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Chapter

Perspectives on Subnational Carbon and Climate Footprints: A Case Study of Southampton, UK

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Abstract

Sub-national governments are increasingly interested in local-level climate change management. Carbon- (CO_2 and CH_4) and climate-footprints—(Kyoto Basket GHGs) (effectively single impact category LCA metrics, for global warming potential) provide an opportunity to develop models to facilitate effective mitigation. Three approaches are available for the footprinting of sub-national communities. Territorial-based approaches, which focus on production emissions within the geo-political boundaries, are useful for highlighting local emission sources but do not reflect the transboundary nature of sub-national community infrastructures. Transboundary approaches, which extend territorial footprints through the inclusion of key cross boundary flows of materials and energy, are more representative of community structures and processes but there are concerns regarding comparability between studies. The third option, consumption-based, considers global GHG emissions that result from final consumption (households, governments, and investment). Using a case study of Southampton, UK, this chapter develops the data and methods required for a sub-national territorial, transboundary, and consumption-based carbon and climate footprints. The results and implication of each footprinting perspective are discussed in the context of emerging international standards. The study clearly shows that the carbon footprint (CO_2 and CH_4 only) offers a low-cost, low-data, universal metric of anthropogenic GHG emission and subsequent management.

Keywords: urban metabolism, cities, community GHG, GHG inventory, carbon footprint

1. Introduction

Increasing GHG emissions have catalysed urban GHG management, with many having established sub-national and transnational climate networks, initiatives or management plans [1]. Carbon- (CO_2 and CH_4) and climate-footprints—(Kyoto Basket GHGs), are single impact category—global warming potential—indicators of life cycle assessment (LCA). These metrics provide an opportunity to develop effective models of GHG emissions from cities, and to facilitate effective mitigation. The frameworks required to calculate a carbon or climate footprint also provide a framework for the application of a more holistic LCA to cities or other geographic areas.

Discussions to date have primarily focused on the appropriateness of the allocation of emissions to the local level, with progress driven by improved understanding of urban metabolism—material and energy flows through the urban system (e.g. [2–6]). Approaches can be categorised as process-led bottom-up approaches, top-down economic led analysis, or top-down "natural laboratory" approaches relying on atmospheric measurement and concentration [7].

"Territorial-based" (alternatively, "in-boundary", "geographically-based", or "production-based") approaches, generally adaptations of the *IPCC Guidelines for National Greenhouse Gas Inventories*, or the *Greenhouse Gas Protocol* developed for corporate GHG reporting, account emissions within geopolitical boundaries [8, 9]. These methods successfully identify local emissions patterns and inform local development policy. However, there has been growing recognition that holistic management of urban GHGs necessitates the inclusion of direct and indirect emissions as urban economies demand resources beyond their geographic locations [5, 10, 11].

"Transboundary" (alternatively, "territorial-plus", "geography plus" or "metabolism-based") approaches add out-of-boundary emissions associated with economic demand to territorial emissions, with the exact boundary conditions and scope varying between studies [2, 4–6]. Top-down "consumption-based" methods include all emissions along the supply-chain of goods and services, with boundary conditions defined by final consumption of households and governments [5]. This approach is useful in the informing mitigation of emissions associated with final consumption, although the exact origin of embodied emissions cannot normally be delineated and emissions from local production for exports are excluded [11]. Consequently, methods are not sensitive to many local strategies to reduce emissions [5].

Ultimately both concepts are complementary, focusing on different aspects of community composition . The primary cause of inconsistency between studies (for a review see: [3, 10]) and emerging standards (e.g. [12, 13]) is the approach taken to boundary conditions (spatial and temporal). Temporal boundaries vary, but typically consider an annual period, with some models operating at finer scales (e.g. [7, 14]). Spatial boundaries vary reflecting goals and application, and the lack of a singular definition for a city or an urban area. However, a 'city' or and 'urban area' is simply a taxonomic division of a 'community'—a specific area or place considered jointly with its inhabitants. Spatial boundaries can thus be decided on a case-by-case basis, defined by motivation application [1].

This chapter reviews urban sectorial methods, results, and policy implications of applying a territorial, transboundary, and consumption-based, carbon or climate footprint to a city, using a case study of Southampton, UK. Based on the framework proposed by Wright et al. [15] the requirements and methods to assess a carbon or climate footprint are presented. We disassemble the framework into 'modules', recognising that each element of the framework would require separate calculation methods. This enables the development of novel methods or the use of existing methods in a novel manner to create an overall methodology for the calculation of all elements of the framework. As proof of concept and to inform the development, the methodology was applied to Southampton, UK. Results are then presented for the carbon footprint and the 'climate footprint' ([15, 16], respectively). The methodology represents a novel approach, building on established practice to enable the sub-national assessment of carbon footprints in communities, which enables the spatial and temporal reporting of results at a sub-community level to enable effective management and policy development. We discuss the results and policy implications and conclude with a consideration of the effectiveness of current practice and highlight ongoing issues.

2. Case study: city of Southampton

Southampton (pop. 239,428 during study period), chosen as a case study as it contains the representative components of many cities, is the largest city in Hampshire, England (area: 51.91 km^2) based on the geographic extent of the city geo-political boundary [17]. The city is governed by Southampton City Council, a unitary authority (a single tier local government responsible for local government functions); the wider region is within the remit of Hampshire County and multiple district councils (a hierarchical system of governance common to many countries).

Southampton is a commerce hub; a major international cruise terminal, and the UK's second largest container port. A significant proportion of Southampton's workforce (circa 42%) commutes from the wider region and surrounding counties [18]. The city has two universities with a transitory student population of in excess of 40,000 [19]. Southampton Airport is a regional domestic and international airport located just outside the city's geopolitical boundary.

3. Methods

3.1 Residential

Large communities contain a significant number of dwellings, and emissions are driven by energy consumption, highly dependent on building structure and the behaviour of residents [20]. Estimation of emissions can be made on fuel consumed (e.g. sales) (e.g. [21]), however this method does not allow for spatial disaggregation. Alternatively energy use can be estimated from census based residential energy consumption models (e.g. [22]). Various methods have been developed for this purpose (for review see [23, 24]). To enable spatial disaggregation the case study applies the assumption that energy use can be simplified with the application of 'average' building categories. Model generalisation parameters are derived for categories of dwelling and applied to individual property build forms with Geographic Information Systems (GIS), eliminating the need for visual inspection [25]. Parameters were derived from the Building Research Establishment Domestic Energy Model (BREDEM) (BREDEM-8—monthly or BREDEM-12—annual) [26]. Total energy demand was assumed to be met using a combination of electricity, natural gas, and other fuels. Consumption data for electricity and natural gas were available from local metering records, with remaining demand assumed to be met using others fuels apportioned on basis of regional sales data. Output is restricted to an aggregation of properties rather than the individual building level, as accuracy would be open to significant variation and introduces confidentiality concerns.

3.2 Commercial and industrial point sources

The commerce and industry sector encompasses emissions associated with industrial physical or chemical processing and non-electrical energy. Complexities exist in the allocation of emissions between the energy and processing sectors (e.g. residual heat may be used for electricity generation). Actual consumption data from sales records or feedstock records is difficult to obtain, primarily due to the sensitive nature of such data. Point source data from larger facilities may be available from legislative emissions reporting schemes, although this often does not encompass small schemes. Proxy consumption data for fuels and processes can be utilised to estimate emissions, however this assumes fuel combustion at place of purchase, and may not accurately reflect the source of emissions. Gurney et al. [7] describe a model to simulate energy demand based on building parameters combined with known local atmospheric emissions. The same study notes that this method is only suitable for large point source emitters. Alternatively, pro-rata allocation of national emissions to local sources provides a reliable method of estimation (e.g. [7, 27]). For the purpose of the case study, supplemented with meter point natural gas and electricity consumption data, emissions by industry were pro-rated on employment by industrial sector (to a 4 digit Standard Industry Classification (SIC2007)).

3.3 Electricity, heat, and steam

Transboundary emissions relating to electricity are commonly calculated using an aggregated factor representing a national system of generators and transmission. Emissions from heat and steam are often reported separately due to data conventions and that composite emissions factors may over- or under- estimate of emission intensity [21]. Similarly, aggregated emissions do not segregate in-boundary generation, or consider low GHG decentralised generation schemes—likely to be a component of meeting carbon reduction targets [28]. In these cases electricity generated in-boundary and fed into national supply grids is representative of the grid average. Alternatively to provide greater disaggregation emissions associated with in-boundary electricity generation can be reported separately, either as a proportion of total consumed or as with the case study an absolute. Emissions for Southampton's electricity consumption were calculated using a national grid emissions factor (accounting for transmission, transformation and other losses (typically circa 6–11%) [21]), estimated from national generation and electricity consumption.

3.4 Road transport

Road transport emissions are often artificially truncated at the city boundary, but commuting represents a significant transboundary emissions source [11]. Economic data on fuel sales can be a viable indicator of road transport emissions, where the study area represents a commuter-shed [21]. However, this method is less effective where significant numbers of commuter trips occur (e.g. Southampton—circa 42% of work related trips are from outside the city [17]). In these cases the location of fuel purchase is not necessarily representative of fuel consumption. An alternative method is through the use of proxy relationships, with emissions estimated through regression based approaches [29] or population density and road density [30]. High temporal and spatial resolutions have been achieved using activity-based approaches, combining vehicle kilometres travelled (VKT) with fleet and fuel data [7, 31]. This approach requires total distance travelled by all vehicles in the study area, fuel efficiency, and fleet composition. Issues arise in comparability of VKT techniques as many cities have their own bespoke modes [21]. However this has the advantage of allowing bespoke modelling of spatial and temporal impacts of traffic policy intervention at high resolutions.

The basic principle of an activity based models is the relationship of the mass of fuel consumed in the distance travelled. The amount of fuel a vehicle consumes in a given distance is dependent on a number of parameters, including drive cycle, engine temperature, ambient temperature, fuel type, and fuel quality [32]. Hot-start emissions were calculated; by modal split, fuel type and installed vehicle technology, using experimentally derived emissions factors for vehicle type and pollutant by trip length and velocity from the ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) methodology and TRL emission factor database [32]. Cold start emissions are accounted using an excess factor over the hot-start emissions rate [33, 34].

3.5 Rail

Trips by rail transportation typically traverse the geopolitical boundary of a number of communities. Rail journeys involve a series of embarkation points between origin and destination, often with multiple stopping locations within the geopolitical boundary. A boundary limited methodology does not account the transboundary demand driven nature of these trips. For trips that originate outside the community boundary only the in-boundary proportion of the trip is accounted, conversely pass through trips that are not a result of city demand are still counted [4]. This issue exacerbates when considering national and internationally connected rail networks—a trip could begin a significant distance from the study community. Accounting in-boundary and transboundary emissions related to rail commuting creates the potential for double counting between communities. Pass through trips are accounted as a direct emission and then accounted again at the destination community. Reflecting these difficulties a number of community based GHG inventories do not explicitly define emissions from rail transportation (e.g. [4, 21]).

These issues can be addressed by accounting emissions based on proportional commuter distances travelled. Assigning emissions from rail commuter demand as passenger kilometres travelled to total passenger kilometres travelled on the relevant routes offers a mechanism to apportion trips to the local community a demand basis. Accounting both in-boundary and transboundary emissions requires a combination of two methods—one to calculate in-boundary emissions and another to allocate transboundary demand emissions. For the purpose of the case study, in-boundary emissions were calculated using ARTEMIS technology specific bottom-up algorithms and emissions factors (function of engine, technology, distance and speed) [32]. All journeys on non-electrified rail were assumed to be power by diesel. Trips on electrified rail were apportioned to diesel or electric locomotives using operator timetables. Total trips, distance travelled, and operational engine time were estimated from train operator time tables [35], combined with the Ordnance Survey Integrated Transport Layer [36]. Emissions associated with commuter trips were estimated as a function of rail demand for Southampton, passenger kilometres travelled [37] were estimated as proportional to the total ticketed exits on the national rail network (collected by automated barrier passes) divided by number of ticketed exits at Southampton.

3.6 Other off-road mobile emissions

Mobile off-road sources represent an extremely diverse range of domestic and commercial emissions. Including controlled activities which are consistent and follow specific procedures (e.g. dockside grab loader) and chaotic activities following no pre-determined procedures or activity patterns (e.g. domestic lawn mowers) [38]. Fuel sales data may be a viable indicator of emissions, where the operation of off-road machinery are geographically constrained to the location of fuel purchase [39], although this method fails where fuel purchase does not represent the location of consumption.

Unlike road transport, the majority of off-road machinery units are not registered making estimation of populations and activity difficult. Proxy estimates of population can be made based on national purchases or populations pro-rated to the local level, as per the case study [40]. This assumes a uniform distribution of machinery across total national population, which may not be representative of local conditions. Alternative allocation methods could be utilised that consider a number of machinery units as a function of purpose or spatial area (e.g. lawnmowers f(greenspace), construction machinery f(growth)), however the wide range and chaotic usage patterns of off-road machinery are likely to confuse this issue.

3.7 Shipping

Cities that are international cruise and container terminals rely heavily on these industries for economic growth and employment, exclusion of emissions from these industries would lead to misinterpretation in policy making [1]. Territorial inventories may, depending on the extent of territorial waters in the geopolitical boundary, include port-side operations or entirely exclude shipping operations. A transboundary approach must consider the indirect emissions (movement between ports) of these sources [1, 5]. Emissions from shipping are a function of engine operation and fuel consumption. Calculation of fuel consumed has broadly been undertaken using two approaches—'engine use models' and 'bunker fuels'. Engine use models apply engine load, power and run-time, by engine and ship type (e.g. ro-ro ferry, liquid bulk), in the three phases of operation (hoteling, manoeuvre and cruise) to calculate emissions [41]. This requires detailed data input on vessel characteristics, routes, and operational time. Detailed data for all ship movements (>250 gross tons) and characteristics are available from the from historic Automatic Identification System datasets. However, the majority of these datasets demand a high cost purchase, which excludes some sub-national governments from using the data (e.g. Lloyds List Intelligence [42]). Alternatively, the method taken in the case study, a bunker fuels approach considers international bunker fuels loaded at the departure port provide a proxy to estimate emissions from shipping [41]. However, shipping companies are likely to source the cheapest available fuel for the route, the result being where fuel cost is low, emissions are overestimated (e.g. Belgium), and where costs are high, emissions are underestimated (e.g. New Zealand) [43, 44].

3.8 Aviation

Aviation emissions are transboundary, smany airports are located outside geopolitical boundaries, and cities often act as aviation hubs with transit passengers occupying a significant proportion of capacity [45]. Allocation of emissions must address these concerns, so as not to generate political tensions. Some territorial studies exclude emissions as almost entirely transboundary and largely beyond the control of local government (e.g. [46–48]). Others include domestic emissions and take-off and landing cycles to 1000 m altitude for international emissions (e.g. [49]). As applied in the case study emissions can be calculated on an activity basis (engine runtime, technology, flight occupancy). Similarly a number of studies have reported transboundary emissions based on quantities of fuels loaded at airports within city boundaries (e.g. [14]). These methods do not consider the movement of passengers between flights and the surface movement of passengers from outside city limits. Previous authors suggest that regional airport usage by community inhabitants can be estimated as a function of local to regional population [4, 21]. Assignment of emissions by community demand offers a truer picture emissions, considering only those emissions associated with the local population. However, this method is fraught with complexity, especially in cases where a number of international airports operate within close proximity (e.g. southern UK—Southampton; Bournemouth; Gatwick; Heathrow; Stansted, London City). Without accurate passenger origin—destination data, subjective judgments must be made to establish the geographic extent of airport demand. Demand from beyond the geographic boundary could be considered a function of the community demand, thus arguably, related aviation emissions should be accounted [4].

3.9 Agriculture, Forestry and Other Land Use (AFOLU)

Some argue AFOLU is potentially insignificant at the urban level and therefore may be excluded [50]. This is based upon the assumption that green space is both relatively limited in urban centres, and the perception that urban green space has limited value due to human modification [51, 52]. This is often untrue (e.g. Southampton Common is 145 hectares; London's Hyde Park is 142 hectares, Beijing's Fragrant Hills Park is 160 hectares, and Vancouver's Stanley Park is >400 hectares), and fails to consider the importance of public and private land in urban centres (e.g. private gardens, green roofs) which, whilst small compared to per unit area GHG emissions, are potentially important stocks of GHGs [53].

Land use and management significantly influences ecosystem processes that effect GHG fluxes, (e.g. photosynthesis, respiration, decomposition). The IPCC [8] guidelines for national inventories contain significant information for the calculation of AFOLU GHG fluxes. These guidelines suggest two methods: (i) net carbon stock change over time and (ii) direct carbon flux rate (more commonly utilised for non-CO_2 species) [8]. AFOLU carbon flux for Southampton was calculated using the first option, to provide consistency with annual reports and promote favourable management of non-urbanised space over an extended time scale.

Estimates of C flux were derived from Rothamsted soil carbon model (RothC-26.3) and the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM) [54–56]. Basic climatic inputs (temperature, precipitation, daylight hours) were required (Met Office, 2014), in addition to data on organic matter inputs (obtained from LPJ-DGVM), soil clay content, and atmospheric CO_2 concentrations [56]. GIS data (OS MasterMap) of land-cover types were used to create a map of the city area; where available this map was augmented with specific vegetation cover data provided by the municipal authority [36]. Land-cover data was classified into 11 broad categories, adapted from a condensed set of JNCC Phase 1 habitat classifications, a standard mode of habitat classification in the UK. (**Table 1**) The Phase 1 habitat classifications provide a specific name and brief description of each habitat type/feature, appropriate for vegetation modelling using LPJ-DGVM [54–57]. In cases where land-cover types are not complete for an area (e.g. scattered trees), the land-cover was assumed to be divided evenly between land-cover types. Where trees are described as 'scattered' (>30% of surface by canopy extent) 20% of total area is classified as that tree type, the remainder is divided evenly between other represented land-cover types [57]. In the grass (cut) category, data are required for total clippings collected, thus removed from the system, and total clippings left in-situ.

Private gardens are representative of multiple land-cover types (e.g. lawn; ornamental planting; patios; tarmac; gravels). Typical land cover types in private gardens were estimated based on a representative sample of private gardens in the study area, categorised for land cover types using aerial photography (expert judgement) (**Table 2**).

The model was run across a temporal period of 1 year, with GHG flux calculated as the change in storage between runs.

3.10 Waste

Waste management generates emissions of CO_2, primarily of biogenic origin, with some fossil carbon and CH_4, often outside the city boundary [5]. Regional or municipal governments are both actors in and managers of waste. Each has their own waste infrastructure, service provision and socio-economic conditions with influence over collection; treatment, and destination with significant emission

Land-cover category	Example land-cover types
Grass (cut 11 times a year)	Natural surface, slope
Rough grass (not mown)	Rough grass, rough grass and other
Other herbaceous plants	Perennials, flowers, roses
Private gardens	Multiple surfaces in private residence
Broadleaved summergreen trees	Non-coniferous trees, scattered non-coniferous trees, orchard
Needle leaved evergreen trees	Coniferous trees, scattered coniferous trees
Scrub	Scrub, shrubs, hedges, heath
Marsh	Marsh reeds or saltmarsh
Sealed surface	Road, made surface, paths, steps, track, structure, traffic calming, pylon, rail, upper level of communications, building, glasshouse, overhead construction, unclassified
Water	Inland water, foreshore, tidal water

Table 1.
Land-cover categories for modelling of vegetation or other land-cover types (adapted from [49]).

Land-cover type	Proportion of total area (%)
Grass (cut 11 times a year)	
Clippings removed	10
Clippings left in situ	30
Shrubs	10
Temperate broadleaved summergreen trees	10
Other herbaceous plants	10
Sealed	30

Table 2.
Assumed proportions of land-cover types in private gardens for the southern UK (expert judgement).

savings available through system reconfiguration [58, 59]. Many previous studies apply 'generic' emissions factors to waste treated. Detailed tools and methods for the accounting of GHG emissions from waste systems have been developed although there are concerns regarding consistency, accuracy and transferability of these methods [60, 61]. The following offers a brief overview of methods applied in the case study with greater detail exploring various stages in the waste system given in supplementary information.

Knowledge of waste composition and subsequent mass balance of CO_2 and CH_4 throughout the waste system is the key determinate in modelling waste emissions. The composition of the wastes in the treatment system will affect the mass balance due to the changes in carbon content and subsequent degradation patterns [60]. Once known waste stream emissions can be calculated on a mass balance or activity basis. Many city based assessments do not suggest breakdown of the various stages of the waste management process, instead offering per unit treated emissions factors. Per unit emissions factors are applicable to processes where the primary main source of emissions are from energy use (e.g. waste recovery and recycling), or for incineration processes (mass balance of carbon could also be applied). Greater accuracy can be achieved in modelling biological processes using a mass balance approach, with CO_2 and CH_4 emissions calculated on mass balance of carbon input to carbon lost from the final product. Emissions estimates from landfill must recognise both operational and closed phases [62]. Following closure, a landfill continues to emit GHGs, possibly for several hundred years, although some carbon will be indefinitely stored in the landfill [63]. Kennedy et al. [21] propose a pragmatic solution, applied in the case study, whereby estimates of long-term emissions were calculated for the waste landfilled in the assessment year.

3.11 Water

The provision of water and waste water services are similar to the provision of electricity. Emissions associated with water are calculated on an end-user basis for water processing, treatment and transportation using per unit consumed emissions factors. Commonly, as during this case study, water use is not metered and thus no actual consumption data are available. In the UK significant effort is being directed to the installation of end-user metering; this will provide improved data resolution for future investigations [64]. Emissions were calculated using standard estimates of water consumption provided by water suppliers.

3.12 Consumption

It is generally accepted that the addition of a consumption-based modelling approach extends the research implications and policy potential of a GHG inventory [2]. Territorial accounts include emissions associated with exports at the point of production; but exclude those associated with supply chains and imports. The upstream impacts of production are allocated to the producer—the tendency is to mask embedded emissions and burden shifting (energy intensive industries are effectively exported). Transboundary approaches add an element of these out-of-boundary emissions, but do not give a full picture of the impact of consumption. Consumption-based accounting focuses on the final consumption of households and governments; methods account all GHG emissions upstream of the community but exclude emissions from production within the city [10]. A consumption based approach compliments a transboundary methodology, capturing emission flows and the driving forces associated with consumption [65].

A consumption-based approach requires linking supply chain emissions with local consumption activities. Input-output (IO) models detail the transactions between industries and sectors within the economy. An IOT requires knowledge of all flows of goods and services among intermediate and final sectors in disaggregated form for a given time period. This implicitly implies high volumes of data, which is difficult to obtain at the sub-national level, necessitating some form of scaling from national data. The core element of an input-output model is a matrix concerning flows through the economy—sales and purchases from an industrial sector (a producer), to other sectors and the sector itself (consumers) [66]. The basic input-output out model assumes homogeneity in sectors (i.e. each sector produces a single product) and linear production (i.e. proportionality of inputs and outputs which precludes economies of scale). The basic IO model can be extended to include material consumption and emissions—an Environmentally Extended

Input-Output (EEIO) model. Effectively this creates an 'environment' sector, and the value of each item represents the 'output' of pollution [67].

Consumption-based emissions factors (GHG/£ spent) for the UK were calculated using an EEIO model. The IO data only holds data on final consumption at the national level. A downscaling methodology was therefore required to estimate final consumption at the local level. The model assumes no variation in emissions per monetary unit spent between the national and local levels. The technical coefficient matrix was derived from UK supply and use tables for the year 2008 with 123 products and industry sectors in basic prices [68]. GHG emissions data by industry sector for the period were taken from the UK Environmental Accounts [69]. The Environmental Accounts provide data on GHG emissions from 129 industrial sectors and 2 household emissions sources (travel and non-travel). The GHG data is provided at a more disaggregated level than the IO data in some sectors, this was scaled to the 123 sectors of the IO model using the parent sector of the lower level disaggregation according to the UK Standard Industry Classification 2007. A domestic technology assumption is applied to imported goods and services, whereby imports are assumed to have the same GHG intensity as domestic equivalents. It assumes the energy structure and economic structure of the imports can be approximated based on the domestic make-up of the UK. This may be a valid assumption for some regions, but underestimates GHG intensities of imports from emerging and developing regions [11].

Expenditure between regions will vary considerably as a result of a range of socio-demographic factors. However, the underlying IO data only provide expenditure at the national level. Household demand was downscaled to the local level using household expenditure data from the UK Living Costs and Food Survey (LCF) (annual survey of household expenditure on consumer products and services), and derived summary datasets provided in the Family Spending report [70, 71]. Government expenditure was downscaled on a per capita basis. Whilst this assumes individuals in the national population benefit equally from all government expenditure, it is considered a reasonable assumption in the absence of alternative data. Researchers have downscaled government expenditure using local expenditure statistics, however these data do not exist for the UK [11]. The study does not consider emissions relating to capital investments.

4. Uncertainty

The city system is inherently complex and comprised largely of non-deterministic features (i.e. responses of the system that are not predicable because of uncertainty within the system itself). Qualification and assessment of these uncertainties is important for both model validation and reliability. Sensitivity analysis is used to assign the uncertainty in the output of the model to different sources of uncertainty in the model's inputs and how the model responds to changes in input data [72]. The sensitivity of the transboundary inventory model is considered using a one-at-time (OAT) local sensitivity analysis technique. Sensitivities for the consumption estimates are considered at the aggregated emission factor per unit expenditure level, rather than at the EEIO input variable level due to complexities involved in this form of modelling [73]. Whilst sensitivity analysis provides a good indicator of variables with high impact on the model, it does not provide qualification of uncertainty and must be accompanied with an uncertainty analysis [72]. A Monte Carlo analysis was performed using random sampling of input variables, based on defined uncertainty probability distributions in input parameters. The analysis consisted of ten thousand model runs, completed for the model as a whole and for three of the broad category areas identified in the OAT transport emissions; power generation; and waste disposal. Supply chain and consumption emissions uncertainty was excluded due a need for further investigation and modelling.

5. Results and discussion

5.1 Summary

As identified, there are three methods for the assessment of life-cycle GHG emissions from cities and other communities—territorial, transboundary, and consumption based. This section discusses the implication of the three methods using the Southampton case study. Furthermore, the Carbon Footprint (CO_2 and CH_4) and Climate Footprint (Kyoto Basket) metrics are compared for each method. The summary results (**Table 3**) indicate increasing size in both the carbon and climate footprints as further emissions sources are added between methods, and a slight increase between the carbon and climate footprint metric.

5.2 Territorial emissions

Southampton territorial emissions suggest carbon and climate footprints of 268ktCO$_2$e and 273ktCO$_2$e, respectively. Addition of end-use electricity consumption increases this figure by 601ktCO$_2$e and 604ktCO$_2$e, respectively (**Figure 1**). The minor increase (0.99%) in emissions between the total carbon and climate footprints is driven primarily through inclusion of additional GHGs in transport (primarily N_2O). Calculation of per capita emissions for the case study indicates 3.7 tCO$_2$e/capita carbon footprint, lower than the equivalent national production-based 10.32tCO$_2$e per capita estimate for the UK [74]. Whilst strictly geographic based methods can successfully identify local production-based emissions patterns and inform local development policy, they fail to capture the full extent of sub-national community infrastructures which extend beyond the geopolitical boundary (e.g. transport) [5, 6].

5.3 Transboundary emissions

Described by Ramaswami et al. [4], Denver (CO, USA) represents the first known community to have been inventoried using a transboundary methodology. The study accounted all in boundary emissions and identified key community flows defined as: food; water; transport, and building materials (for shelter). Hillman and Ramaswami [75] suggest, based on a study of eight US cities that these

Method	Carbon footprint (ktCO$_2$e)	Climate footprint (ktCO$_2$e)
Territorial	268	273
Territorial+	601	604
Transboundary	2643	2787
Consumption	3160	3590

Note: territorial+ includes emissions from end-user electricity consumption.

Table 3.
Summary carbon and climate footprints for the case study of Southampton.

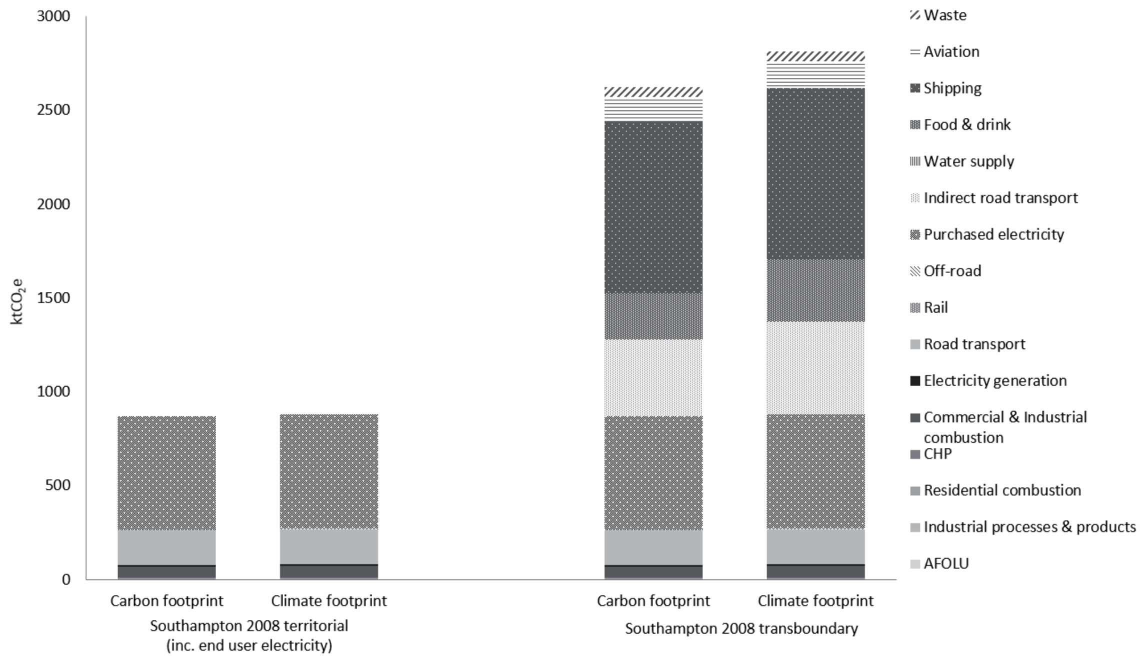

Figure 1.
Comparison of case study territorial and transboundary carbon (CO_2, CH_4) and climate (Kyoto Basket) footprints.

cross-boundary activities contribute on average 47% more than the in-boundary emissions sources. This consideration is reflected in developing international standards (e.g. [12, 13]) which suggest a transboundary approach to account both the territorial and transboundary aspects of a community—ideally moving towards an approach that replicates the process(s) of urban metabolism [2].

The Southampton transboundary inventory includes direct emissions with the addition of: commuter road transport; shipping; aviation; out-of-boundary waste emissions; water and wastewater supply/treatment; construction materials, and food and drink—representative of the requirements of recent PAS2070 standard. The 2008 results, carbon footprint 2643 ktCO_2e, and climate footprint 2787 ktCO_2e, are, as expected, substantiality larger than the comparative territorial results (**Figure 1**). The results of the Monte Carlo simulation suggest a 95% confidence interval of 3395–4295 ktCO_2e. The two footprinting techniques, as per territorial emissions methods produce results within 1%. The increased emissions in the climate footprint stem primarily from transboundary transport. The largest contributor, shipping emissions, are a result of the extended travel distance and subsequent high fuel demands. Whilst sub-national governments have limited control (typically only port-side operations) over these emissions sources, inclusion is important due to the strong economic reliance on these industries [1]. However sub-national governments do have access to control to address these emissions through local air quality control. Similarly road transport control can be found through air quality control and additional controls in planning and road management.

Energy emissions comprise a large component of total emissions, electricity provides the dominant contribution to this sector. The disaggregation of emissions related to heat production from emissions associated with electricity generation impacted >1% on emissions per unit electricity consumed. At a local level, renewables account for an equivalent grid emission of 3 ktCO_2e. Evidently emissions from electricity are mainly dependent on the intensity of supply, highlighting a powerful interlink between local and national policy making. This interlink will become particularly pertinent with the potential advent of locally led energy initiatives (e.g. micro-generation; rail electrification; electric vehicle charging networks) [76].

Emissions from AFLOU are minimal, however this masks the carbon stored in urban green space (470.00 $ktCO_2e$). Exclusion of these emissions assumes green space storage is minimal; the results demonstrate this may not be the case. Careful consideration must be given to development that affects community green space (both negative—e.g. green space urbanisation—and positive—e.g. installation of green roofs), for the creation of carbon sinks, the wider potential social, and economic benefits [52].

Supply chain and infrastructure related emissions form the majority of total transboundary emissions, highlighting the importance of supply chains in community footprinting. The recent PAS2070 [13] suggests further inclusion of all materials making >2% material contribution to the community. This would add a further 1315 $ktCO_2e$ and 1435 $ktCO_2e$ (carbon and climate footprint, respectively) to the Southampton results. However, there are concerns about double counting with the territorial element of the assessment.

The primary advantage of a transboundary footprint is the level of completeness created through inclusion of in-boundary emissions sources and transboundary infrastructures that supply these activities. Given this completeness, transboundary based footprints can be utilised to inform a broad range of mitigation and management strategies at the local, regional, and national scales. Additionally transboundary footprints are more relevant and easier to communicate to residents due to the inclusion of major activities included in personal and home carbon calculators [6].

The main shortcoming of the transboundary method is the inconsistency in approach and application of metrics between studies. Standards (e.g. PAS2070 [13], GHG Protocol for Community Reporting [12]) are emerging that attempt to clarify and develop consistency in reporting structures. Comparability is also difficult; results require normalisation to enable inter-community comparisons. The majority of territorial inventories are normalised using a per capita metric, however this may not be appropriate for transboundary approaches. Metrics for the representation and comparison of transboundary approaches require further research.

5.4 Consumption emissions

Results for Southampton (carbon footprint 3160 $ktCO_2e$, climate footprint 3590 $ktCO_2e$) (**Figure 2**) are consistent with previous studies where consumption-based estimates are higher than production-based emissions, with the majority of emissions driven by households [77]. The disparity between the carbon and climate footprint is higher (circa 12%), this is primarily driven by high emissions of N_2O in agriculture, highlighting the need for a climate footprint approach in certain situations where high emission of GHGs other than CO_2 and CH_4 occur [15].

The addition of a consumption based account extends the policy implications of a local GHG inventory [2]. The approach provides value for the assessment of household consumer lifestyle on GHG emissions, making the consumption impact of households and government visible [6]. Arguably a consumption based approach provides for the most rigorous method for per capita GHG comparison, as consumption is driven by the residents of a community. Additionally a consumption based approach can inform local policy to reduce supply chain emissions as, when accurate local data are available, imports/exports can be traced. Recognising these advantageous policy implications, the new PAS2070 requires the separate completion of both a transboundary inventory, and a consumption-based inventory [13]. However consumption-based methods are data intensive, and are only truly valuable where accurate IO data are available. Misallocation of emissions can occur where physical flows do not match monetary flows represented in local IO tables [6]. Additionally, the consumption method effectively divides the community into

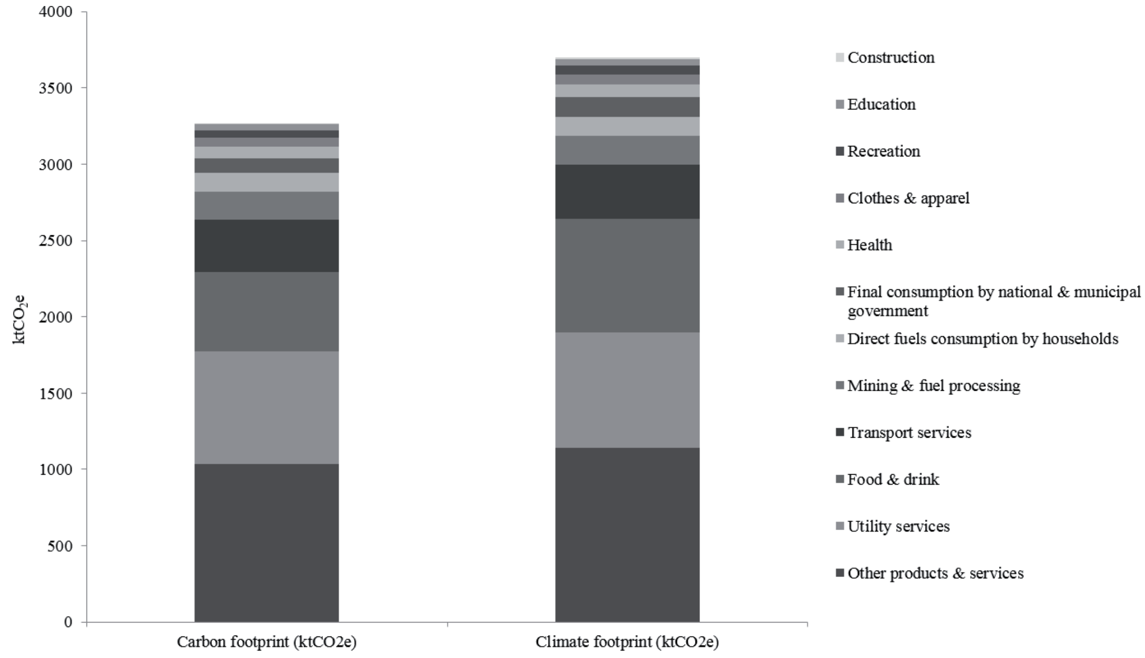

Figure 2.
Comparison of case study consumption carbon (CO_2, CH_4) and climate (Kyoto Basket) footprints.

two, with activities for exports not included in the unit of analysis. This can exclude a large element of a local economy (e.g. resorts, industrial communities) which could be managed through local policy.

In this study, there are limitations to note. The assumption of a homogenous technology mix in the EEIO model presents a level of inherent uncertainty—imports come from a range of countries using a range of different emission and resource intensities. This may be a valid assumption for some regions, but under-estimates GHG intensities of imports from emerging and developing regions. The accepted solution is to employ a Multi-Region Input-Output (MRIO) model. MRIO models represent the interactions between any number of regions with potentially differing technology mixes, by internalising trade flows within internal demand [78]. The method of downscaling presents two important limitations. Firstly expenditure can only be estimated for broad categories—partially a result of the homogeneity assumption of the underlying IO model, this assumes common per unit emissions in these categories, which may not be entirely representative. Secondly, this generalisation may misrepresent the quantity of product purchased. For example the same expenditure on a high cost product variant would provide less quantity of product and potentially lower emissions, than a high quantity low cost product.

6. Conclusions

This study has presented several important developments to the assessment of community carbon footprints. Methods have been developed to assess emissions at a spatial and temporal disaggregation suitable for use by policy makers at the community level. The methods have been presented to show the policy implications of territorial, transboundary, and consumption based accounting procedures. To explore the uncertainties associated with the model a Monte Carlo simulation was constructed. The effort required for a comprehensive uncertainty analysis of this type is considerable, the alternative however, is to provide decision makers with incomplete information. At best this will lead to a false sense of reliability, at worse incorrect assumptions and decision making. We strongly recommend that as more studies become available continuous effort to identify and improve uncertainty be applied; leading to a better communication of information to policy makers and a better underpinning of their decisions. Only a limited difference in emissions totals was observed between the carbon and climate footprints for the case study city, clearly showing that the carbon footprint (CO_2 and CH_4 only) offers a low cost, low data, universal metric of anthropogenic GHG emission and subsequent management.

Territorial accounts may be suitable for national GHG inventories, but cannot represent the transboundary infrastructures of sub-national communities. Transboundary approaches extend the territorial approach to include emissions from key infrastructures essentially to sub-national communities. The addition of a consumption-based account further extends the policy relevance and research applications of community accounting. Consumption-based approaches show the impact of household consumer lifestyle on GHG emissions, and making the supply chain impact of households and government visible.

Recognising the advantages of transboundary and the simultaneous application of a consumption-based approach, standards, such as PAS2070, advocate combining a transboundary approach with a consumption-based approach in order to provide a comprehensive report.

Finally, the establishment of a global network of low carbon cities requires the appropriate tools. PAS2070 and related standards represent a significant step towards the development of a comparative assessment of urban community GHGs. Barriers still exist—comparable metrics need to be further developed and local governments often do not possess the resources and skills required to complete an inventory assessment.

Conflict of interest

The authors have no conflict of interest.

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