Disaggregating Ecosystem Benefits: An Integrated Environmental-Deprivation Index

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Abstract: The valuation of ecosystem services has become an integral part of smart urban planning practices. Traditionally designed to bridge ecology and economy through economic language and logic (e.g., goods and services), this conceptual framework has developed into an effective tool for interdisciplinary work. The concept of ecosystem services is used to improve the management of ecosystems for human well-being. However, gaps in how to govern ecological benefits remain. Specifically, identifying which stakeholders benefit the most from the provision of ecosystem services remains largely unaddressed. This study examines the spatial discordance between ecosystem services and the residential stakeholders who may benefit. Using a landscape approach to quantify urban ecosystem services, an area-based composite index was developed for the City of Toronto, Canada, based on the three pillars of sustainability in order to identify potentially vulnerable populations. This method combines the use of principal component analysis (PCA) and spatial multicriteria decision analysis (GIS-MCDA) to combine and weight a select grouping of socioeconomic and ecological indicators. In addition, two sets of enumeration units (i.e., dissemination areas and census tracts) were evaluated to assess the potential impact of measurement scale on subsequent decision or policy outcomes. Results indicate the spatial interdependencies between ecological and socioeconomic processes in an urban setting, offering a unique framework for novel planning and policy intervention strategies. The influence of measurement scale was demonstrated, creating an opportunity to assess an appropriate policy scale by which to measure and evaluate trends over time and space. This approach seeks to provide a flexible and intuitive planning tool that can help to achieve goals relating to urban sustainability, resiliency and equity.

Keywords: ecosystem services; ecosystem benefits; GIS-MCDA; PCA; sustainability indicators

1. Introduction

The interdependencies between social equity, ecological systems and the economy have continued to be recognized by decision makers as vital elements of functional public policy formation. Indeed, policies that fail to consider all three pillars of sustainability are thought to be less effective in terms of enacting the change required for future generations to thrive. Consequently, studies connecting human welfare with ecological processes are on the rise [1-3], with the valuation of urban ecosystems receiving increased attention by governing agencies, researchers, and policy makers [4,5]. This interest is triggered by the awareness that a city’s natural systems play a significant role in moderating urban resiliency and sustainability outside of local ecological processes [6]. Here, the concept of ecosystem services (ES) provides a new paradigm by which to model the relationship between humans and the natural environment.

ES are generally defined as the value humans obtain, whether social, economic or ecological, from natural ecosystems (both wild and managed) and the flora and fauna species they comprise [7,8]. Research addressing ES has increased over the past two decades as part of the policy debates regarding
the value of ecological systems for long-term human well-being and sustainable development [9,10]. As a result, many definitions or classifications of ES currently exist. For the purpose of this study, a broad yet operational approach to defining ES is taken, which includes the benefits that humans derive, either directly or indirectly, from ecological functions and processes [11]. In this context, these functions or processes only become services if individual (i.e., human) beneficiaries exist [12].

To promote a sustainable and resilient city, a comprehensive understanding of significant demographic and ecological trends affecting the population is required. The valuation of ES and user benefits can operate on multiple, often conflicting dimensions. Traditionally designed to bridge ecology and economy through economic language and logic (e.g., goods and services), this conceptual framework has developed into a useful tool for interdisciplinary work, acting as a ‘boundary object’ [13], whereby different actors collaborate to inform sustainable planning practices [14,15]. A ‘boundary object’ is an analytical concept or tool used to theorize and identify how different groups can work together [15]. In this sense, ‘boundary objects’ can be abstract, such as a concept that promotes collaboration across disciplines (i.e., ecosystem services), or concrete, such as an interdisciplinary tool or application (i.e., a map).

Developed as a conceptual framework aimed at quantifying human reliance on the environment, the idea of ES has taken root in more practical applications such as policy development and evaluation metrics [16–18]. The ES framework is used in a variety of planning and policy applications, including environmental policy assessment and the design of market-based incentives for environmental conservation [19]. Recent trends indicate that cities seek to increase the amount and quality of green space to ensure ES user benefits are produced and available at a range of ecological and institutional scales [16,20]. However, the capacity of ES to inform policy is still limited by the complexity of, and interaction between, human societies and ecological systems [9].

This paper aims to quantify ES user benefits spatially by developing an integrated urban environmental-deprivation index. The development of an area-based environmental-deprivation (or sustainability) index offers a unique approach to support decision makers and smart urban planning practices by combining multiple environmental and socioeconomic indicators into one performance measure at various measurement scales (or resolutions). The examination of spatial discordance between ES and the residential stakeholders who may benefit from them, provides a novel planning tool that can assess urban sustainability and equity at the neighbourhood level. Investigating spatial scale and stakeholder benefits can promote the application of ES to support practical decision-making processes. Therefore, the objectives of this study are threefold:

1. To evaluate relative urban environmental performance and community deprivation at a small measurement scale to provide a detailed analysis of spatial trends;
2. To develop an integrated environmental-deprivation index based on the three pillars of sustainability in order to identify potentially vulnerable communities;
3. To address the potential impact of using different measurement scales when evaluating ES and user benefits on decision-making processes or policy outcomes.

The term scale often refers to both spatial extent and resolution. However, for the purpose of this study, the extent will remain constant (i.e., the City of Toronto). Thus, the term ‘scale’ will refer specifically to data resolution (i.e., the granularity of data) or the measurement scale, which, in this case, relates to the number of enumeration units (or census levels). The construction of an environmental-deprivation index is based on a landscape approach to quantifying urban ES, whereby specific land use and land cover properties act as representatives of ecosystem processes [16,18]. This approach allows for detailed analysis of key factors spatially.
2. Research Background

2.1. The Concept of Urban ES

ES is a conceptual framework that provides a referencing system used to characterize and manage human–environment interactions [21]. The general notion of ES differs from traditional environmental frameworks that tend to focus on the impact human populations have on the environment through various industrial or commercial activities [7]. In this approach, natural ecosystems are treated as externalities, whereby the environment is affected by human activities. Conversely, the ES framework considers the natural environment (including corresponding goods and services) as playing a central role in achieving sustainable development.

ES can be broadly categorized into four groups including supporting services (e.g., biodiversity and habitat), provisioning services (e.g., food and water), regulating services (e.g., temperature regulation, noise reduction, and air purification) and cultural services (e.g., recreation, aesthetics, and cognitive development) [6,13]. However, these groups are not mutually exclusive, with many ecological processes and functions producing multiple benefits. Further, ES and user benefits are not always identical [12]. For example, recreation is classified as a cultural ES. However, this service requires additional social and built capital and is, therefore, a benefit of multiple inputs not just the ecological component [22].

Urban ES are generally defined as the services and benefits of urban and peri-urban ecosystems. Specific density measures or the proportion of the built area within a region have been used to delineate or categorize an area as urban. However, [23] put forward a framework of cities that encompasses much more than a prescribed density or cluster of humans and development, focusing instead on the complex social-ecological systems underlying these unique ecosystems. Often characterized as a highly fragmented or patchy landscape, urban spaces are heavily influenced by human development and social constructs. ES and user benefits within an urban context are usually interrelated and the result of complex underlying social-ecological patterns [24]. Therefore, in urban planning practices, ecosystems are normally composed of both built and ecological infrastructure. In addition, the trend of high-intensity demand of local environmental systems to a large population of immediate beneficiaries or users nearby generally separates urban centres from rural areas [5].

Ecological infrastructure normally encompasses all ‘green and blue spaces’ that may be found within the boundaries of, or adjacent to, an urban centre [6]. This includes city parks, community gardens, urban forests, street trees, designated green roofs, ravines, rivers, lakes and wetlands [5]. The complexities associated with exploring broader-scale relationships between ES, user benefits, and geography are somewhat diminished in an urban setting, as local planning policies generally delineate or dictate specific land use patterns. Urban ES are particularly crucial for providing residents with direct benefits regarding health and security, such as air purification and urban cooling mechanisms [6].

As urban centres continue to grow exponentially, the need to balance inherent trade-offs in developing urban space (e.g., retail and residential development) with conserving natural space (e.g., increasing the tree canopy coverage) will continue to be a major conflict for urban planners and decision makers. Bringing together multiple perspectives and modeling the ES framework spatially allows us to foster more pragmatic and integrated policy development and implementation tools.

2.2. Measuring ES User Benefits: Human Well-Being and Spatial Scale

Human well-being is inherently connected with ES [25]. Specifically, ES user benefits, while dependent on particular services, are linked directly to changes in human well-being. In this sense, the term ‘well-being’ is extracted from a population health perspective, whereby the most important determinant of human well-being is the socioeconomic characteristics of an individual and the neighbouring population. Factors of socioeconomic status vary and can include income, unemployment, health, and security variables, categorized as contextual measures in general. Cities as dynamic,
yet highly designed and managed landscapes allow for the exploration of complex relationships that exist between ES and user benefits, offering unique models for investigating potential spatial links and interdependencies [26].

Arguably, the consideration of ES trade-offs from a well-being perspective can provide an appropriate evaluation tool to guide urban land use and planning practices [27]. Within an urban setting, natural ecosystems are limited yet contribute significantly to the population's relative health, well-being, and the economy. Research has demonstrated that access to urban green spaces can improve mental health and reduce stress [28,29]. Empirical studies have shown that an increase in natural coverage and greenspace positively correlates with physical health, noting significantly less chronic health conditions such as diabetes or heart disease [30]. Furthermore, green infrastructure has demonstrated capabilities as a municipal asset that provides valuable services such as recreation, climate regulation and air quality control.

Conceivably, while the concept of ES is often used to improve ecosystem management for human well-being, specific gaps in how to govern ecological benefits remain. Identifying which stakeholders benefit the most from the provision of ES remains largely unaddressed. Recognizing spatial patterns of ES and user benefit would further highlight what [31] define as ES trade-offs in space, whereby an ES management decision benefits one group or stakeholder at the expense of another group or stakeholder. These trade-offs are common in managing human–environment interactions [32]. Therefore, understanding and managing these relationships between services and across spatial and temporal scales is thought to produce better outcomes [24]. Consequently, spatially explicit approaches to mapping ES have continued to develop [33–36], with a particular focus on the spatial distribution of ES in terms of social welfare [3].

ES research bridges gaps in landscape ecology and urban planning by addressing issues related to the distribution and utilization of user benefits [12]. ES are produced at all scales [20]. For example, a backyard tree can provide direct supporting (i.e., habitat) and cultural (i.e., aesthetics) services at the scale of an individual or a household, while also contributing to regulating services such as air purification or carbon sequestering for a much larger urban region. The scale at which ES user benefits are quantified can portray unintended consequences of specific decision-making actions. For example, human activities and decisions in one region can impact the availability of ES in distant areas, highlighting the inherent links between social and ecological systems that are separated geographically [37]. Some researchers suggest that addressing this challenge requires identifying synergies and trade-offs between ES at various spatial scales [24].

Spatial scale is especially relevant when assessing which stakeholders are benefitting from which ES [3]. There are many possible spatial relationships between the scale at which an ES is produced and the scale at which people may benefit from it. Social structures further exacerbate these complex spatial interdependencies (i.e., built infrastructure), and the constructs that govern access to these services [38]. Mechanisms of access determine which individuals or groups benefit from which ES [32]. Although the interdisciplinary framework underlying most ES studies aims to identify and mitigate this uneven access, it has yet to eliminate the unequal power relations that exist between different stakeholders and benefits [39]. Identifying operating scales and stakeholder benefits can highlight potential conflicts in environmental management [20]. Often, how user’s benefit from certain ES depends on their relative proximity to the service produced and access to decision-making processes in general [9,40].

3. Materials and Methods

3.1. Case Study: The City of Toronto, Canada

The City of Toronto is a major Canadian city situated in the province of Ontario (see Figure 1). Although Toronto is densely populated, with approximately three million residents and growing [41], many natural occurring ravines and designated green spaces are found throughout the urban landscape. Balancing urban infrastructure development and environmental protection has become a key priority...
For City officials, with demonstrated efforts to understand and evaluate ES within the urban boundaries. For example, the ES and associated user benefits provided by the urban forest and natural ravine systems within the City have recently been evaluated and quantified [42,43]. Consequently, the City of Toronto was purposely chosen for this study as key decision makers have recognized the value of urban green spaces. This recognition has, in turn, led to the development of key environmental datasets and information needed to further explore the spatial discrepancies in ES at a small measurement scale.

Figure 1. The City of Toronto, Ontario, Canada (the study area or geographic scale).

To investigate spatial inconsistencies in socioeconomic and ecological trends, and to support informed decision-making processes, an integrated environmental-deprivation index (Enviro-Dep Index) was developed. The following provides a breakdown of the two composite indices combined for this study, including the material deprivation index (Dep-Index) and the urban environmental index (Enviro-Index).

3.2. Methodology

Figure 2 depicts the general workflow process implemented for this research, specifically the construction of the integrated environmental-deprivation index (Enviro-Dep Index). The urban environmental index (Enviro-Index) was developed using GIS-MCDA methods. The first step in this approach is to determine a theoretical framework, which, in this case, is urban environmental quality. Steps to defining objectives and selecting criteria that best represent the urban environmental quality follow and are presented in Table 1. Specific measurement scales were chosen to be consistent with the material deprivation index (Dep-Index). Criteria were then re-scaled, weighted and combined using weighted linear combination (or WLC). The material deprivation index (Dep-Index) was developed by local and provincial health agencies that use principal component analysis (or PCA) to combine individual indicators. These two disparate indices were then converted and combined into one categorical index characterizing urban sustainability measures (i.e., the integrated environmental-deprivation index or the Enviro-Dep Index).
3.3. The Material Deprivation Index (Dep-Index)

The material deprivation index (or Dep-Index) used for the socioeconomic component of this study is based on the Ontario Marginalization Index or ON-Marg. The ON-Marg is an area-based composite index developed by researchers at the Centre for Urban Solutions at St. Michael’s Hospital in Toronto, Canada, and Public Health Ontario (PHO), a provincial health agency in Ontario, Canada. The ON-Marg index is openly available for public use. For the purpose of this study, the material deprivation dimension, which refers to the ‘inability for individuals and communities to access and attain basic material needs’ [44] (pp. 8), was used. Based on previous literature, this dimension measures housing, income, education, and family structure characteristics thought to be closely associated with community poverty [45]. Variables representing neighbourhood material deprivation (e.g., proportion of lone-parent households, housing conditions, poverty rate, etc.), were combined using principal component analysis (PCA) to create an area-based score for each areal unit at each spatial resolution [44]. The principal component scores indicate a negative relationship with socioeconomic measures, whereby higher scores equate to lower socioeconomic status (i.e., higher community material deprivation).
Table 1. Selected attributes, standardized variables, normalization strategy and weighting schemes used for the Enviro-Index.

| Attributes (a)                  | Standardized Variable (b)               | Transformation (c) | Weight (d) |
|--------------------------------|-----------------------------------------|--------------------|------------|
| Tree Canopy                    | Proportion of Tree Canopy Cover (%)     | Maximization       | 9%         |
| Grass/Shrubs/Bare Earth        | Proportion of Grass/Shrub/Earth Cover (%) | Maximization       | 8%         |
| Natural Areas/City Parks       | Proportion of Natural Cover/Parks (%)   | Maximization       | 25%        |
| Green Roofs                    | Distance to Green Roof Area (m)         | Minimization       | 8%         |
| Population Density             | People/sq.km.                           | Minimization       | 12%        |
| Major Roads                    | Density of Major Roads (km/sq.km)       | Minimization       | 5%         |
| Building Height                | Average Building Height (m)             | Minimization       | 8%         |
| Elevation                      | Average Elevation (m)                   | Minimization       | 5%         |
| Slope                          | Average Slope (% change)               | Maximization       | 10%        |
| Aspect                         | Average Aspect (degrees) *              | Maximization       | 10%        |

* Aspect was calculated from the digital elevation model (DEM) slope and reclassified into seven categories to reflect preferred sun exposure for optimal biodiversity, then averaged for each areal unit. For more details regarding this indicator, refer to [46].

3.4. The Urban Environmental Index (Enviro-Index)

The second component of the integrated Enviro-Dep Index was the urban environmental index derived from [46]. The urban environmental index (Enviro-Index) was developed using the conceptual framework of GIS-MCDA which provides a rational framework for structuring decision problems by way of objectives, criteria, and weights. GIS-MCDA is a set of techniques and procedures used to model complex spatial decisions by combining spatial and non-spatial data, and evaluating decision alternatives (i.e., area-based scores) [47]. GIS-MCDA is a process that transforms and combines a set of criteria that best characterizes the spatial phenomenon assessed using weighted optimization techniques and decision maker preferences (or priorities) based on an underlying model or framework [16]. For the purpose of this study, the GIS-MCDA index takes a normative (or value-laden) approach to decision making (i.e., how rational agents should make decisions).

Ten criteria were chosen to characterize desirable urban environmental quality (see Table 1). These criteria were adapted from the urban biodiversity index presented by [46] and were mainly derived from topographic features and land cover attributes readily available from open datasets. The construction of a GIS-MCDA based index requires the developer to transform all variables to a common scale or value range (see Table 1, column c). Normalized variables entered into the application were re-scaled using the maximum score procedure, then weighted and combined using a weighted linear combination (WLC) approach in order to produce composite index scores. The maximum score procedure transforms each criterion to a common scale between 0 and 1 that is anchored at 0 for cost criteria (i.e., lower values are preferred, minimization) or 1 for benefit criteria (i.e., higher values are preferred, maximization) [48]. The WLC decision rule then applies weights to each indicator based on their perceived importance within the decision-making context and combines them into a final composite score for each areal unit based on their performance within the framework.

3.5. The Integrated Environmental-Deprivation Index (Enviro-Dep Index)

In order to integrate these two distinct composite indices, we adopted a similar approach to [49], whereby area-based evaluation scores were first standardized for comparison and then combined. Composite index scores were converted to z-scores for the Dep-Index and Enviro-Index at each measurement scale (i.e., dissemination area and census tracts). Cut-offs points were then determined based on the area-based z-score, whereby a z-score is reclassified as ‘high’ if ≥1, ‘medium’ if between 1 and −1, and ‘low’ if ≤−1. Using standardized z-scores allows each separate index to be reclassified into three categories (i.e., high, medium, or low) that represent either relative community deprivation or environmental quality. This process transforms the original GIS-MCDA and PCA scores, represented as continuous variables, to categorical variables based on z-scores, resulting in nine groups of areal units.
that characterize the human–environment relationship (see Table 2). ES modeled as a composite index allows researchers to combine multidimensional concepts to derive more meaningful information relating to the inherent trade-offs between individual indicators [50]. These nine categories were then re-grouped (or further generalized) into three classifications of sustainability, including ‘sustainable’, ‘somewhat sustainable’, and ‘not sustainable’. This transformation of index scores into ordinal measurements (or categories) thus provides an intuitive area-based ranking system. For example, an area identified as ‘High-Low’ using the integrated Enviro-Dep Index could represent a community situated near urban ES (i.e., green spaces) with little poverty (i.e., relatively low material deprivation), thereby justifying its classification as ‘Sustainable’.

Table 2. Integrated Enviro-Dep Index based on combined z-score classifications (i.e., z-score = ‘high’ if ≥1, ‘medium’ if (1, −1), and ‘low’ if ≤−1) that result in a total of 9 categories that characterize the human–environment relationship for each areal unit. These nine categories are further classified as three levels of sustainability including ‘sustainable’, ‘somewhat sustainable’, and ‘not sustainable’.

| Classification          | Enviro-Dep Index | Definition                                                        |
|-------------------------|------------------|------------------------------------------------------------------|
| Sustainable             | High-Low         | High Enviro. Performance/Low Material Deprivation                 |
| Sustainable             | Medium-Low       | Medium Enviro. Performance/Low Material Deprivation               |
| Sustainable             | High-Medium      | High Enviro. Performance/Medium Material Deprivation              |
| Somewhat Sustainable    | High-High        | High Enviro. Performance/High Material Deprivation                |
| Somewhat Sustainable    | Low-Low          | Low Enviro. Performance/Low Material Deprivation                  |
| Somewhat Sustainable    | Medium-Medium    | Medium Enviro. Performance/Medium Material Deprivation            |
| Not Sustainable          | Low-High         | Low Enviro. Performance/High Material Deprivation                 |
| Not Sustainable          | Medium-High      | Medium Enviro. Performance/High Material Deprivation              |
| Not Sustainable          | Low-Medium       | Low Enviro. Performance/Medium Material Deprivation               |

3.6. Measurement Scale and Uncertainty

Scale is one of the most fundamental concepts in social and ecological research, as spatial patterns are subject to the scale of observation (i.e., geographic and measurement scale) [51]. Often, criteria are assessed and indicators built using spatially aggregated data. However, the level of aggregation can either conceal local variance (coarser resolution) or spatial patterns can become too confounded (finer resolution). In this sense, the spatial discordance between certain phenomena must be assessed within the context of the measurement scale chosen, as the relationship between different indicators (social and ecological) is thought to vary significantly with scale, a concept referred to as the modifiable areal unit problem (MAUP). The MAUP is a well-documented statistical biasing effect concerning the use of areal units or spatially aggregated data, whereby the study results are subject to the size and shape of the areal units chosen [52,53]. There are two different, but related issues that concern the MAUP—the scale effect (i.e., the number and size of areal units) and the zoning effect (i.e., the shape of areal units) [53,54]. In general, the use of aggregated units can call into question study reliability, as the results are sensitive to the often arbitrarily defined areal units used to aggregate the data. Ref. [55] suggest that uncertainty due to analytical methods (i.e., scale mismatches or the MAUP) can be minimized by considering the scale and boundary limitations throughout the investigative process. Further, exploring various spatial resolutions can address the potential impact of different scales on policy outcomes [56,57], enabling such measures to be integrated into land use planning practices.

To address the limitation of using aggregated data, this study developed the integrated environmental-deprivation index using two different measurement scales, including dissemination areas (DAs) and census tracts (CTs), to explore the impact of scale on study outcome, as well as potential policy implications. DAs are small, somewhat stable geographic units normally comprising one or more adjacent dissemination blocks, average approximately 400 to 700 persons and covering Canada’s entire geography [58]. Comparatively, CTs are only available in Canada’s census metropolitan areas and census agglomerations (defined by a core population of 50,000 persons or more) and usually have a population of fewer than 10,000 persons [58].
4. Results

4.1. The Urban Environmental Index (Enviro-Index) and the Material Deprivation Index (Dep-Index)

Figure 3 visualizes the two indices (i.e., Enviro-Index and Dep-Index) at two different measurement scales or census levels (i.e., DAs and CTs) using standard deviations to reclassify the datasets into groups that depict how much a feature (i.e., areal unit) value varies from the mean. This two-colour ramp distinguishes values that are above the dataset mean (depicted in blue/green tones) from those below the dataset mean (depicted in red/brown tones). Here, we can see some interesting patterns emerge in comparing the Enviro-Index and Dep-Index, and the impact of areal unit size on the geographic pattern (i.e., MAUP). For all four indices, most of the DAs and CTs fall within the ‘medium’ category (i.e., z-score between −1 and 1), ranging from 70% to 80% of all areal units falling within this classification.

For the Enviro-Index (see Figure 3a,c), 12.2% of DAs and 15.6% of CTs performed well in terms of urban environmental quality, while 8.3% of DAs and 10.7% of CTs were considered poor environmental performers. In general, the areas that scored high in the Enviro-Index were situated near local protected areas (i.e., ravines), large urban parks (e.g., High Park) and the lakeshore. Comparably, areas of low environmental quality were located in the downtown core and other areas of high industrial or commercial development.

The Dep-Index (see Figure 3b,d) had a similar split in terms of the proportion of areal unit categories as ‘High’ or ‘Low’, with 12.5% of DAs and 14.3% of CTs classified as vulnerable populations.
(i.e., high material deprivation scores), and 12.4% of DAs and 14.0% of CTs depicting areas of low material deprivation. Generally speaking, more vulnerable populations tend to be situated in areas of low environmental performance.

4.2. The Integrated Environmental-Deprivation Index (Enviro-Dep Index)

Figure 4 provides a geographical representation of the integrated Enviro-Dep Index at the DA and CT levels (see Figure 4a,c). Combining the Enviro-Index and Dep-Index allows us to identify potential spatial discrepancies in ES and user benefits by assessing the human–environment interactions across varying city neighbourhoods. In this context, the term neighbourhood is defined as either a DA or CT depending on the measurement scale. The majority of communities fall within the ‘Medium-Medium’ category (see Table 3), defined as areas of adequate environmental quality and material deprivation, representing approximately 54% of the total population. The next two most extensive classifications include ‘Medium-High’ and ‘High-Medium,’ representing approximately 10% of the total population, respectively, for each measurement scale. Of particular note are areas categorized as ‘High-Low’ (i.e., areas that exhibit high environmental quality/low material deprivation), which account for only 1.7% (DAs) and 2.3% (CTs) of the total population. These areas are generally clustered linearly along known urban ravines such as the Don Valley and Humber River. Comparably, areas classified as ‘Low-High’ (i.e., areas that represent poor environmental quality/high material deprivation) account for 2.6% (DAs) and 1.8% (CTs) of the total population and exhibit a U-shaped pattern with pockets located in east and west portions of the City.

Interestingly, areas categorized as ‘Low-Low’ (i.e., communities that performed poorly in terms of environmental quality but indicated less material deprivation) accounted for between 1.6% (DAs) and 4.1% (CTs) of the total population and were found to be mostly clustered in the downtown core west, whereas areas categorized as ‘High-High’ (i.e., communities that performed well in terms of environmental quality but also indicated high levels of material deprivation) accounted for 2.7% (CTs) to 4.2% (DAs) of the total population and were generally situated in small clusters in east and west portions of the City.

Figure 4. The integrated Enviro-Dep Index at the DA and CT level. This index was further classified into three levels of sustainability including ‘sustainable’, ‘somewhat sustainable’, and ‘not sustainable’.
### Table 3. Population summary statistics of the integrated Enviro-Dep Index.

| Classification       | Integrated Enviro-Dep Index | % of DAs | Total DA Pop. | % of DA Pop. | % of CTs | Total CT Pop. | % of CT Pop. |
|----------------------|----------------------------|----------|---------------|-------------|---------|---------------|-------------|
| Sustainable          | High-Low                   | 1.7%     | 46,375        | 1.7%        | 3.1%    | 63,305        | 2.3%        |
| Sustainable          | Medium-Low                 | 8.2%     | 282,485       | 10.3%       | 7.9%    | 199,205       | 7.3%        |
| Sustainable          | High-Medium                | 8.5%     | 256,200       | 9.4%        | 9.8%    | 268,915       | 9.8%        |
| Somewhat Sustainable | High-High                  | 2.0%     | 113,555       | 4.2%        | 2.6%    | 72,580        | 2.7%        |
| Somewhat Sustainable | Medium-Medium              | 62.7%    | 1,462,085     | 53.6%       | 54.2%   | 1,483,275     | 54.3%       |
| Not Sustainable      | Low-High                   | 1.9%     | 69,695        | 2.6%        | 1.7%    | 48,965        | 1.8%        |
| Not Sustainable      | Medium-High                | 8.6%     | 295,300       | 10.8%       | 10.0%   | 264,825       | 9.7%        |
| Not Sustainable      | Low-Medium                 | 5.5%     | 160,550       | 5.9%        | 7.7%    | 217,390       | 8.0%        |

Interestingly, areas categorized as ‘Low-Low’ (i.e., communities that performed poorly in terms of environmental quality but indicated less material deprivation) accounted for between 1.6% (DAs) and 4.1% (CTs) of the total population and were found to be mostly clustered in the downtown core west, whereas areas categorized as ‘High-High’ (i.e., communities that performed well in terms of environmental quality but also indicated high levels of material deprivation) accounted for 2.7% (CTs) to 4.2% (DAs) of the total population and were generally situated in small clusters in east and west portions of the City.

### 4.3. Measurement Scale and Uncertainty

Tables 4–7 represent key demographic and environmental indicators associated with the three levels of sustainability at two different measurement scales (see Figure 4b,d). Tables 4 and 6 depict summary statistics of specific environmental indicators that account for the most model variation in the Enviro-Index, including the proportion of tree canopy coverage, the proportion of natural areas and city parks, population density, average slope and elevation for each level of sustainability. Tables 5 and 7 depict summary statistics for some of the socioeconomic indicators that comprise the Dep-Index, derived from the 2016 Canadian Census (Statistics Canada).

### Table 4. Summary statistics of key environmental indicators associated with the sustainability of a community at the DA level.

| Classification       | Total Pop. (2016) | % of Total Pop. | Pop. Density (per sq.km) | Tree Canopy Coverage (%) | Natural Areas/City Parks (%) | Average Elevation (m) | Average Slope (% change) |
|----------------------|-------------------|-----------------|--------------------------|--------------------------|-----------------------------|------------------------|--------------------------|
| Sustainable          | 585,060           | 21.4%           | 2692.2                   | 38.0%                    | 43.3%                       | 132.23                 | 5.16                     |
| Somewhat Sustainable | 1,619,430         | 59.3%           | 4568.9                   | 23.7%                    | 11.6%                       | 150.82                 | 2.48                     |
| Not Sustainable      | 525,545           | 19.3%           | 9467.5                   | 17.8%                    | 7.0%                        | 153.95                 | 2.20                     |
| City-Wide Trends     | 2,730,035*        | 100%            | 4594.8                   | 28.3%                    | 22.4%                       | 144.54                 | 3.40                     |

* Total population by DA and actual municipal total may differ slightly due to data suppression and rounding.

### Table 5. Summary statistics of key socioeconomic indicators associated with the sustainability of a community at the DA level.

| Classification       | No. of DAs | % of DAs | Pop. without Degree, Diploma or Certificate (%) | Lone-Parent Households (%) | Unemploy. Rate (%) | LICO (%) | Homes in Needs of Major Repairs (%) |
|----------------------|------------|----------|-----------------------------------------------|---------------------------|-------------------|----------|-------------------------------------|
| Sustainable          | 682        | 18.4%    | 4.7%                                          | 14.7%                     | 6.3%              | 12.2%    | 4.3%                                |
| Somewhat Sustainable | 2425       | 65.5%    | 10.0%                                         | 20.1%                     | 8.1%              | 16.0%    | 7.0%                                |
| Not Sustainable      | 595        | 16.1%    | 18.0%                                         | 32.4%                     | 11.4%             | 27.8%    | 10.8%                               |
| City-Wide Trends     | 3702       | 100%     | 10.3%                                         | 21.2%                     | 8.2%              | 17.4%    | 7.1%                                |

Communities classified as ‘sustainable’ (represented as dark green) or ‘not sustainable’ (represented as light green) each account for approximately 20% of the total population (i.e., sustainable = 21.4% (DAs) and 19.5% (CTs) of the total population; not sustainable = 19.3% (DAs) and 19.4% (CTs) of the total population), with the remaining communities classified as ‘somewhat sustainable’ (i.e., 59.3% of DAs and 61.1% of CTs of the total population). Communities classified as ‘somewhat sustainable’ closely tracked with the city-wide socioeconomic averages at both the CT and DA level, but generally had below-average performance for many environmental indicators.
Table 6. Summary statistics of key environmental indicators associated with the sustainability of a community at the CT level.

| Classification          | Total Pop. (2016) | % of Total Pop. | Pop. Density (per sq.km) | Tree Canopy Coverage (%) | Natural Areas/City Parks (%) | Average Elevation (m) | Average Slope (% change) |
|-------------------------|------------------|----------------|--------------------------|--------------------------|-----------------------------|-----------------------|--------------------------|
| Sustainable             | 531,425          | 19.5%          | 2980.6                   | 40.8%                    | 40.8%                       | 131.71                | 5.13                     |
| Somewhat Sustainable    | 1,668,760        | 61.1%          | 4326.3                   | 23.7%                    | 15.3%                       | 149.69                | 2.71                     |
| Not Sustainable         | 531,180          | 19.4%          | 7569.9                   | 21.5%                    | 22.4%                       | 148.75                | 2.84                     |
| City-Wide Trends        | 2,731,365*       | 100%           | 4306.9                   | 28.3%                    | 22.4%                       | 144.54                | 3.40                     |

* Total population by CT and actual municipal total may differ slightly due to data suppression and rounding.

Table 7. Summary statistics of key socioeconomic indicators associated with the sustainability of a community at the CT level.

| Classification          | No. of CTs | % of CTs | Pop. without Degree, Diploma or Certificate (%) | Laws-Parent Households (%) | Unemploy. Rate (%) | LICO (%) | Homes in Needs of Major Repairs (%) |
|-------------------------|------------|---------|-----------------------------------------------|---------------------------|-------------------|---------|-----------------------------------|
| Sustainable             | 119        | 20.8%   | 5.4%                                          | 16.5%                     | 7.3%              | 12.3%   | 5.7%                              |
| Somewhat Sustainable    | 342        | 59.8%   | 10.1%                                         | 20.3%                     | 7.9%              | 16.5%   | 6.9%                              |
| Not Sustainable         | 111        | 19.4%   | 16.0%                                         | 29.1%                     | 10.5%             | 25.4%   | 9.2%                              |
| City-Wide Trends        | 572        | 100%    | 10.3%                                         | 21.2%                     | 8.2%              | 17.4%   | 7.1%                              |

Communities deemed ‘sustainable’ generally had above-average education levels and below-average poverty indicators such as income, unemployment and major housing repairs. Most of these communities clustered along established protected areas, large urban parks and along the lakeshore. On average, the ‘sustainable’ communities had approximately 10% (DAs) to 13% (CTs) more tree canopy coverage and 18% (CTs) to 21% (DAs) more natural areas and green spaces compared to city-wide trends. Comparably, communities depicted as ‘not sustainable’ had a much higher prevalence of poverty, below-average education and homes in need of major repairs. In terms of environmental indicators, ‘not sustainable’ communities had, on average, approximately 7% (CTs) to 11% (DAs) less tree canopy coverage and 7% (CTs) to 15% (DAs) less natural areas and green spaces compared to City of Toronto as a whole.

5. Discussion

These results demonstrate the inherent spatial interdependencies between socioeconomic indicators, environmental quality (i.e., most notably, available green space), and spatial scale. The term scale, in this context, is broadly defined as the physical dimension in space of the observations being modelled [59]. As outlined in Figure 5, ecological, socioeconomic, and administrative scales are varied and generally address a hierarchical structure from global to local, distinguishing the spatial context. This study is specifically focused on the spatial discrepancies in local or neighbourhood-level trends. This section discusses the interdependencies between the small-scale distributions of ES and user benefits, and the policy implications for governing urban ES both locally and regionally.

Figure 5. Select ecological, socioeconomic, and census geography scales (adapted from [20]).
5.1. Mapping ES User Benefit and Scale Interdependencies

Mapping ES user benefits using an environmental-deprivation area-based composite index allows us to explore the concept from multiple perspectives, providing unique spatial insights. Several studies have argued that investigating inherent trade-offs in ES and stakeholder benefits requires multiple factors to be considered [12, 60, 61]. The spatially explicit approach adopted here, which combines and compares multiple socioeconomic and environmental data, can further develop our understanding of the unique intricacies of urban ES and user benefits.

Comprehensive spatial analysis of landscape and neighbourhood characteristics can offer a powerful tool for uncovering relationships between human activities, well-being, and the environment. Particularly in cities, a broad range of landscape characteristics (i.e., land use) and stakeholder interests co-exist in very close proximity, resulting in a complex network of resource availability, accessibility, and population needs [1]. Urban ES can moderate many environmental and socioeconomic issues in cities, yet abrupt transformations in land use or transitions in socioeconomic, natural and built systems within a city can often occur at the scale of a city block [61, 62]. Accordingly, a spatially explicit approach to quantifying both ecological and socioeconomic systems can provide a new decision-support tool used to identify potential trade-offs in urban planning priorities [16].

These results highlight areas of particular concern, whereby low environmental quality is spatially correlated with high levels of material deprivation. The decision context assesses the spatial distribution of ES in terms of potential socioeconomic or user benefit. The range of studies that characterize ES at various urban scales is still relatively limited [61]. Yet the exploration of sustainability concepts such as ES provides a unique opportunity for experiments that connect urban design principles and ecological processes. This approach demonstrates the spatial interdependencies of human–environment systems using small-scale planning geographies or units for more tailored policy intervention strategies.

The issue of (measurement) scale in ES studies is complex. The interactions between human and ecological systems or ES are generated at a variety of scales (both spatially and temporally). They can range from short-term, site-specific benefits such as a community park or local amenity to larger, long-term or global benefits such as climate regulation and carbon sequestering [20]. Consequently, decision makers need to have a comprehensive understanding of the different scales at which ES are produced, used and accessed in order to identify, manage and quantify associated values. In this sense, detecting and reporting ES patterns at multiple scales provides an effective management strategy for decision making [18]. Researchers further suggest that determining what scales are adequate for exploring ES patterns ultimately depends on the overarching purpose of the ES assessment to begin with [18, 61]. Studies that aim to highlight cost–benefit analysis or trade-off assessment, for example, are typically carried out using a subnational or local/regional approach to mapping ES trends, and derived from land use/cover appropriate for finer-resolution (or measurement scale) assessments [61]. This compares to ES compliance or consistency studies which may focus on a more global level [61]. Generally speaking, a meaningful assessment of ES patterns for decision makers requires information that is developed and modelled using units that represent a level at which certain ES decisions are actually managed and evaluated over time and space (i.e., neighbourhood, municipality, watershed, etc.), instead of just the underlying ecological processes [18, 61].

This study aims to address spatial discordances in human–environment interactions using two urban neighbourhood levels or measurement scales. A challenge to assessing these inherent links or trade-offs is the extensive range of scales at which ecological and socioeconomic systems operate (see Figure 5). Natural systems are often characterized as heterogeneous, flexible, and cooperative and can range from the entire biosphere (where life exists) to an individual component such as a tree [20]. Comparably, human systems tend to be more centralized and represent a rigid hierarchy of institutional scales from international agencies to a person or a household [20]. Quantifying broad-scale ES that measure trends on a global or regional level, while important, is often burdened with complexities associated with global resource chains, conflicting policies, political challenges, and management actions that coincide. Generally speaking, as the geographic scale of a study increases (i.e., a larger
scope or study area), so do ES trade-offs in space, whereby optimizing one service leads to a reduction in other services geographically. Such trade-offs become increasingly hard to evaluate and manage [31]. Within an urban context, however, both systems are often heavily influenced by human actions, interests, and priorities, allowing in some sense for more direct links between the human and ecological systems to be established. The scale at which an ES is supplied often then determines which stakeholders can benefit from it.

5.2. Governing ES and Policy Implications

Cities worldwide expect to absorb the majority of the future population growth [63]. This demographic shift concentrates the need to better manage ES in and around urban areas. Urban ecosystems are unique in composition, demonstrating the interconnectedness between biological and physical features, and built and social components that influence spatial structures and landscapes [64]. As urbanization trends continue, challenges persist in creating and maintaining sustainable cities in an equitable way. It has also become increasingly evident to policy makers and planning practitioners that nature-based solutions can mitigate some key population issues in a more cost-effective and sustainable manner [4].

A central component of most cities is green space (i.e., city parks, protected areas, and community gardens) that varies in size and function between cities and across urban landscapes. Urban green spaces contribute significantly to ecological processes (e.g., biodiversity), social constructs (e.g., infrastructure) and quality of life measures [65]. Proximity to green spaces provides residents with opportunities to connect with nature and benefit from certain ES generated from these systems [66]. For example, studies have found that the demand for smaller green spaces in dense urban areas can be higher than the demand for large green spaces found in adjacent or peri-urban areas [60]. The demand for green space in urban areas is less correlated to size or function due to the unique dependencies of urban populations on nearby green spaces to provide critical social connections and neighbourhood cohesiveness [67].

Urban green spaces can provide monetary (e.g., pollution removal and energy saving) and non-monetary value (e.g., social cohesion and cognitive development) through a variety of complex mechanisms. Such ES are particularly crucial for diverse communities affected by low employment rates, poverty, and housing disrepair [68]. The degree to which any community can benefit from local ecosystems is dependent on a range of sociocultural institutions rooted in complex geographies of access [3]. This study contributes to urban planning practices more broadly by identifying areas of unique human–environment interactions that require further investigation. For example, areas of high environmental quality and high material deprivation (see Figure 4) are identified. These communities have above-average population density, tree canopy coverage, and proportion of natural areas or city parks, yet are burdened with high rates of relative household or neighbourhood unemployment and poverty. Such communities are interesting to evaluate in terms of specific monetary benefits (e.g., lower energy bills, accessibility to community gardens) and non-monetary benefits (e.g., reduced risk of certain physical or mental health implications associated with poverty) provided by the local urban green spaces that could potentially offset some socioeconomic indicators in terms of long-term neighbourhood sustainability and well-being.

Further, research has indicated that urban ecosystems provide opportunities for cognitive development and education. Public spaces bring people together in cities [69]. This is particularly salient for more vulnerable populations, yet these findings indicate that, generally speaking, there is a tendency for areas of high environmental quality to be consistently situated in high-income neighbourhoods (i.e., ‘Sustainable’). Most urban planning inherently includes decisions about justice, equity, and access. For example, the concept of a neighbourhood is promoted as a tool with which complex urban space can be subdivided for planning purposes. Urban space in this context can be split along socioeconomic and cultural lines, with some areas not meant to be accessible to all residents [69].
This inequity further promotes separation of elite and marginalized spaces, exacerbating the unequal access to and benefit from certain ES.

These findings demonstrate that mapping spatial inconsistencies between ecological and socioeconomic characteristics on a small scale (i.e., finer measurement scale) provides a framework for exploring areas that potentially require unique intervention strategies. In this sense, such integrated frameworks can contribute to smart planning practices that promote resilient and sustainable communities by tailoring policy to these unique circumstances [70]. In urban areas, spatial scale and ES user benefits tend to be correlated. Often, the scale at which an ES is provided determines who may benefit from it [20]. This index approach (i.e., the Enviro-Dep Index) can highlight areas of varying environmental quality and social deprivation at a relatively small spatial scale delineated by DA or CT boundaries. This method is beneficial as it disaggregates the city-wide trends that dictate broad policy implementation often aimed to meet political desires than provide concrete, on-the-ground solutions.

The highly altered landscapes present in urban areas such as the City of Toronto are generally an outcome of many human processes that are spatially complex and permeated with sociocultural meaning that reflects governing agencies and individual or household intent [26]. For example, protected urban spaces and ravines would fall within the domain of a public asset managed through a municipal or regional government. In contrast, privately-owned green spaces (i.e., backyards) display an intricate pattern of land ownership, environmental quality, and function. In this context, both public and private ecological assets can contribute to ES at a variety of scales including locally (i.e., individuals and households) and regionally (i.e., neighbourhoods and the greater urban area). Thus, the highly regulated and small-scale nature of dense urban centres provides a unique opportunity to explore spatial trade-offs in ES in more detail, compared with broad-scale or regional approaches. On the one hand, broad-scale studies that employ more regional trends may protect certain ES undervalued by local residents. On the other hand, locally derived ES management strategies can produce more customized solutions that reflect the ‘uniqueness’ of each neighbourhood composition in terms of available resources and population needs. In effect, flexible planning policies can better connect urban social systems and local ecological processes. Through regulation of access, governing agencies can define how certain ES user benefits accrue to stakeholders across different spatial scales [20].

5.3. Study Limitations and Future Work

This study employs area-based composite indexing techniques to explore the inherent links between human and environmental processes. This approach has several limitations, most notably the impact of the modifiable areal unit problem (or MAUP) on study outcomes and the oversimplification of ES modelling in general. The MAUP is a study limitation when quantitatively modelling any spatial phenomena [71]. In particular, this study assumes the delineated boundaries of CTs and DAs not only for socioeconomic data for which they were originally created, but also for environmental indicators that do not necessarily adhere to such predefined scales or zones. Furthermore, spatial data were acquired from different sources, in different formats (i.e., raster, vector) and at different resolutions. Thus, the process of resizing and aggregating the disparate datasets inevitably introduces a level of inaccuracy and uncertainty.

Arguably, this approach simplifies a very complex and intricate network of spatial, institutional, and natural dependencies. The aim, however, is to provide a novel decision-making application that informs high-level planning practices—simply put, a tool that can potentially generate unique insights regarding inconsistencies in ES and user benefit distribution patterns across the City. Furthermore, the index criteria are broad in terms of what constitutes an ES user benefit (i.e., available urban green space within a residential neighbourhood). It is derived from available land cover and land use datasets as proxies for specific ES potentially present within a community. In this sense, this research is missing a key component to modelling urban sustainability, which is humans. Stakeholder and resident priorities regarding index purpose, criteria and outcomes would provide a more thorough understanding of ES user benefit variability and potential policy implications.
Although the approach presented in this paper generates a relative measure of urban sustainability for this geography specifically, generally speaking, it can be applied to any study area. The following provides some key insights or recommendations for future work:

1. Incorporate local, relevant and contextually nuanced indicators. This is particularly true for the environmental quality dimension of this sustainability index. In theory, the approach used in this research covers most available green space (both public and private). However, more effort towards better defining the uniqueness of an urban ES within the context of community planning and policy making should be made. In particular, developing strategic datasets that are more pertinent to highly dense neighbourhoods, such as small community gardens, green roofs, and other privatized common goods would provide a more comprehensive assessment of urban ES user benefits and stakeholder trade-offs.

2. Facilitate more community input. What constitutes an urban ES user benefit is in many ways unique to the individual or neighbourhood under evaluation. The conceptual framework of GIS-MCDA provides an intuitive platform by which residents can contribute to the selection and prioritization of criteria used to quantify locally relevant ES that are more representative of the unique urban landscape and population needs.

3. Promote transparency in process. Generally speaking, removing decision opacity and focusing on convergence and consensus-finding strategies in the decision-making process are becoming increasingly important in policy and political settings, saddled with skeptics, misinformation, and polarizing viewpoints. The spatial discordances in ES user benefits strongly correspond to discussion surrounding sustainable development, equity and access. To facilitate and sustain public buy in, we need more accessible and interactive tools that better communicate to the public the inherent trade-offs in the decision-making process.

6. Conclusions

In brief, this research explored the spatial discordance between ES and the residential stakeholders who may benefit by developing an integrated approach to mapping human–environment relationships at the neighbourhood level. General knowledge about ES distribution patterns can foster and support sustainable development within large urban centres. Observing patterns of ES and user benefits on a map is useful for functional and efficient management strategies [18]. The mainstream concept of ES to frame the highly complex human–environment dependencies provides an integrated platform for informed decision-making practices. Furthermore, this conceptual framework acts as a ‘boundary object’ to implement interdisciplinary work and research. This research addresses critical gaps in ES literature by explicitly linking socioeconomic and ecological trends spatially for more integrated policy implementation strategies based on all three pillars of sustainability. Further, this approach seeks to provide a flexible, and intuitive policy planning or evaluation tool that can help to better achieve goals relating to urban sustainability, resiliency and equity.

ES and user benefits are generated at a range of ecological and institutional scales [20]. The disaggregation or breakdown of key socioeconomic and ecological trends to a neighbourhood level provides a valuable assessment tool for decision makers. Here, the importance of scale becomes clear. Scale offers a window of perception and observation that should reflect the underlying processes being studied and simplify the mechanism by which we view certain things spatially. Thus, the reliability of study outcomes is closely linked with scale. In order to reduce uncertainty associated with results, the scale at which data are analyzed (i.e., the model scale) should closely match the scale at which the predominant underlying processes (social and ecological) operate as well as the scale at which decisions are actually made (i.e., policy scale).

The proposed integrated environmental-deprivation index (or Enviro-Dep Index) explored the interdependencies between urban social and ecological processes at two different measurement scales. This approach addresses key issues relating to the use of area-based composite indices as policy evaluation tools. Developing the index at two different measurement scales acknowledges the impact
of scale, most notably the MAUP, and reframes this limitation as a process-oriented learning opportunity. Recognition of the inherent variability of each underlying indicator and interactions between and among different factors on many scales should occupy our attention [51]. Here, the investigation into the degree and extent to which the choice of aggregation level impacts results can provide additional insights into how to enhance model specifications. Policy makers should assess model uncertainty associated with scale by reporting results at different levels (or measurement scales). This process, in turn, guides the choice of policy scale. The establishment of an appropriate policy scale requires a comprehensive understanding of the underlying spatial processes and model parameters, as well as insights regarding how particular policies or land use practices will be valued and managed over time and space.

Recommendations for future work focus on the inclusion of local and contextually relevant indicators, better facilitation of community preferences and continued emphasis on transparency in the process to support consensus-finding strategies in decision making and policy. These recommendations coincide with the unique strengths of GIS-MCDA specifically as a composite indexing technique. As such, future work that can incorporate more bi-directional engagement strategies and decision-making frameworks that combine top–down (or expert-led) and bottom–up (or public-led) approaches to modelling urban sustainability are required for functional and effective policies.

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