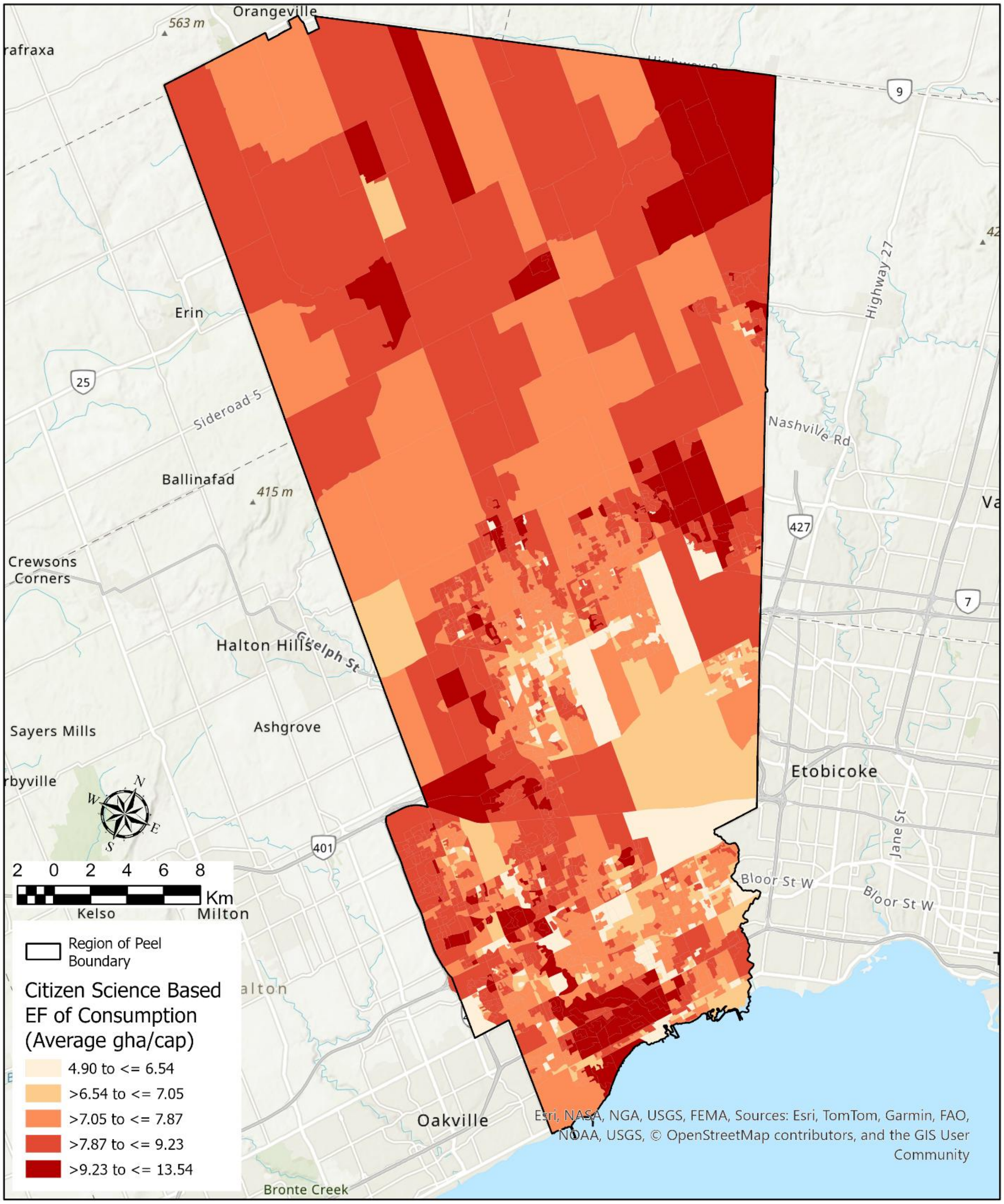


Figure 35. Citizen Science-based EF of consumption distribution in the Region of Peel based on the averages from GGHA, 2021.

Greater Golden Horseshoe Area Average-based Approach: *Primary Results*

Comparing the Disaggregation Method and Citizen Science Method within the Region of Peel using the Averages from GGHA

The citizen science data show leptokurtic kurtosis and a reasonably normal skewness (Table 20). A *t*-test was also performed by removing the outlier DAs (values > 10.3 gha/cap) to examine whether there was a difference in results between the original values and those without the outliers. The study proceeded with all values because there was no significant difference.

Table 20. Data distribution within the Region of Peel using average citizen science data from GGHA.

Description	**Value**
Average gha/cap	8.30
Min gha/cap	4.90
Max gha/cap	13.54
Standard Deviation	1.70
Skewness	2.14
Kurtosis	4.31

A *t*-test and Cohen's *d* were used to determine whether there was a significant difference in EF of consumption from two methods: the disaggregation method (Kuzyk, 2011) and the citizen science-based method within the Region of Peel using GGHA averages.

A two-sample *t*-test was performed to compare the EF of consumption in this primary analysis (using GGHA average) between disaggregation method and citizen science method. There was a significant difference in EF of consumption between disaggregation method (M=11.01, SD=1.96) and citizen science method (M=8.30, SD=1.70); t(df)=1745, p =0.00E+00 (Tables 21 and 22).

Cohen's *d* test was used to estimate the magnitude of the difference between the methods. *The primary results (with GGHA averaged benchmark) based on Cohen's d test show that they are significantly different (p ≤ 0.05), with a large effect size (d = 1.48, 95% CI [1.41, 1.56])* (Table 21). In other words, in this study *I reject H01 and conclude that the EF of consumption differs significantly between the disaggregation and citizen science methods*. Therefore, this maybe useful to use as a coefficient to calibrate the EF of consumption at the local level.

For the *t*-test, the "two-sample unequal variance" type was selected in the formula. This *t*-test accounts for unequal variance, based on Welch's *t*-test. The F-test results (Table 22) indicate significant differences in variances ($p \leq 0.05$); therefore, data with unequal variances were used for the *t*-test. The test results without the outliers also showed $p \leq 0.05$. Given the higher number of DAs and no significant difference between the results (with or without those DAs), those DAs with higher gha/cap (or outliers) were also included in further analyses.

Table 21. Results of Cohen's d test and t-test between Kuzyk's disaggregation method versus citizen science-based GGHA average for the Region of Peel, 2021.

Cohen's *d* test		***t*-test**	
Pooled SD (equal n)	1.83	T-test results (2-tailed) P value	0.00
Cohen's d	1.48	Variance (disaggregation method)	3.83
Standard Error of d	0.04	Variance (citizen science method)	2.89
95% Confidence Interval (L)	1.41		
95% Confidence internal (U)	1.56		
Effect size	Large		

A Cohen's *d* = 1.48 (95% CI [1.41, 1.56]) indicates a large difference in the estimation of EF between the disaggregation method and the citizen science method. This means the disaggregation method's EF estimate is 1.48 standard deviations higher than that of the citizen science method. This large effect indicates that the groups differ, representing a meaningful difference. The results from the 95% confidence interval show that 95% of those studies would produce an effect size between 1.41 and 1.56, indicating that we are 95% confident that the true difference between the groups lies within the range. In practice, because both upper and lower bounds are positive, we can confidently say that there is a positive difference between the two groups and that it is statistically significant at the 95% confidence level.

Table 22. F-test results showing unequal variances between disaggregation and citizen science methods based on GGHA averages used in the Region of Peel, 2021.

Description	Disaggregation Method	Citizen Science Data
Mean	11.01	8.30
Variance	3.83	2.89
Observations	1746.00	1746.00
df	1745.00	1745.00
F	1.32	
P(F<=f) one-tail	0.00	
F Critical one-tail	1.08	

Based on the results from the two methods, Table 22 shows the averages in DAs within the Region of Peel.

Correlation Test and Linear Regression Test using GGHA Averages in the Region of Peel

A correlation test was conducted to examine the relationship between the patterns of data from the disaggregation as per Kuzyk (2011) and citizen-science methods using GGHA. Pearson's correlation results, which measure the strength and direction of the linear relationship, showed that both datasets are strongly positively correlated ($r = 0.99$). The R^2 value of 0.99 for those two variables indicates that it accounts for 99% of the variability in estimating the EF of consumption per capita (Figure 36). The linear regression results with a strong R^2 (0.99) showed that for every 1 gha/cap increase in citizen science-based results, a 1.15 gha/cap increase occurs based on the disaggregation method (see Figure 36; y =1.15x+1.49 with R^2 of 0.99).

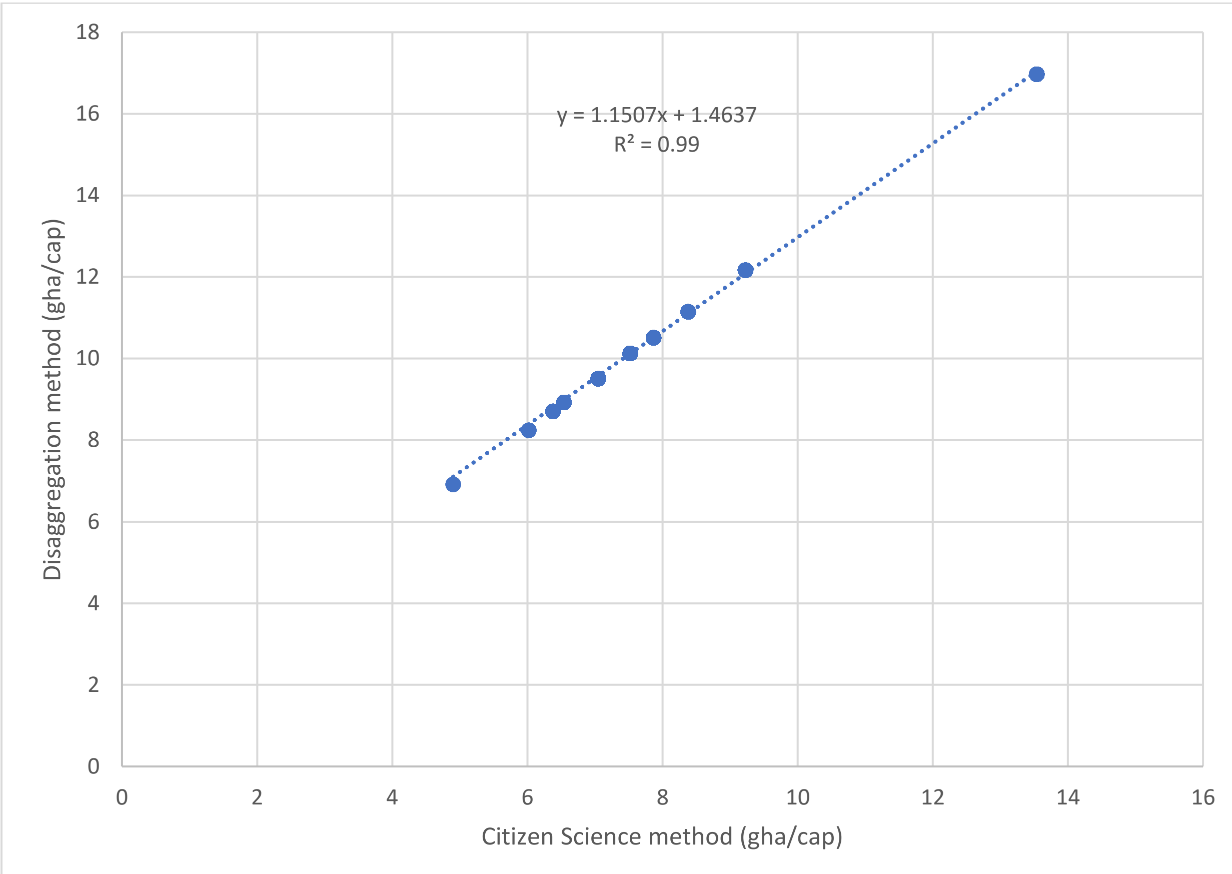


Figure 36. Correlation (r = 99) and R^2 results comparing the disaggregation method versus citizen-science-based data, augmented based on income-deciles, 2021.

The results from the *t*-test discussed earlier, and the correlation show that there is a strong positive correlation in the patterns of the methods; however, the results from those two methods are significantly different.

A comparison of the disaggregation methods (Kuzyk, 2011) and the citizen-science method yields different results when evaluated using an average-based approach versus a linear regression approach. This finding indicates that we can use a coefficient from the citizen science-based results to better reflect the local reality of EF of consumption. For example, using the average comparison, for every 1 gha/cap in citizen-science-based results, the direct comparison showed that 1.33 gha/cap (11.01 divided by 8.30) is estimated from the disaggregation method (Table 22), whereas the linear regression method showed that for every *1 gha/cap increase in citizen science-based results, a1.15 gha/cap increase occurs based on the disaggregation method* (Figure 36). In other words, the disaggregation method (Kuzyk, 2011) consistently showed higher EF values for consumption than the citizen science method in both approaches (average-based comparison and linear regression). In other words, citizen science can detect relative differences at the local level but yields lower EFs than the disaggregation method. Given that the local differences are captured using citizen science, the coefficient from this study can be applied to calibrate the local EF of consumption. *This is a key finding of this study.*

In comparison, using the raw data from the Region of Peel in the previous section *(Region of Peel Raw Data Only Approach:* without using the GGHA average as a base), the direct comparison showed that for every 1 gha/cap EF of consumption from the citizen science-based data results in 1.29 gha/cap (Table 17: 11.01 divided by 8.52) EF of consumption from the disaggregation method (Kuzyk, 2011). Similarly, the linear regression method showed that every 1 gha/cap EF of consumption from the citizen science-based data results in a 1.10 gha/cap EF of consumption from the disaggregation method (Figure 28). Both results show a similar pattern in both the exploratory (*Region of Peel Raw Data Only Approach*) and primary (*Greater Golden Horseshoe Area Average-based Approach)* analyses.

EF of Consumption for Established Canadians versus Recent Immigrants based on the GGHA average for the Region of Peel

To identify differences between established Canadians and recent immigrants, the original rule (used earlier in the study) was applied to determine which DAs referred primarily to established

Canadians, and which to recent immigrants. Of the 598 DAs within the Region of Peel attributed to established Canadians, the average EF of consumption based on citizen science data was 8.73 gha/cap, and recent immigrants had a slightly lower EF of consumption at 8.07 gha/cap (Table 24). It is similar to the disaggregation method by Kuzyk (2011) (Table 14), which showed 11.51 gha/cap for established Canadians and 10.75 gha/cap for recent immigrants.

Statistical Test of Significance based on GGHA average for the Region of Peel

A *t*-test and Cohen's *d* were used to determine whether there was a significant difference in EF of consumption between established Canadians and recent immigrants, and to estimate the magnitude of the difference *using the citizen-science method. The results show that they are significantly different ($p \leq 0.05$), with a small effect size ($d = 0.39$, 95% CI [0.29, 0.49])*(Table 23). In other words, *I reject $H0_2$ and conclude that the recent immigrant communities EF are different from those of established Canadians.*

Cohen's *d* of 0.39 (95% CI [0.29, 0.49]) indicates a small effect size in EF between established Canadians and recent immigrants (Table 23). Established Canadians exhibited an EF 0.39 standard deviation higher using the citizen-science method. The communities differ statistically, but the effect is small. The study had a fairly small sample size. Although a larger sample size doesn't necessarily impact the effect size directly, it might be possible to demonstrate a medium-to-large effect size by reducing data noise if the sample size were more representative. Although the effect size is small in this comparison, it could be of importance, as Ivarsson et al. (2013) argue that the context of the effect size (small or large) is very important, regardless of its size, with an example highlighting how even a slight recovery of a patient is critical. The results from the 95% confidence interval show that 95% of those studies would produce an effect size between 0.29 and 0.49, indicating that we are 95% confident that the true difference between the groups lies within the range. In practice, because both upper and lower bounds are positive, we can confidently say that there is a positive difference between the two groups and that it is statistically significant.

Table 23. Results of Cohen's d test and student's t-test (comparing recent immigrants versus established Canadians), Region of Peel, 2021.

Cohen's *d* test		***t*-test**	
Pooled SD (unequal n)	1.67	T-test results (2-tailed) P value	6.5E-12
Cohen's d	0.39	Variance (recent immigrants)	2.10
Standard Error of d	0.05	Variance (established Canadians)	4.11
95% Confidence Interval (L)	0.29		
95% Confidence internal (U)	0.48		
Effect size	Small		

For the *t*-test, the "two-sample unequal variance" type was selected in the formula (type 3 in Excel-based formula). This *t*-test, accounts for unequal variance, based on Welch's *t*-test. The F-test results (Table 24) show significant differences ($p \leq 0.05$) in the variances; therefore, data with unequal variances were used for the *t*-test.

Table 24. F-test results between the established Canadians and recent immigrants (using the GGHA average for the Region of Peel), 2021

Description	**Established Canadians: Total EF of Consumption Per Capita**	**Recent immigrants: Total EF of Consumption Per Capita**
Mean	8.73	8.07
Variance	4.16	2.09
Observations	598.00	1148.00
df	597.00	1147.00
F	1.99	
P(F<=f) one-tail	0.00	
F Critical one-tail	1.12	

Relationship between EF of Consumption based on Citizen Science data (from GGHA average for the Region of Peel) and Health and Well-being

Using the EF of consumption from the citizen science data that was applied to the Region of Peel in the previous section (based on the GGHA average), a correlation test was performed with the health and well-being data from the Canadian Community Health Survey, as discussed in previous sections (Canadian Index of Wellbeing, 2024; Environics Analytics, 2023). It was done to examine whether there was a relationship between health and well-being and the EF of consumption. *The results show a moderate positive relationship between those variables (r = 0.46 and $p \leq 0.05$)* (Figure 37). The results indicate that the model does not account for all random or other variables related to health and well-being outcomes; however, a moderate positive trend is observed. The outcomes indicate that there is an association between higher health quality (encompassing health and well-being) and an increased EF of consumption. This is in line with the studies from Middle Eastern and North African (MENA) countries (see Kassouri & Altıntaş, 2020).

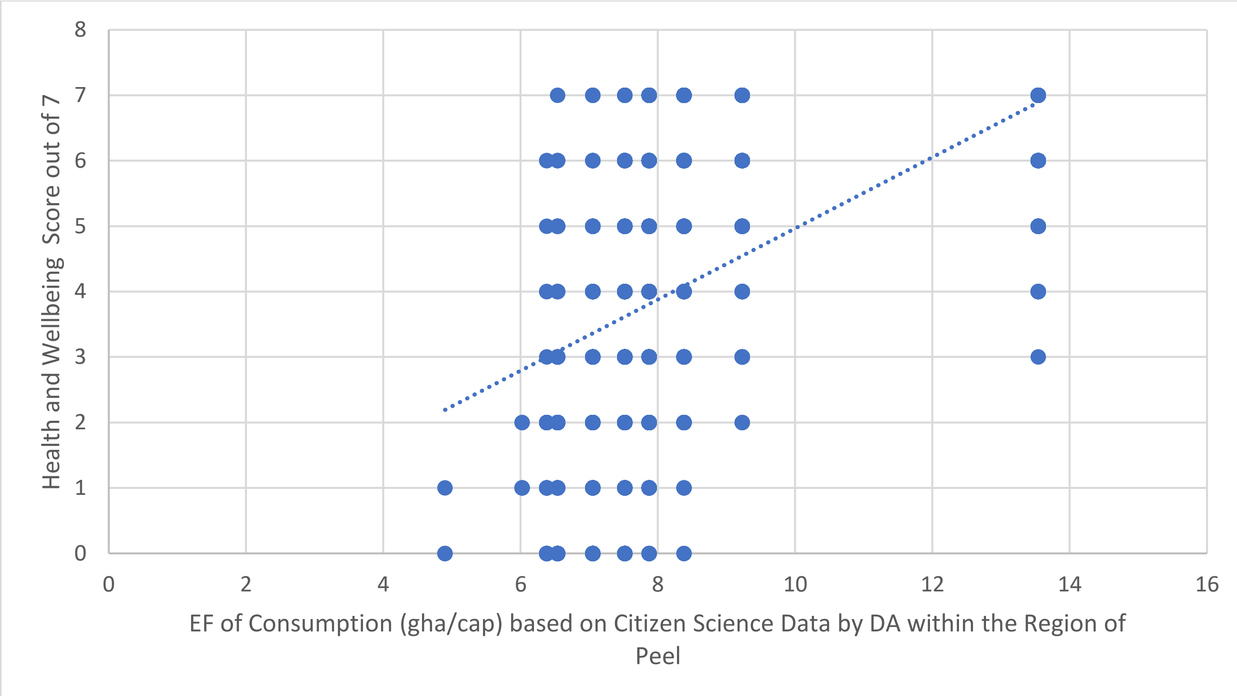


Figure 37. Correlation (r = 0.46) between health and well-being with EF of consumption within the Region of Peel, 2021 (using the citizen science data).

Relationship between EF of Consumption using Citizen Science data and Health and Well-being among Established Canadians versus Recent Immigrants based on GGHA average for the Region of Peel

A correlation test was performed on data comparing established Canadians and recent immigrants to explore whether there is a relationship between health and well-being and the EF of consumption in the citizen science data for these subpopulations. *The results show a moderate positive relationship between those variables (Figure 38 and 39).*

Based on the result from this study, the recent immigrants are likely to have higher health and well-being, with an increased EF of consumption compared to established Canadians, which is in line with the healthy immigrant effects related studies in the past (Brabete, 2017; Ng, 2011). The positive relationship between health and well-being and EF of consumption is slightly stronger among the recent immigrants (r value of 0.47; Figure 39) than that of established Canadians (r value of 0.49; Figure 38). The results are in line with the general population and overall health and well-being from the MENA countries (Kassouri & Altıntaş, 2020). There are a few outlier DAs in which the EF of consumption is higher than that of the majority; however, the health and well-being outcomes remain consistent with those of the other DAs.

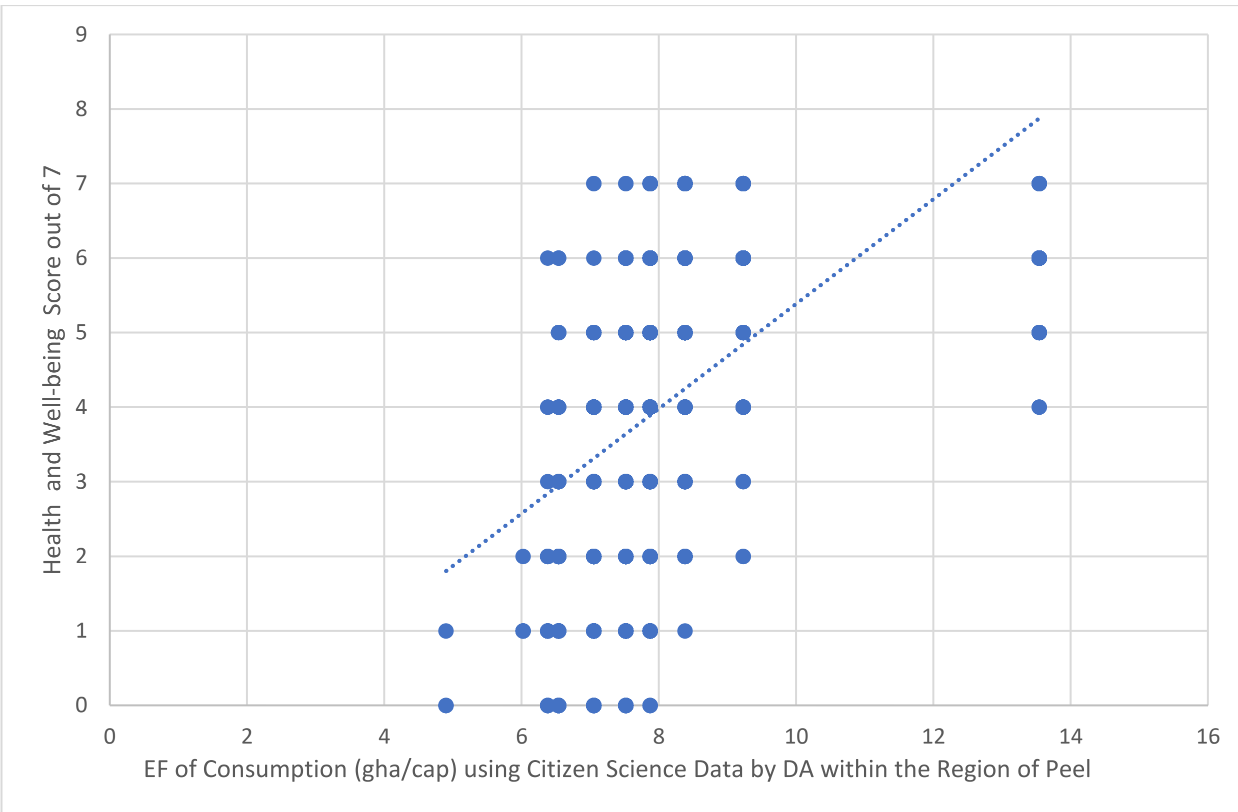


Figure 38. Correlation (r = 0.49, p ≤ 0.05) between health and well-being and EF of consumption among recent immigrants in the Region of Peel, 2021.

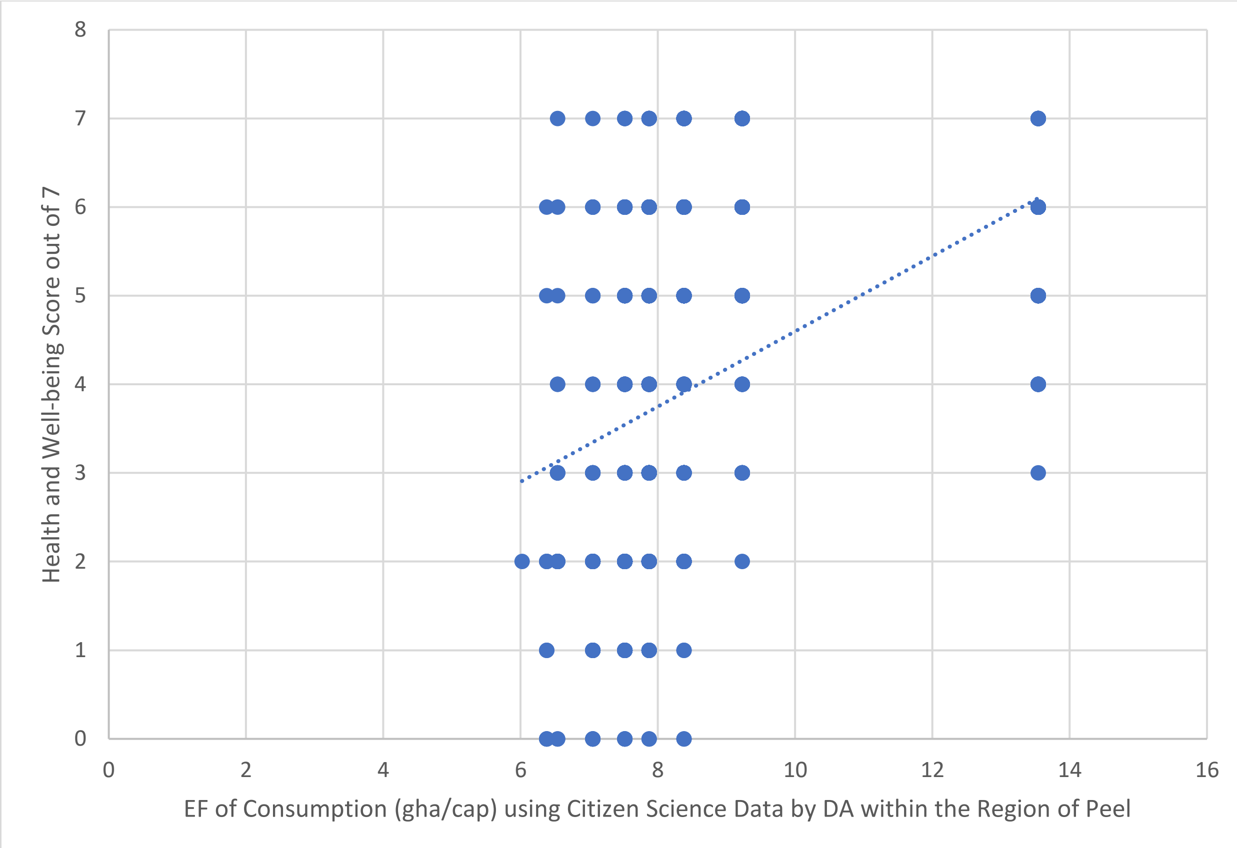


Figure 39. Correlation ($r = 0.47$, $p \leq 0.05$) between health and well-being and EF of consumption among established Canadians in the Region of Peel, 2021.

In summary, the results show that there is a moderate but significant ($r = 0.49$, $p \leq 0.05$ (Figure 38) and $r = 0.47$, $p \leq 0.05$ (Figure 39)) relationship between the EF of consumption from the citizen science data and health and well-being among subpopulations.

Discussion and Summary

Confirmation of Hypotheses

The results from this study provided evidence to reject both null hypotheses, indicating meaningful differences in both methodological EF estimates and between population groups. Firstly, the citizen science approach yielded significantly different (lower) EF values than the traditional top-down method. Secondly, recent immigrants, as a group, demonstrated a statistically lower EF than the established Canadians in the Region of Peel. These findings validate the alternate hypotheses and align with expectations that methodologies capturing EF of consumption differently produce different results, and demographic factors (such as duration of residency/integration) can influence consumption patterns. This proof-of-concept study concludes that, given that citizen science captures the granularity of local reality, it can serve as a basis for calibrating reporting of EFs of consumption at the local level.

Interpretation of EF Discrepancies (Citizen Science versus Disaggregation method)

The citizen-science-based data consistently under-reported the EF of consumption by about 25–30% relative to the disaggregation method. There are a few plausible explanations for this gap:

- *Potential Sampling Bias:* Participants in the survey were likely more environmentally conscious or aware, given that this project was published as a research project from a University's environmental program. This group might include people who are likely to be interested and potentially concerned about environmental issues, which could be reflected in their lifestyle choices. This group is likely to have somewhat lower consumption (e.g., more likely to use public transit and avoid waste) than the average. Thus, their footprints could naturally be lower.
- *Underestimation or Under-reporting:*Even willing participants might unintentionally or intentionally under-report specific consumptions – for example, not accounting for all goods purchased. The conversion factor we used (0.06) was based on national averages; if survey respondents systematically rated themselves "better" than they actually are, the converted EF would come out low.

- *Non-representative sample:*156 local samples out of a population of over 1.3 million in Peel is a tiny fraction. If the sample size allowed, the Region of Peel-based stats would have been preferred; however, the GGHA provided a better representative sample size despite having a larger area. Therefore, the primary result uses the GGHA base (average) as a foundational statistic for this study. It is likely that these individuals are not fully representative of the region's demographic and economic diversity. For instance, perhaps fewer high-income residents participated. That would skew the citizen EF of consumption as high-income (and likely high-EF) households' behaviour might be missing from the sample.
- *Scope of data collected:* The citizen science project may not capture certain aspects of consumption that the EF calculation includes (like indirect goods/services footprint). Participants answered questions within a limited framework, possibly missing some consumption categories, which were later adjusted to reflect the average consumption. The impacts of imports and domino effects from them might not have been adequately considered, leading to a smaller self-calculated footprint.

Despite these differences in magnitude, it is important to note that the spatial pattern of consumption was well captured by citizen science data (r ~ 0.99). This means such community-collected data could reliably indicate which neighbourhoods are higher or lower than others, which is valuable for local engagement and planning. The citizen science approach is thus promising for *mapping relative differences* and raising awareness (Bonney et al., 2009, 2014; Cohn, 2008) even if it *underestimates absolute EF*. For policymaking, this suggests that citizen science can supplement data by providing granular insights quickly; however, for carbon accounting or setting targets, a calibration or adjustment factor may be needed to align with known totals.

Recent Immigrants versus Established Canadians' Consumption

The study revealed that recent immigrants have, on average, a ~0.7 gha/cap lower footprint than established Canadians, consistent with the literature on consumption acculturation (Choi et al., 2009). New immigrants often arrive with different consumption habits, potentially more modest, due to either lower initial income, different cultural norms (e.g., diets with lower meat content, less living space per person), or simply being in a life stage with fewer possessions (many are young families or students). Over time, as immigrants settle and incomes rise, their consumption may increase, approaching local norms (a phenomenon observed in various studies, where immigrants' environmental footprints converge with those of native-born residents after years or generations) (e.g. Brabete, 2017; Ng, 2011). This suggests that exploring immigrants at different time intervals, such as 10-year and 15-year intervals, could be valuable for future research (see more details in *Chapter 7).*

The results of the study suggest that in the Region of Peel, this convergence is well underway, with the difference on the order of 7%. That implies many recent immigrants have already adopted local consumption patterns to a large degree, or that the diversity of immigrant experiences (some are high-skilled, high-income arrivals, others are not) averages out to near the regional norm. The statistically significant difference indicates a real effect – perhaps first-generation immigrants still maintain slightly different lifestyles (e.g., more communal living, less initial use of personal vehicles).

It is also notable that simply looking at immigrant-centric vs non-immigrant-centric neighbourhoods (50% cut off) showed a minimal difference in EF (10.9 vs 11.2). So if immigrants are spread out among the population, their presence does not strongly lower a community's footprint unless they form a dominant supermajority. This suggests that local leaders should consider immigrant status alone as a minor determinant of consumption at the community level; rather, economic status is likely more significant. In the Region of Peel, many immigrant-centric areas are also middle-class suburbs (hence similar EF). The clusters of slightly lower EF might coincide with areas where recent immigrants cluster in more urbanized, multi-family housing settings, inherently curbing per capita consumption.

Health and EF: A Sustainability Conundrum

The moderate positive correlation between EF and health/well-being presents a challenge: higher consumption (often facilitated by higher income) can enhance material living conditions and access to healthcare resources, thereby correlating with better self-reported health. This aligns with findings in development economics and studies, such as Kassouri and Altıntaş (2020), in MENA countries. On the other hand, rising consumption and emissions accompany improved life expectancy and health, at least up to a point. In our context, communities in Peel with very high EFs are usually wealthier (e.g., large homes in Caledon or Mississauga) – these also have higher rates of people saying they are in very good health. Conversely, lower-EF communities, which tend to be lower-income or more recent immigrants, might report slightly worse health outcomes due to more stressors or less access to healthcare, etc..

This creates a policy conundrum: efforts to reduce the community EF (encouraging less energy use, fewer cars, smaller homes) might impact the efforts to maintain or improve public health and well-being. The correlation we found is not extremely strong (r ~0.5), meaning many low-EF areas still have good health, and some high-EF areas have only average health. Therefore, sustainable living and health and well-being are not necessarily mutually exclusive. Ideally, communities could seek ways to improve health and well-being without proportional increases in consumption. For example, promoting active transport (walking, cycling) can improve health while lowering EF, a win-win that could break the correlation. The study and data provide a snapshot, but they suggest that simply cutting consumption in high-EF areas, if done in ways that reduce comfort or perceived well-being, may face resistance. The challenge is to find smart solutions (like energy efficiency, social services, community health programs) that allow EFs to shrink without harming quality of life.

Citizen Science Contributions and Engagement

The qualitative feedback from the citizen science project (participants) indicates strong personal motivation to act sustainably and be healthy. This is a positive sign of community engagement – those who participated are likely to be ambassadors of sustainable lifestyles. Their optimistic self-view indicates that people want to see themselves as part of the solution. From a municipal perspective, leveraging this existing enthusiasm is key. For instance, community challenge programs, local ecological footprint pledges, or citizen monitoring projects could harness these individuals to spread awareness. However, we must also reach beyond the "low-hanging fruit" of already converted citizens. The underrepresentation of certain groups (e.g., newcomers who are shy to participate or affluent folks who may not engage in such surveys) needs to be addressed in future citizen science efforts to provide a fuller picture.

Summary of the Results

In this chapter, I explored results and analyses that involved applying an EF disaggregation method to estimate the EF of consumption at the local level using national data. I investigated the application of the ratio adjustments to reflect current data. I explored the Dissemination Area (DA) level EF of consumption and how it differed between established Canadians and recent immigrants. In conclusion, this chapter summarizes that the analysis of citizen-science-based data shows how it can be used to enhance the estimation of local EF of consumption and that there is a difference in EF of consumption between established Canadians and recent immigrants. I also explored whether there was a relationship between health and well-being and EF of consumption among those sub-populations in this chapter. The next chapter reflects on the approaches applied in this study, its limitations, and future research opportunities.

Chapter Six: Summary

This proof-of-concept study examined the application of a disaggregation method to scale down national-level ecological footprint (EF) data and assessed the potential of citizen science-based data to enhance the estimation of local EFs of consumption across different sub-populations. The study demonstrated the feasibility of using data at the community level. Additionally, it examined the potential relationship between the EF of consumption and indicators of health and well-being within these sub-populations.

A key objective was to address the methodological challenge of disaggregating EF of consumption data, which is traditionally reported only at the national scale, to a more granular local level. To achieve this, the study applied an existing disaggregation approach, updated it with the most recent available data, and compared its results with those derived from citizen science-based data collection. Given the diverse sources and origins of national EF data, the analysis evaluated the alignment between the disaggregation approach and citizen science data, and the potential to improve local EF estimates by incorporating citizen science contributions. Furthermore, the study compared EF of consumption between recent immigrants and established Canadians, with particular attention to the interplay between EF, health, and well-being outcomes.

Based on the findings from this study, it was determined that Kuzyk's (2011) disaggregation approach for scaling the national ecological footprint (EF) from consumption data to local levels requires an update to its foundational data model for consumption patterns. Specifically, the underlying base model of consumption patterns, initially developed by Mackenzie et al. (2008), should be updated to more accurately reflect current Canadian consumption behaviours.

In this study, the base model was revised using the most recent data from Statistics Canada. Comparative analyses between the existing disaggregation method (Kuzyk, 2011) and the citizen science-based approach revealed broadly similar trends and a strong positive correlation (Table 17); however, statistically significant differences were observed between the two methods (Table 16). Notably, the citizen science-based results showed consumption patterns more closely aligned with the national average than those generated by the Kuzyk (2011) approach.

It is essential to recognize that the citizen science framework is grounded in the national average, assuming that all participants initially represent an “average” Canadian consumption profile until individual-level data are collected and analyzed. Furthermore, the citizen science data do not employ stratified sampling, which should be considered when interpreting the results. Additional discussion of the citizen science methodology, its applications, and limitations is provided in Chapter 3 of this study.

Reflections on the Approaches and Original Contributions

This study examined an existing method, updated it with new consumption data, applied a ratio derived from the existing method, calculated the national EF of consumption data at the local level, and employed various approaches to motivate citizens to participate in data collection. Through those processes, the following methodologies are some of the key original contributions of this study:

i. Disaggregation method and usage of proxies and ratio updates with recent data;
ii. Comparison of EF of consumption between recent immigrants and established Canadians in this poof of concept study might be helpful to for immigration and long-term policy planning at different scales;

iii. Community health and well-being analysis using eight indicators within the healthy population domains that can be useful to help make plans for long-term health and well-being for authorities;

iv. Creation of a new method to convert the citizen science data into EF of consumption, first at the national level and then applied at the local level.

A key finding of this study is that citizen science data can be used to estimate the EF of consumption at the local level. Given that nine out of the citizen science principles were addressed, this approach differs from a regular survey approach (Table 1, Chapter 3). There are a few approaches to estimating the EF of consumption at the local level. However, these approaches have either complex data requirements, require commercial (paid) data, or are very difficult to obtain from national or international governments and private sources (such as for input-output analyses). While all approaches have their pros and cons, this citizen science-based method may be better suited to bringing practical applications to the local level. This could support work from planning and policy-based decisions to simple awareness campaigns about the EF of consumption. Additionally, the approach can be applied at the local level in combination with Kuzyk's (2011) method, where the citizen-science approach serves as a cross-check to validate whether the models' results accurately reflect what citizens claim their consumption to be.

The citizen science method differed significantly from the disaggregation method per Kuzyk (2011) when compared with various approaches, including direct raw submission, the average-based approach (primary analysis, GGHA) based on income-decile argumentation within the study area, and the linear regression methodology. However, the trend was consistent in all those approaches (i.e. 1 gha/cap in the citizen science approach resulted in 1.29 gha/cap (*Region of Peel Raw Data Only Approach*) or 1.33 gha/cap (*Greater Golden Horseshoe Area Average-based Approach)* EF of consumption in the disaggregation method. Whereas 1 gha/cap from the citizen resulted in, using the linear regression method, 1.10 gha/cap (*Region of Peel Raw Data Only Approach*) or 1.15 gha/cap (*Greater Golden Horseshoe Area Average-based Approach*) EF in the disaggregation method, respectively (Figure 28, chapter 5; Figure 36, chapter 5). To strengthen the analysis with larger sample sizes, the GGHA average (*Greater Golden Horseshoe Area Average-based Approach*, primary analysis) was employed as a final approach. This suggests that it is feasible to estimate the EF of consumption by combining the established method with a ratio from this study.

To conclude, a more effective comparison between the citizen science approach and the disaggregation methods (Kuzyk, 2011) would be to compare "apples to apples" using the citizen science results based on the GGHA average as a baseline (primary results). All DAs in the Region of Peel had an EF of consumption calculated using the citizen science method, using the average base from GGHA, which was augmented by an income-decile-based approach. When compared using average comparison versus linear regression tests, the results exhibit two different values. For example, using the average comparison, for every 1 gha/cap in citizen science-based results using the GGHA average as a base for the study area (primary analysis or Greater Golden Horseshoe Area Average-based Approach), the direct comparison showed that 1.33 gha/cap (11.01 divided by 8.30) is estimated from the disaggregation method (Table 22). In comparison, *the linear regression method showed that for every 1 gha/cap increase in citizen science-based results, a1.15 gha/cap increase occurs based on the disaggregation method*

(Figure 36). Both of those results are similar in pattern, although a linear regression method with the GGHA average as a base constitutes a larger foundational data.

These results suggest an opportunity to adjust the data from the disaggregation method using citizen science data that reflects local communities. To enhance data quality, it may be possible to run an algorithmic disaggregation of EF data from a national or regional database to the local level and apply the ratio (based on the citizen science results), as long as the study area comprises a similarly urbanized area similar to the current study area. It is essential to note that if a citizen science approach is desired but the resources and time constraints do not permit conducting the entire study, the consumption pattern may be affected by sampling and representativeness (e.g., self-selection) and may need to be adjusted/reflected over time, based on nationally published data. After all, a variety of factors influence the EF of consumption.

In terms of the factors influencing a higher EF in the study area, the results show a strong positive correlation with the higher median income decile (after tax). This means the EF tends to be higher in higher-income neighbourhoods, which aligns with some previous studies conducted at national or regional levels (Kassouri & Altıntaş, 2020). The studies by Tsuchiya et al. (2021) to scale down and evaluate EF at the prefectural level from national data using EE-MRIO-based GTAP 9 model also resulted in a similar finding: prefectures with higher average incomes had higher EF per capita. These findings are in line with some other studies using similar methods, such as the one by Baabou et al. (2017). There could be many factors influencing this component, given that higher-income families are likely to consume more through different means, such as multiple vehicles per household for transportation, larger homes, and greater consumption of exotic foods, which ultimately contribute to a higher EF of consumption.

The relationship between the EF of consumption and health and well-being was a moderate positive correlation (Figure 37; $r = 0.46$ and $p \leq 0.05$). Although the correlation was moderate but statistically significant, the results showed that higher health and well-being were associated with higher EF of consumption. This may be related to the original findings that a higher median income was correlated with a higher EF. This is likely because families with a higher EF can afford to take care of their health and well-being from a financial point of view, which may include paying for and going to the gym often, eating healthy food, going on vacations for mental well-being, seeing family doctors on time or more frequently, etc. However, it is important to note that studies have shown a "healthy immigrant effect" among immigrants, indicating that immigrants have better health than the established population of the country (Brabete, 2017). Research also concluded that, over time, the health status of immigrants deteriorates to a similar level as that of the established population. This is why the current study explored the differences between recent immigrants and established Canadians.

Limitations of the Study

Although the results provide a broader understanding of the EF of consumption, health, and well-being, as well as sub-population-based differences, this study has some limitations. The study includes income-decile-based and expenditure-based methods to disaggregate EF of consumption data at the local level. Many other approaches, such as geographically weighted (GW) models, utilize correlations among variables like GDP and population density (Luo et al., 2019). According to some studies, the EF is not necessarily a fully reliable measure of sustainability (Graymore et al., 2010; Kuzyk, 2011; Stiglitz et al., 2008; Yue et al., 2006), especially at sub-national or local scales, where it overlooks the environmental effects associated with imports and exports. Some other models require intensive data gathering from multiple government entities and may be limited to only a few components of the EF, such as carbon (Luo et al., 2019). The basis for the model of EF of consumption in this study is the median-income-based metric (Kuzyk, 2011) and a consumption pattern ratio for EF components, as per Mackenzie et al. (2008). This could pose a limitation since we are relying on the median household income to estimate the EF of consumption. Other potential variables, such as regional consumption patterns, may have been ignored. However, it remains a standard method adopted in the industry, as it is easy to use and provides a practical approach to estimating the EF of consumption at the local level (Kuzyk, 2011). Some of the key limitations in this study are grouped in the following categories:

1. ***Data representativeness:*** As noted in the discussion sections, the citizen science data had a limited sample size and biases. While we used statistical methods to extend its reach, those estimates are only as good as the assumptions, specifically, that income-based behaviour patterns apply equally to citizen data, which might not always be the case.
2. ***Geographic Aggregation****:* DAs are an average over a few hundred people. Within a single DA, there could be a mix of wealthier and poorer households, immigrants and non-immigrants. That intra-DA variation is not captured well. We assume each DA is relatively homogeneous (which, in some cases, such as suburban census tracts, is reasonably true and accurate, but not in others, where it may blur differences).
3. ***Temporal Differences****:* The EF is calculated for approximately 2021 consumption data, whereas health survey data might be from 2019 or an aggregate period. It was assumed to be stable over the short term. Additionally, recent immigrants were defined using a 20-year window; some in that category arrived 15–20 years ago and may no longer follow "newcomer" patterns, yet our coarse grouping treats them the same. It would be

important to note that some sources define recent immigrants as those who moved to Canada in the last 5 or 10 years (Gilkinson & Sauve, 2010; Statistics Canada, 2025). A future comprehensive study has the opportunity to compare time-series analyses to explore differences with established Canadians.

4. ***External Validity****:* These findings are specific to the Region of Peel. Other regions with different immigrant compositions or urban forms might see different relationships. The immigrant population in the Region of Peel is relatively high and diverse, which might lessen differences (versus a scenario in which immigrants are mostly low-income manual labourers or, conversely, mostly high-income professionals).

Acknowledging these limitations, we need to interpret trends carefully. For instance, while I found a significant difference in EF between groups, the absolute difference was small, indicating partial convergence in lifestyles. Moreover, while I noted the correlation of citizen and official EF patterns, I caution that the absolute values from citizen data should not be used for inventory or carbon budgeting without adjustment.

Other limitations: The study had several limitations, including the reliance on volunteers, limited health and well-being data, and limited coverage of participation. Getting people to volunteer sensitive information is challenging. Active data collection took over a year, despite numerous efforts, including networking events, community meetings, online presence in the target areas, paid advertising, and a participation reward. Additionally, the mobilitytransportation component of the EF does not include distance travelled (despite other aspects being captured), even though 15% of the national transportation-related weighting is based on national data. Furthermore, some of the collected data lacked complete information, and some used default locations instead of their actual locations, due to potential privacy concerns. Additionally, the data were not collected using a stratified sampling method.

Given that it is citizen science, it was collected from all over the place at random, which may have influenced the results. Overall, this is still a very good geographical representation, with 407 total submissions that included information on the study's primary subject (EF of consumption).

The results may vary across different regions with distinct demographic compositions, particularly in rural areas, municipalities with varying age compositions, and diverse groups, as well as different mixes of diversity. Consumption patterns are likely to differ in rural settings, given that public transportation is less available and housing is generally less dense than in highly urbanized areas. Data collection is always a challenge in these types of projects. Feedback to the participants and incentives such as the draw of Apple™ watches were used in this study; however, it was still a challenge to collect citizen-based data. Although more than the minimum required data for the study was collected, more data would have enhanced the study.

The study used eight indicators in the healthy populations domains that were identified in the well-being studies. However, there are additional variables that could enhance the outcome. My approach aimed to make the methodology accessible to the general public, city/jurisdictional planners, and leaders of awareness campaigns, with data readily available and free of privacy constraints (aggregated, openly accessible). Those authorities can use these methods to help understand the consumption patterns of the sub-population so that local programs can be targeted towards bringing awareness or reducing ecological footprint with locally targeted approaches (e.g., flyers, digital marketing (sponsored ads)) which could include incentives for good behaviours towards the greater good. Other applications could include locally targeted campaigns to recent immigrant communities to maintain or improve their health and well-being, based on local evidence of the EF of consumption. The scope of the study targeted healthy population domains to facilitate a simple comparison, where accessibility to data for the study is not limited.

Recommendation: Implications for Policy and Practice

This proof-of-concept study explored various approaches to find practical usage for policy planners and implementers at the local or regional level. The results demonstrated the distinctiveness of citizen science-based results compared to those obtained through other disaggregation methods. With local input from citizens, this approach is more relevant and thus important to consider when making policy-based decisions at the local level, whether it is to enhance an awareness campaign or support good citizen behaviours through tax incentives. Some of them are categorized as follows:

1. **Local EF Plans:** The gap between local and national EF suggests that *using national averages to estimate local footprints can be difficult*. Region of Peel's actual consumption (using local data) appears higher than one might guess. If someone took the Canadian average (7.42 gha) and assumed the Region of Peel is average, in reality, many Region of Peel communities are higher than that. Conversely, citizens perceive their footprint to be lower. For local governments, conducting such localized EF studies is valuable for setting realistic baselines. The standard disaggregation method, while not perfect, revealed internal disparities that national reports would mask.

2. **Citizen Science as a Tool:** Involving the public in data collection increased awareness and provided rich qualitative insights. Although the data needs careful interpretation, the approach can be **iteratively improved**. Future citizen science campaigns could aim for a broader reach (perhaps through schools and community centers) to gather a more representative sample. Although attempted in this study as an encouragement to participate, additional feedback showing actual results to participants and comparing them with the measured average could help with behavioural changes. My findings suggest that participants mostly report positive habits, which might indicate that simply participating already correlates with good behaviour. The selection bias is something that needs to be taken into account. To engage those with high EF, different outreach methods may be needed (since they may not volunteer readily).
3. **Addressing High-EF Outlier Communities:** The recognition of specific neighbourhoods with very high EF (often due to income and lifestyle) could allow for targeted sustainability initiatives. For instance, areas with large homes could be targeted for home solar incentives or energy retrofit programs, and high-transportation-related-footprint areas could get improved public transit options or electric vehicle infrastructure. Recognizing that these areas also enjoy high well-being, interventions should be framed as *enhancing efficiency and future-proofing lifestyles* rather than the perceived or actual measures to reduce quality of life. On the other hand, lower-EF areas could be studied for best practices (e.g., if an immigrant community has lower car usage, how can that be supported and sustained as incomes rise?).
4. **Addressing Immigrant Communities:** The result showed that the recent immigrants have lower EF, which opens an opportunity: as this population grows (the Region of Peel

is a major immigrant hub), *policies can aim to preserve some of the low-EF behaviours* that recent immigrants bring. For example, many immigrants may have diets that include more grains/vegetables and less meat. Promoting multicultural food options and food education might help reduce everyone's overall food footprint. Many also initially use transit; ensuring transit service remains attractive and improving first-mile/last-mile connectivity in immigrant-heavy neighbourhoods might encourage them not to “upgrade” to car-centric lifestyles over time. Essentially, there’s an opportunity to learn from recent immigrants’ practices to promote sustainability more broadly.

5. **Health and Well-being Co-benefits:** The positive EF and health and well-being link suggests that reducing consumption in ways that also benefit health would be ideal. Policies such as urban designs that encourage walking (reducing driving emissions and improving fitness), or programs that reduce energy consumption (efficient homes that improve indoor air quality and comfort while cutting energy use) can be promoted. Since high consumption currently shows a correlation with better health (likely due to wealth), policies and measures should ensure that, in the transition to sustainability, support systems are in place to prevent lower consumption from coinciding with lower quality of life or hardship. The goal would be to *break the correlation*, e.g., achieve high health outcomes even in low-EF communities through targeted public health interventions.

Using citizen-science data at the local level to support the citizens of that jurisdiction is not only a preservation of local knowledge but also a fair approach to using public funding to support local initiatives. The results from the health and well-being components of the study can be used by local authorities to raise public awareness and improve well-being in their neighbourhoods. Using citizen science to support the “precautionary principle”, these results, which explore recent immigrants, their EF of consumption, and their health and well-being, can be helpful to settlement agencies and other local authorities. For example, we can raise awareness and take the first steps to minimize the EFs of consumption and improve health and well-being from the moment immigrants arrive in the country by including learning requirements on the EFs of consumption and on health and well-being-related aspects.

The results from the study indicate that there is an opportunity to use a ratio from the citizen science project in the algorithmically calculated consumption-based EF via the existing method, even if it is not possible to collect citizen science-based data. Suppose a citizen science-based data collection project is feasible. In that case, it is recommended that the wording of the questionnaires and any other supporting clarifications (such as a hint button to learn more about the questions) be included in the questions to enhance the participant experience. Before using the Mackenzie et al. (2008) ratio, it must be updated using the best available (current) data.

Future Research

Given the limitations and potential of this study, further research could investigate the causal factors underlying the EF differences. A longitudinal study following recent immigrant from their arrival in the country over time could quantify how quickly and why their EFs increase. Similarly, expanding the citizen science approach with more specific questions or a larger sample could reduce bias (perhaps by providing participants with a way to track their purchases for a week to get more accurate data). The study is based on a mainly urbanized area, the Region of Peel, and is relevant in that context. Although it is beyond the scope of the study, there is an opportunity in the future to compare results in different municipalities within northern Ontario or in the western provinces and rural areas. Additionally, in the health and well-being section, the study targeted healthy population domains to facilitate a simple comparison. A further study could include more variables from the health and well-being studies.

Conclusion

This study detailed approaches to integrate citizen science data as a local voice of the EF of consumption, how the *ecological footprint of consumption varies across the Region of Peel* and between its communities, and how incorporating *citizen science data* can enhance local insights. The key findings are:

- **Methodological Differences:**citizen-contributed data suggest a significantly lower EF than the conventional disaggregation method, highlighting the importance of data sources and raising awareness of potential under-reporting in self-assessments and a variation among these methods.

Nonetheless, citizen science captured local variations and proved to be useful in mapping relative differences, showing potential as a complementary tool for local sustainability assessments

- *Sub-population Patterns: Recent immigrants exhibit slightly more sustainable consumption patterns* on average than the established Canadians, although the gap is not large.

This indicates an opportunity to support low-footprint lifestyles among growing immigrant communities.

- **Consumption-Health Nexus:** There is a measurable *positive correlation between higher consumption (EF) and self-reported good health* at the Dissemination Area (DA) level.

This highlights the challenges of achieving environmental sustainability while maintaining a good quality of life, a challenge that must be met with holistic solutions that deliver better health and well-being with lower resource consumption.

- **High-EF Outlier DAs:** A few areas in the Region of Peel have very high per capita EF (exceeding 15 gha), linked to high incomes and spending. These could be important targets for sustainability initiatives, as reductions here can significantly impact the region's overall EF.
- **Citizen Engagement:** The project engaged a segment of the population that is keen on sustainability and health and well-being. Their input, although not fully representative, adds qualitative depth and a human dimension to the quantitative data, and their enthusiasm can serve as a catalyst for future community-based sustainability programs.

Overall, the analysis in this proof-of-concept study demonstrates that a granular, community-level examination of ecological footprint data is essential for identifying where and why resource use is high, and for tailoring interventions or sustainability measures accordingly. It also shows that community characteristics (such as immigration status) correlate with consumption patterns, which can inform more equitable and effective policy design.

This study aimed to demonstrate a novel approach to adapting national-level data to local contexts, thereby providing policymakers and practitioners with a framework for decision-making**.** By enabling sustainability assessment at the community scale, this approach has the potential to raise individuals' awareness of their local consumption's EF, which may, in turn, encourage actions to reduce it. After all, as Kates (2011) states, sustainability science is a different kind of science that is primarily use-inspired!

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Appendices

Appendix A: History of Sustainability, Theories and Frameworks

Origin of Sustainability Assessment:

The terms ”sustainable development,” “sustainability,” and “environmental/sustainability assessment” began to emerge in the 1960s in wealthy nations to address the overheated consumption that followed World War II (Gibson & Hassan, 2005). Material gains and consumer confidence had brought about a heated technological and industrial boom in developed nations. Material prosperity inspired people to think beyond everyday struggles during the war and the era of the Great Depression. The post-war era of the 1970s became a cornerstone in igniting a paradigm shift about sustainability. Special interest groups that formed around this timeframe began to question authorities about how environmental issues were being addressed. Rachel Carson’s introduction of global-scale chemical contaminations in 1962 and the publication of a series of books indicating a risk of global overpopulation and resource depletion awakened people to the danger of potential environmental degradation (Gibson & Hassan, 2005, ch. 2). The formation of special interest groups, driven by dissatisfaction with authorities and supported by media advocacy, significantly heightened environmental awareness. This increased awareness contributed to the establishment of several environmental laws in developed nations, including the National Environmental Policy Act of 1969 (NEPA, 1969) in the United States, the more stringent Canadian Environmental Protection Act of 1999 (CEPA, 2023), and the Ley General del Equilibrio Ecológico y la Protección al Ambiente [General Law of Ecological Equilibrium and Environmental Protection of 1988] (last amended in 2008) in Mexico (Yang & Percival, 2009).

Although the ideas behind protecting people and the environment are not new, none of the authorities during that period explicitly addressed the concept of sustainability. The Conservation Authority Act of 1954 (Conservation Ontario, 2019) in Ontario, Canada, which was formed after Hurricane Hazel (1954), did not use the term "Sustainability" in its core mandate. Conservation Ontario (2019) identifies that "The core mandate of Conservation Authorities is to undertake watershed-based programs to protect people and property from flooding and other natural hazards and to conserve natural resources for economic, social and environmental benefits". The mandate highlights the interrelationship between the environment and people, a concept discussed by Gibson (2001) as one of the schools of thought that supports the two pillars of sustainability, which later evolved into the three pillars now widely accepted as a foundation. The Conservation Authority Act of Ontario includes the environment and society and a need to 'conserve' for the future, but the economy, the third pillar, is not addressed. This is due to the nature of the businesses that the Conservation Authorities are mandated to carry out. Various authorities and special interest groups were formed to address specific items on their agendas, but a holistic approach to creating a 'sustainable future' remained unhatched.

In recent years, the northern region of Canada has emerged as a testing ground for various dimensions of sustainability, including whether significant reductions in greenhouse gas (GHG) emissions can be achieved through reductions in GHG intensity (Victor, 2012). Other studies have highlighted the absence of comprehensive baseline data, intercultural complexities, conflicts between developers and First Nations, and their remoteness from densely populated Canadian urban centers (Mulvihill & Baker, 2001). The authors discuss the issues of scoping the project by asking questions about the legitimacy of public input in shaping EIA (Environmental

Impact Assessment) guidelines, which vary depending on ambition and their ‘restrictive’ nature, particularly in the northern Canadian context.

Public policies such as the Clean Water Act of 1972 (US EPA, 2013) started to emerge in the 1970s to address some of the “impaired waters” in the USA (Sze, 2018). The Environmental Policy Agency (EPA) and similar organizations in Europe, Canada, and worldwide were established soon after (Kepner, 2016). The European Environmental Policy (EEA) was established in 1993, whereas Canada introduced the Canadian Environmental Protection Act (CEPA) in 1999 (CEPA, 2023; EPA, 2024). The creation of public policies helped establish governance in the field of sustainability, raise public awareness, and open the door to exploring various sustainability measures.

According to Ness et al. (2007), sustainability assessment is intended to support decision-makers with an integrated, global-to-local evaluation of the nature-society system to help them develop long-term action plans (p. 499). Sustainability measures or sustainability assessments are critical for identifying the impact of resource consumption, the capacity of the Earth's resources, and how sustainability can be achieved or maintained. We must view sustainability assessment as “a tool” within the family of impact assessments (Pope et al., 2004) to characterize the underlying impacts of a proposed solution. The environmental impact assessment processes “…are among the most promising venues for application of sustainability-based criteria” (Gibson, 2001, p. 3).

The literature suggests that the approaches to sustainability assessment can be grouped into two categories, one that is closely related to EIA (Environmental Impact Assessment) related projects and SEA (Strategic Environmental Assessment) applied to policies, plans and programs (PPPs)

(Devuyst et al., 2001; Mulvihill & Milan, 2007; Pope et al., 2004). The concerns and limitations are also well understood in these processes. Based on previous literature, Pope et al. (2004, p. 599) summarize that EIA-related assessments take place at a later stage of the project and hence, have minimal effects on decision-making, whereas SEA-related assessments take place at a very early stage of strategic planning with a potential for much broader applications and influences in the decision-making processes.

The "EIA-driven" assessments are generally reactive with very few alternatives left, whereas the "SEA-driven" assessment, also known as "objectives-led SEA", is a proactive approach and is generally a part of the process in creating policies, plans and programs (PPP) that seek comprehensive analyses of alternatives in advance (Sheate et al., 2003; Pope et al., 2004). The authors also discuss the "EIA-driven SEA," which refers to the influence of an EIA on an SEA, specifically a project-level EIA implemented through policies, plans, and programs (PPP). Typically, this form of SEA is characterized as a responsive procedure. This process involves evaluating the environmental impacts of policies, plans, or programs relative to a baseline to determine their acceptability or identify necessary modifications to improve environmental outcomes.

A study by Ness et al. (2007) examines temporal factors, focus areas and the integration of a nature-society system to characterize tools of sustainability assessments. According to the authors, the sustainability toolset has three broader categories: a. indicators and indices, b. product-related assessment tools with a focus on the material and energy flow of a product or service, and c. integrated assessment. These tools are discussed in detail later.

Although various approaches have been employed with different tools for sustainability assessments, a common theme among most of them is a traditional assessment approach. The traditional approach, known as normal science, encounters roadblocks when anomalies arise (Kuhn, 2012). In the post-war era, as awareness grew that Earth's systems were being jeopardized by complex issues such as climate change, resource depletion, and population growth, the question of humanity's role in determining the planet's future gained increasing prominence. The growth was fueled by a paradigm shift in thinking that began around the 1980s and has accelerated in recent years (Bettencourt and Kaur, 2011). As the sustainability concept started to gain momentum, it "…emerged as three things: a critique, a set of principles implying positive objectives, and a focus for strategies for change." (Gibson, 2001, p.9). The author discusses how environmental degradation, resource depletion, and damage to ecological functions and services were issues that sustainability was expected to address.

The Brundtland Commission report on sustainability (WCED, 1987), with its first official definition, may have been an attack on conventional thinking, marking the beginning of a brewing scientific revolution and a paradigm shift, with an applied side that was critical to addressing the global problems at hand. Then, the Industrial Revolution had already created a big divide between the poor and the rich. It had left the biggest environmental footprint humans had ever experienced. Pollution problems in big global cities and irreversible environmental degradation were only adding more fuel to the cumulative global effects of environmental issues. Scientific revolutions are required to address anomalies that normal and everyday science cannot address or does not explore (Kuhn, 2012).

Normal science does not address the complexity of the interconnected and multidimensional issues that include "uncertainty, value loading and a plurality of the legitimate perspectives" (Funtowicz & Ravetz, 2003). As Kuhn (2012) puts it:

> "…normal science, the activity in which most scientists inevitably spend almost all their time, is predicated on the assumption that the scientific community knows what the world is like. Much of the success of the enterprise derives from the community's willingness to defend that assumption, if necessary, at considerable cost." (p.5)

In this process, if scientific commitments are met, some novel concepts are accepted to address anomalies that arise during routine work. However, when normal science cannot address anomalies that are different and complex, a paradigm shift accompanied by a scientific revolution is necessary. The sustainability issues we face require a shift in thinking to address the anomalies that are creating crises. The crisis, as one of the four phases during the scientific revolution that Kuhn (1962) identifies, either results in a solution that returns to normal science by resolving the anomalies or leads to a new set of paradigms through a scientific revolution. The sustainability issues stemming from anomalies created by climate change, increased consumption-based ecological footprints, global population pressure, and global migration are growing at an unprecedented rate post-industrial revolution, so that normal science lacks a "formula" to address them. Post-normal science is required to address complex, interrelated issues.

Post-normal science (also referred to as Mode 2 science) has a greater appreciation of uncertainty than normal science (Funtowicz & Ravetz, 2003; Kay et al., 1999; Turnpenny et al., 2011). Kuhn (2012) would still argue that the new paradigm is not necessarily better than the old paradigm because there is no neutral standard to measure the objective differences, using the term he coined "incommensurability". However, critics argue that there is always progress when a paradigm shift occurs. Mizrahi (2015) strongly opposes Kuhn's incommensurability argument by saying that there is no deductive or inductive support for his incommensurability thesis.

Nevertheless, a new model to address these challenges has emerged in the scientific community: sustainability science (Sala et al., 2015). The science that emerged to address those challenges primarily stemmed from the practicality of the 'use-inspired' implementations. As Kates (2011) describes it, a primarily use-inspired science, where applied knowledge and a commitment to moving knowledge into societal action plans were critical (p. 19450).

The "solution-oriented discipline" that studies the complex interdependence between humans and the environment calls for a holistic approach. The dynamic nature of earth systems (humans and ecosystems) is not only complex but also self-organizing. It can be explained with models such as Self-Organizing Holarchic Open (SOHO) systems (Kay et al., 1999) and similar concepts such as panarchy and resilience thinking based on understandings of systems and complexity science (Berkes & Ross, 2016; Curtin & Parker, 2014; Holling, 2001; Holling, 2004). Traditional scientific approaches to modelling and prediction are inadequate for these systems due to their non-linear characteristics of causality. To make critical decisions, sustainability assessments must consider the non-linearity of cause and effect. A sustainability assessment (SA) is "a complex appraisal method" that accounts for broad environmental, economic and social contexts to come up with a scientific evaluation (Sala et al., 2015).

Early environmental assessments were very limited in scope. The US National Environmental Policy Act (NEPA) of 1969 (NEPA, 1969) was the first of its kind. However, its scope remained constrained (Gibson & Hassan, 2005, ch. 2). Expansion began gradually, but not without resistance from traditional thinkers. Despite the underlying fear of atomic warfare during the Cold War era and the subsequent boom in consumption, the strong push from a select few to raise awareness about sustainability did not fade.

With public policies such as the Clean Water Act of 1972 (US EPA, 2013), Sze (2018, Ch. 2) explains that the Anthropocene "sparked" a critical engagement among humanities scholars with the concept of 'sustainability' and 'sustainable development' that eventually resulted in the institutionalization of environmental humanities, such as the American Society of Environmental History (later Environmental Ethics) starting in the 1970s. In recent years, the sustainability indicator network, which has evolved into the Community Indicators Consortium (CIC) in the US and the Canadian Sustainability Indicators Network (CSIN), has expanded to include government and business sector members (CIC, 2019; CSIN, 2019). A recent analysis focusing on the temporal evolution and structure of sustainability science revealed that the field is growing exponentially, with a doubling period of 8.3 years (Bettencourt and Kaur, 2011).

The dystopian outlook necessitated a balance among the environment, society, and the economy. Environmental problems were only one of the "three pillars" as the divide between the rich and the poor widened worldwide. The advanced nations, as a group, were generating pollution to advance their economy, whereas others were left behind. The idea of development was a requirement for getting out of a destitute situation, but it had to be done in a way that allowed you to think globally and act locally. Sustainable development was a societal demand that should be "…pursued in ways that would protect resources and ecological integrity over the long term while greatly improving human well-being, especially among the poor" (Gibson, 2001, p. 9).

On a global scale, it is not easy to "implement" sustainable development due to the varying levels of technological, economic, and sociological advancement across countries. The Sustainable Development Goals (SDGs) were adopted by the United Nations in 2015 to help end poverty, conserve our ecosystems and the planet as a whole, and ensure peace and prosperity worldwide, introducing 17 interrelated SDGs (UNDP, 2016). Any action in any of the integrated SDGs impacts outcomes in the other SDGs; therefore, development needs to balance all social, economic, and environmental sustainability. The Brundtland Commission report aimed to create a balance by providing poorer countries with more opportunities in open markets, along with other incentives, to improve their state (WCED, 1987). A comprehensive understanding of indicators such as planetary boundaries and ecological footprints has recently enhanced our ability to assess the progress of countries and regions toward achieving the Sustainable Development Goals.

While we have gained considerable knowledge of societal and physical changes, including economic progress and decline, population growth, waste generation, consumption patterns, and carbon footprints, our understanding of biophysical systems and the impact of human activities on them remains less certain. "Human well-being is utterly dependent on the integrity of biophysical systems, at every scale from the local to the global" (Gibson, 2001, p. 13). With knowledge of economic systems, we have the power to predict, control, and manipulate outcomes as we see fit. However, our understanding of biophysical systems and their interrelationships with human health and well-being is limited. This results in difficulty in assessing the three pillars and how our sustainability goals are measured. To address this difficulty, the sustainability assessment was designed using a variety of tools and approaches. The three pillars have been tested with different approaches and frameworks to measure the “strength of sustainability”. Some of these key approaches and tools are explored further in the subsequent sections.

Sustainability Assessment: Theories and Frameworks

Our environment is complex; there are things that we do not understand due to the complexity of the processes, whether natural or cultural. If we know that ‘not doing anything’ causes greater degradation of the environment, human health, or the economy, it is imperative that we do something to address the issues and mitigate the problems. The rationale for implementing actions and policies to address issues despite limited knowledge, driven by the understanding that inaction could lead to greater negative consequences, is known as the "precautionary principle" (Agyeman & Evans, 2003; Raffensperger & Tickner, 1999). The precautionary principle encourages us to use available information to develop solutions that avoid potential negative impacts in the future, rather than creating policies that improve situations by blaming a lack of complete scientific evidence. From a philosophical point of view, a sustainability assessment is an evaluation that assesses the situation using the best available information and applies the precautionary principle to minimize the risk of future disasters.

There are various philosophical stances on sustainability assessments that influence what should be included. If we want to understand the three pillars of sustainability, how can we be confident that they are adequately represented without over- or underestimating their contributions? The economy is embedded in society, which is in turn embedded within a larger ecological system from which resources are derived. To address this, scientists and researchers have developed various guiding principles (Gibson, 2006; Rockström et al., 2009). Still, the precautionary principle is debated vigorously regarding its merits (Rockström et al., 2009). Although the application of the precautionary principle is frequently observed in the public health domain, where potential risks to human health and civilization are substantial and rapidly spreading (Agyeman & Evans, 2003; Raffensperger & Tickner, 1999), its application is less common in the contexts of environmental protection, societal well-being, and long-term economic stability. Politicians and policymakers, influenced by their own interests, tend to look the other way, partly because of their short-term focus on public empowerment. This creates difficulty in using approaches that are all-encompassing, precautionary, and forward-looking. We still, at times, debate whether we should protect the environment for sustainability, and hence, human health and well-being. However, driven by a focus on short-term outcomes, a segment of society has become accustomed to compensation plans. This mindset suggests, for instance, that it is acceptable to fragment an urban woodland and sacrifice its ecological contributions, provided that "double" the land is allocated for a "new woodland," even if the new area lacks the ecological connectivity necessary for the woodland to thrive. In the context of sustainability assessment, this begs the question of what the industry standards or commonly used sustainability measurements are or should be.

Sustainability assessment has many direct and indirect roots in the past. If we examine the key aspects of our health and well-being, the dynamics of the biophysical system play critical roles. However, the metrics in the biophysical system dynamics are limited at best. Based on what we know about how society, the economy, and the environment behave, there are various approaches to assessing sustainability or sustainable development. To promote consistency and guide sustainable development, scholars in the field developed the Bellagio principles in 1997 (Jesinghaus, 2014) to provide guidance and best practices related to sustainable development (Pinter et al., 2012).

Before we explore the Bellagio principles, a prominent scholar in the field, Gibson, argues that sustainability is defined using two schools of thought, one of which focuses on the green movement with the necessity for a society as "a pre-requisite", where the economy is embedded in society and society is embedded in the environment. Another thought focuses on extending sustainability beyond the green movement. The second way defines sustainability as part of a larger society, where the economy, environment, and social aspects all contribute to it as a triple-bottom-line (TBL) approach (Gibson, 2001; Gibson & Hassan, 2005; Pope et al., 2004). The standards surrounding sustainable development, based on the TBL concept, led to the development of the Global Reporting Initiative (GRI) framework (Pinter et al., 2012, p. 22).

The Bellagio Principles were created in the Rockefeller Foundation's Bellagio Centre in Bellagio, Italy, in 1996, where a group of experts came up with sustainability principles known as "the Principles" to assist with a guide for measuring and evaluating progress related to sustainability assessment (Hardi and Zdan, 1997; Jesinghaus, 2014; Pinter et al., 2012). At the most recent meeting, the Principles were renamed "Sustainability Assessment and Measurement Principles" (STAMP). The principles contain the following eight items as per Table 1 (Pinter et al., 2012, p. 22-24):

Table 25. Summary of eight items as per Bellagio Principles (Pinter et al., 2012, p. 22-24).

Number	**Principles**	**Coverage**
1	Guiding Vision	Assessment of progress toward sustainable development will be guided by the goal of delivering well-being within the capacity of the biosphere to sustain it for future generations.
2	An essential consideration	Assessment of progress toward sustainable development will consider: - the underlying social, economic and environmental system as a whole and the interactions among its components, including issues related to governance; - dynamics and interactions between current trends and drivers of

		change; - risks, uncertainties, and activities that can have an impact across boundaries; - implications for decision making, including trade-offs and synergies.
3	Adequate scope	Assessment of progress toward sustainable development will adopt: - an appropriate time horizon to capture both short- and long-term effects of current policy decisions and human activities; -an appropriate geographical scope.
4	Framework and indicators	Assessment of progress toward sustainable development will be based on: - a conceptual framework that identifies the domains within which core indicators to assess progress are to be identified; - standardized measurement methods wherever possible, in the interest of comparability; - comparison of indicator values with targets, as possible.
5	Transparency	Assessment of progress toward sustainable development will: - ensure the data, indicators and results of the assessment are accessible to the public; - explain the choices, assumptions and uncertainties determining the results of the assessment; - disclose data sources and methods; - disclose all sources of funding and potential conflicts of interest.
6	Effective communications	In the interest of effective communication, to attract the broadest possible audience and minimize the risk of misuse, assessment of progress toward sustainable development will: - use clear and plain language; - present information fairly and objectively that helps to build trust; - use innovative visual tools and graphics to aid interpretation and tell a story; - make data available in as much detail as is reliable and practicable.
7	Broad participation	To strengthen its legitimacy and relevance, the assessment of progress toward sustainable development should: - find appropriate ways to reflect the views of the public, while providing active leadership; - engage early on with users of the assessment so that it best fits their needs.
8	Continuity and capacity	Assessment of progress toward sustainable development will require: - repeated measurement; - responsiveness to change; - investment to develop and maintain adequate capacity; - continuous learning and improvement.

The Bellagio Principles, or STAMP, encompass integrating sustainability assessments that extend beyond project completion. The continuity and capacity principle makes sure that there is ongoing monitoring and responses to the changes that occur. This enables ongoing improvement in the situation (Jesinghaus, 2014; Pinter et al., 2012). While discussing the principles, Pinter et al. (2012) highlight that the foundation of sustainability is influenced by the two recent perspectives of sciences, one that deals with post-normal science such as the study of the interactivity of the “linked socio-ecological” systems, and another that focuses on policy relevancy such as how science can play an enhanced role in addressing real-world practical problems. Recent perspectives in sustainability sciences have influenced the approaches to sustainability assessment.

Sustainability Assessment Frameworks: Sustainability assessment encompasses a high-level guiding structure or framework, the integrated tools used to assess, and the objective measures or indicators employed for assessment. The tools are analytical methods for measuring the indicators. However, a tool-focused framework, an indicator-based framework, and an integrated, overarching framework can all exist (Ness et al., 2007).

Sustainability requirements are key to determining the type of sustainability assessment needed. Those considerations are generally very comprehensive, and the three pillars are at the core. Long- and short-term insights are crucial, along with the use of precautionary principles (Agyeman & Evans, 2003; Raffensperger & Tickner, 1999). Gibson (2006) highlights the need to respect uncertainty in the sustainability assessment, noting, “[w]hile sustainability assessment demands more coherent and comprehensive decision-making, it must also respect context and uncertainty” (p. 178). Gibson (2006, p. 180) outlines the following steps as priority steps to implement the sustainability assessment process:

a. establish a contribution to sustainability as the main test;
b. evaluation criteria and trade-off rules must reflect the core requirement of sustainability;
c. decision criteria and rules must be specific and informed by the stakeholders;
d. apply those insights in the full process and alternative scenarios for continual improvements; and
e. decisions should be open to criticism and debate and must be accountable in law.

Appendix B: Citizen science questionnaire used in the study

Background Information on the project including disclaimer		
Let's get to you know you and your neighbourhood:		
Please type in your postal code:		
Select your gender:	Gender choice drop down (including "I do not want to disclose" as an option)	
Your age group (adult only, one per household):	Age group drop down	
How many years have you lived in Canada (type in 1 to 50. If you have lived more than 50 years, leave it as 50).	Select 1 to 50	
Do you consider your health and well being is generally in a good shape?:	Yes, No Or I am not sure	
Do you consider your family's health and well being is generally in a good shape?:	Yes, No Or I am not sure	
Would you say that you are generally aware of your, food consumption, how you travel, how you heat your house, as a family or individually (if single)?:	Yes, No, I have no idea	
If you selected "I have no idea", can you estimate approximately or come back to the survey later with a bit of that information above?:	Yes or No (if you choose "no", you will be existing the survey at this point. Please participate at a later date).	
Let's go and see where you stand!		
Ecological Footprint (consumption) Category		**Code**
Food		
1	**How many meals per week do you eat meat or fish?**	
	0	FM1
	1 to 3	FM2

	4 to 6	FM3
	More than 7	FM4
2	**How many home cooked meals do you eat per week prepared from fresh ingredients?**	
	0	FH1
	1 to 3	FH2
	4 to 6	FH3
	More than 7	FH4
3	**How often do you buy or use locally produced goods (i.e. within 50 km from your neighbourhood, or via Farmer's market) per week on average?**	
	Never	FL01
	Sometimes (less than once a week, but more than 13 times a year)	FL02
	Once a week during summer months (due to accessibility, farmers market etc.)	FL03
	Regularly (at least once a week every week)	FL04
4	**How many times a week (on average) do you consume exotic fruits or vegetables (i.e. star fruit, mangos) that might have traveled more than 1,000km to reach you?**	
	0	FD01
	1 to 2	FD02
	3 to 4	FD03
	More than 4	FD04
Shelter		
5	**How many people live in your household?**	
	One	SH01
	Two	SH02
	Three	SH03
	Four	SH04

	Five or more	SH05
6	**How do you heat your house?**	
	Oil	ST01
	Electricity	ST02
	Natural gas	ST03
	Renewable energy (solar, wind)	ST04
7	**How much do you believe you spend for energy cost for in-house uses (electricity, heating etc.). On average Canadian spend 7.9% of total annual spending and Ontarian spend 7.5 % of total annual spending.**	
	Less than 3.5% of total spending	SE01
	About 7.5% of total spending	SE02
	More than 10 % of total spending	SE03
	Not applicable because I/we use renewable energy	SE04
8	**What type of home do you live in?**	
	Apartment/flat	SS01
	House	SS02
9	**How many bathrooms (including just with toilet and sink) do you have in your house?**	
	One	SB01
	1 to 3	SB02
	3 to 5	SB03
	More than 5	SB04
Mobility		
10	**What is your means of transportation to school/work?**	
	Private vehicle (car, motorized bike)	MT01
	Public transportation or school bus	MT02
	Electric vehicle (excluding hybrids)	MT03

	Active means (walking, biking etc.)	MT04
11	**How does your travel/vacation look like annually (exclude COVID-19 era)?**	
	local vacation within the province or region	MV01
	national vacation to another province or region	MV02
	International vacation	MV03
	No travel or vacation at all (think about last 5 years get the averages)	MV04
12	**How many weekend trips do you typically take per year (exclude COVID-19 era)?**	
	zero	MW01
	1 to 5	MW02
	6 to 10	MW03
	More than 10	MW04
Goods and Services		
13	**How many products have you bought/acquired that are big purchases (electronics, TV, cars, computers etc.) over $500 in the last year?**	
	Zero	GP01
	1 to 3	GP02
	4 to 6	GP03
	More than 6	GP04
14	**Did you buy the majority of the energy-efficient products in the last year (if they require energy)? This includes light bulbs to dish washer etc.**	
	Yes	GE01
	No	GE02
15	**Do you try to attempt to reduce wastage at home by reusing, recycling, reducing?**	
	Always	GR01
	Sometimes	GR02

	Rarely	GR03
	Never	GR04
16	**Does your household compost?**	
	Always	GC01
	Sometimes	GC02
	Rarely	GC03
	Never	GC04
17	**How many bags of waste (standard black bags used at the municipality) do you produce per week and leave on the curb on the garbage pick up day?**	
	zero	GG01
	Half a bag	GG02
	1 to 2 bags	GG03
	More than 2 bags	GG04
Health and well-being		
18	**Over the past 1 year would you say your health condition has been… (exclude COVID-19 related health issues)?**	
	Very good	HC01
	Fairly good	HC02
	Not very good	HC03
	Worse than ever	HC04
19	**Do you have any health problems or disability that limits your daily activities or work you can do?**	
	Yes	HP01
	No	HP02
20	**How would you relate your level of physical fitness compared to others in your age group?**	
	Very good	HF01

	Fairly good	HF02
	Not very good	HF03
	Worse than ever	HF04
21	**How would you rate the quality of your life as it relates to your psychological or emotional well-being**	
	Very good	HW01
	Fairly good	HW02
	Not very good	HW03
	Worse than ever	HW04
22	**In the past 1 year, have you done any of the following to keep yourself fit and healthy?**	
	Followed a fitness program or played a sports regularly	HH01
	Have switched to healthy diet and/or reduced alcohol consumption	HH02
	Have a sustained active lifestyle (walking 5,000 to 10,000 steps a day, etc.)	HH03
	Did nothing	HH04
23	**Overall, how satisfied are you with your mental well-being?**	
	Very satisfied	HM01
	Satisfied	HM02
	Neutral	HM03
	Not satisfied at all	HM04
24	**How satisfied are you with your relationships with spouse/partner and other family members (immediate or extended)?**	
	Very satisfied	HR01
	Satisfied	HR02
	Neutral	HR03
	Not satisfied at all	HR04
25	**How optimistic do you feel about the future?**	

	Very optimistic	HO01
	Optimistic	HO02
	Neutral	HO03
	Not optimistic at all	HO04
26	**Has any of the following items brought more stress to your life in the last year (think of it as at least once a month)?**	
	Work load and responsibilities	HS01
	Financial worries	HS02
	Health and well-being (exclude COVID-19 related concerns)	HS03
	No	HS04
27	**How do you address your stress in general?**	
	Regular or occasional exercise	HA01
	Driving in my private vehicle for a while (more than 5 km)	HA02
	Walking/hiking in the treed area/nature trail	HA03
	Consuming alcohol or comfort food	HA04
28	Type in two keywords or phrases (on your own) that describe your food habit (i.e. local eater, high fiber etc.)	KF01
29	Type in two keywords or phrases(on your own) that describe your shelter pattern (i.e. lonely, big family etc.)	KS01
30	Type in two keywords or phrases (on your own) that describe your transportation situation (i.e. public transporation, car lover etc.)	KT01
31	Type in two keywords or phrases (on your own) that describe your goods, services and consumption pattern (i.e. love to spend, environentally friendly, etc.)	KG01
32	Type in two keywords or phrases (on your own) that describe your health and well-being (i.e. healthy and active, bulky and happy, etc.)	KH01

Appendix C: Scoring method to convert citizen science data into gha/cap

Ecological Footprint (consumption) Category		Code	Distribution of value assignment based on the Canadian average EF of consumption	Percentage of total consumption (as per Canadian stats)	Notes
Food				**0.15**	
1	**How many meals per week do you eat meat or fish?**		**out of 0.05**	0.15	
	0	FM1	0.0000	0.15	
	1 to 3	FM2	0.0250	0.15	
	4 to 6	FM3	0.0375	0.15	
	More than 7	FM4	0.0500	0.15	
2	**How many home cooked meals do you eat per week prepared from fresh ingredients?**		**out of 0.05**	0.15	
	0	FH4	0.0500	0.15	
	1 to 3	FH3	0.0375	0.15	
	4 to 6	FH2	0.0250	0.15	
	More than 7	FH1	0.0000	0.15	
3	**How often do you buy or use locally produced goods (i.e. within 50 km from your neighbourhood, or via Farmer's market) per week on average?**		**out of 0.025**	0.15	
	Never	FL01	0.0250	0.15	
	Sometimes (less than once a week, but more than 13 times a year)	FL02	0.0125	0.15	
	Once a week during summer months (due to accessibility, farmers market etc.)	FL03	0.0188	0.15	
	Regularly (at least once a week every week)	FL04	0.0000	0.15	
4	**How many times a week (on average) do you consume exotic fruits or vegetables (i.e. star fruit, mangos) that**		**out of 0.025**	0.15	

	might have traveled more than 1,000km to reach you?				
	0	FD01	0.0000	0.15	
	1 to 2	FD02	0.0125	0.15	
	3 to 4	FD03	0.0188	0.15	
	More than 4	FD04	0.0250	0.15	
Shelter				**0.31**	
5	**How many people live in your household?**		**out of 0.07**	0.31	
	One to two	SH01	0.0000	0.31	
	Three	SH02	0.0350	0.31	
	Four	SH03	0.0525	0.31	
	Five or more	SH04	0.0700	0.31	Four or more combined
6	**How do you heat your house?**		**out of 0.07**	0.31	
	Oil	ST04	0.0700	0.31	
	Electricity	ST02	0.0350	0.31	
	Natural gas	ST03	0.0525	0.31	
	Renewable energy (solar, wind)	ST01	0.0000	0.31	
7	**How much do you believe you spend for energy cost for in-house uses (electricity, heating etc.). On average Canadian spend 7.9% of total annual spending and Ontarian spend 7.5 % of total annual spending.**		**out of 0.07**	0.31	
	Less than 3.5% of total spending	SE02	0.0350	0.31	
	About 7.5% of total spending	SE03	0.0525	0.31	
	More than 10 % of total spending	SE04	0.0700	0.31	
	Not applicable because I/we use renewable energy	SE01	0.0000	0.31	
8	**What type of home do you live in?**		**out of 0.03**	0.31	To avoid double-counting the effects/see energy spending, heating, and

					occupants parameters
	Apartment/flat	SS01	0.0000	0.31	
	Row townhouse or semi-detached (generally on average 1500 sq feet or less in size)	SS02	0.0150		
	Small detached house (generally between 1500- 2500 sq. feet in size)	SS03	0.0225		
	Large detached house	SS04	0.0300	0.31	
9	**How many bathrooms (including just with toilet and sink) do you have in your house?**		**out of 0.07**	0.31	
	One	SB01	0.0000	0.31	
	1 to 3	SB02	0.0350	0.31	
	3 to 5	SB03	0.0525	0.31	
	More than 5	SB04	0.0700	0.31	
Mobility				**0.15**	
10	**What is your means of transportation to school/work?**		**out of 0.05**	0.15	
	Private vehicle (car, motorized bike)	MT04	0.0500	0.15	
	Public transportation or school bus	MT03	0.0250	0.15	
	Electric vehicle (excluding hybrids)	MT02	0.0250	0.15	
	Active means (walking, biking etc.)	MT01	0.0000	0.15	
11	**How does your travel/vacation look like annually (exclude COVID-19 era)?**		**out of 0.05**	0.15	
	local vacation within the province or region	MV02	0.0250	0.15	
	national vacation to another province or region	MV03	0.0375	0.15	
	International vacation	MV04	0.0500	0.15	

	No travel or vacation at all (think about last 5 years get the averages)	MV01	0.0000	0.15	
12	**How many weekend trips do you typically take per year (exclude COVID-19 era)?**		**out of 0.05**	0.15	
	zero	MW01	0.0000	0.15	
	1 to 5	MW02	0.0250	0.15	
	6 to 10	MW03	0.0375	0.15	
	More than 10	MW04	0.0500	0.15	
Goods and Services				**0.39**	
13	**How many products have you bought/acquired that are big purchases (electronics, TV, cars, computers etc.) over $500 in the last year?**		**out of 0.08**	0.39	
	Zero	GP01	0.0000	0.39	
	1 to 3	GP02	0.0400	0.39	
	4 to 6	GP03	0.0600	0.39	
	7 or more	GP04	0.0800	0.39	
14	**Did you buy the majority of the energy-efficient products in the last year (if they require energy)? This includes light bulbs to dish washer etc.**		**out of 0.07**	0.39	Lower weight compared to other questions due to a lower variation in the response.
	Yes	GE00	0.0000	0.39	
	No	GE04	0.0700	0.39	
15	**Do you try to attempt to reduce wastage at home by reusing, recycling, reducing?**		**out of 0.08**	0.39	
	Always	GR01	0.0000	0.39	
	Sometimes	GR02	0.0400	0.39	
	Rarely	GR03	0.0600	0.39	
	Never	GR04	0.0800	0.39	
16	**Does your household compost?**		**out of 0.08**	0.39	
	Always	GC01	0.0000	0.39	
	Sometimes	GC02	0.0400	0.39	
	Rarely	GC03	0.0600	0.39	

	Never	GC04	0.0800	0.39	
17	**How many bags of waste (standard black bags used at the municipality) do you produce per week and leave on the curb on the garbage pick up day?**		**out of 0.08**	0.39	
	zero	GG01	0.0000	0.39	
	Half a bag	GG02	0.0400	0.39	
	1 to 2 bags	GG03	0.0600	0.39	
	More than 2 bags	GG04	0.0800	0.39	
Health and wellbeing					Only 2 variables used for quantification
18	**Over the past 1 year would you say your health condition has been… (exclude COVID-19 related health issues)?**		**out of 1**		
	Very good	HC04	1	1	
	Fairly good	HC03	1	1	
	Not very good	HC02	0.0000	1	
	Worse than ever	HC01	0.0000	1	
19	**How satisfied are you with your relationships with spouse/partner and other family members (immediate or extended)?**		**out of 1**		
	Very satisfied	HR04	1.0000	1	
	Satisfied	HR03	1.0000	1	
	Neutral	HR02	0.0000	1	
	Not satisfied at all	HR01	0.0000	1	
	Not satisfied at all & need to do something	HM00	0.0000	1	