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To cite this article: Melissa Pang *et al* 2020 *Environ. Res. Commun.* **2** 011003

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Environmental Research Communications



LETTER

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OPEN ACCESS

RECEIVED
12 August 2019

REVISED
6 November 2019



ACCEPTED FOR PUBLICATION
20 November 2019

PUBLISHED
29 November 2019

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Keywords: environmentally-extended input-output analysis, Switzerland, carbon footprint, urbanization, household consumption, budget surveys

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

Abstract

Greenhouse gas (GHG) emission inventories form the basis of evidence-based climate change planning across the local, regional, national, and international levels. In this letter, we present a consumption-based GHG accounting approach for estimating the carbon footprint (CF) comprising direct and indirect emissions of households in Switzerland for 2008, 2011, and 2014 and examine the impact of urbanity and socioeconomic variables on these estimates. The CF model used herein couples regionalized household budget surveys (HBS) with environmentally-extended input-output analysis (EEIOA). We provide greater insight into the obscure process of combining bottom-up consumption data (i.e., HBS) and top-down input-output tables (IOT) in a CF model. The findings show that urban households tend to have lower direct emissions than rural households whereas indirect emissions are higher. Therefore, the nature of both direct and indirect emissions should be considered when evaluating the role of urbanization, as each has a different focus. Overall, our results indicate that income is the most important driver of household total cf. Some local features specific to Switzerland have also been found to be important in shaping the relationship between the household CF and its drivers. We argue that household composition should be the focal point for future study of CF mitigation in Switzerland, and that policies should prioritise measures that target consumer behaviour and lifestyles, rather than solely focus on improving physical infrastructure and adopting new technologies.

1. Introduction

Responsible for 80% of the world's greenhouse gas (GHG) emission, cities form a crucial piece of the climate change mitigation puzzle [1]. While figures like this are attention-worthy, its interpretation and implications with respect to the accounting method must first be considered. GHG emissions are typically estimated either with a production or consumption-based perspective. Both consider the emissions associated with household consumption of fuels, electricity, as well as goods and services produced domestically; but production-based accounting further includes emissions associated with domestically-produced exported goods and services, while consumption-based accounting includes emissions associated with domestically-consumed imported goods and services. Depending on the accounting method applied, the final results and conclusions can differ greatly [2, 3]. Even across studies adopting the same accounting perspective, it remains an open debate whether urbanity and urban design principles can lead to a reduction in GHG emissions [4–7]. Whereas some studies have demonstrated that urban households have a larger CO₂ emissions volume than their rural counterparts [4, 6, 8–10], others have indicated that dense urban centres could have a carbon-saving effect [7, 11], or could have comparatively higher or lower per capita carbon footprints (CF) across density gradients than rural areas

[5]. However, there is general agreement across the literature that socioeconomic variables have an opposing effect to urban density on the volume of carbon emissions. Thus, as an environmental impact of high versus low density living, the overall CF depends on the relative strength of the opposing drivers, which is in turn determined by a country's specific socioeconomic and infrastructural circumstances at the location level [5]. In China, income and subjective personal-level variables (such as happiness and security) were found to have an important effect on household carbon emissions [12]. In Finland, socioeconomic variables such as income play a much more significant role than urbanity in determining carbon emissions volumes, thus leading to a larger CF in urban areas where the positive impacts of population density are outweighed by increased rates of consumption [4, 8, 10]. This is also observed in the case of energy, where urban Australian households consume more total energy than rural households despite requiring less direct energy [13]. Conversely, results from Germany indicate that the significant carbon savings effect of density do offset the environmental impacts of increased consumption in urban areas [7]. Therefore, specific local features can contribute differently to consumption patterns, which in turn lead to varying overall CFs.

As described, the relationship between urbanity, socioeconomic variables, and GHG emissions has been examined to varying extents. Some authors have individually analysed direct and indirect emissions [14, 15], whilst others consider the total emissions [4–8, 16] with respect to a range of explanatory variables. However, most of these studies focus on a handful of cities across a few countries. There is hence value in performing complementary research taking Switzerland as a case study given its comparable economic profile and standard of living. The results would enrich the existing body of research on urban carbon footprints by providing perspectives from an area where similar studies have not been conducted, and by discussing the impact of local Swiss features on its household consumption patterns.

We consider two questions: Would similar results be obtained when separately considering direct and indirect emissions? Furthermore, to what extent would the explanatory power of the considered variables change for each? To address these questions, it is first necessary to scrutinize the method employed to estimate CO₂ emissions. The above-cited studies apply a consumption-based accounting approach to quantify the environmental impacts of consumption. There is general consensus that such methods provide a more accurate estimate of household CFs in import-heavy areas such as cities than can be achieved using production-based approaches [2, 3, 17–20]. Thus, in order to adequately quantify household consumption CFs and analyse their drivers across the urban-rural divide, there is a need not only for more consumption-based empirical studies at a high level of granularity, but also for greater methodological clarity. The process by which existing CF estimation models relate consumption data to production data remains vague [4–6], which could contribute to the uncertainty of final GHG estimates [21].

The main goals of this study are therefore to: (i) present a consumption-based GHG emissions accounting model to estimate the household CF in Switzerland from 2008 to 2014; (ii) provide more detailed insights into the process of mapping consumption to production in CF modelling; and (iii) investigate the impacts of urbanity and other socioeconomic variables on the estimated CF via multilinear regression analysis.

2. Study design and methods

2.1. Input data sources

2.1.1. Household Budget Survey (HBS)

Conducted annually by the Federal Statistical Office (FSO), the HBS provides detailed information on the structure, characteristics, income and expenditure of survey respondents [22]. This study used HBS data from 2006 to 2014. These were taken as 3-year aggregates (2006–2008, 2009–2011, 2012–2014), each of which has a total sample size of approximately 10000 households and was used to estimate the CF for 2008, 2011, and 2014 respectively. At the highest level of aggregation, 19 consumption categories (labelled with 2-digit codes; e.g., 51) are reported in the survey. Among these, eight are associated with mandatory taxes, insurance, and other financial-based services and were excluded from this study. Each of the 2-digit coded categories is also presented as further disaggregated categories (labelled with up to 6-digit codes; e.g., 5111.01). A sample of the structure of the HBS can be found on the website of the FSO (in French)¹.

In order to ultimately associate household consumption to the economic sectors (Classification of Products by Activity (CPA)) of the employed input-output table (IOT), consumption categories reported in the HBS must be compatible with the final use categories presented in the IOT. In this study, category 69 (Other goods and services) was disaggregated using household expenditure data at a finer resolution to derive the two categories 67

¹ Dépenses détaillées de l'ensemble des ménages selon l'année : <https://bfs.admin.ch/bfs/fr/home/statistiques/catalogues-banques-donnees/communiqués-presse.assetdetail.1400628.html>.

(Education) and 68 (Other goods and services). As delineated below, the HBS categories could then be directly mapped to the classification of individual consumption according to purpose (COICOP) categories in the IOT:

UN COICOP categories	←	Swiss HBS consumption categories
01 Food and non-alcoholic beverages	←	51 Food and non-alcoholic beverages
02 Alcoholic beverages, tobacco and narcotics	←	52 Alcohol and tobacco
03 Clothing and footwear	←	56 Clothing and shoes
04 Housing, water, electricity, gas and other fuels	←	57 Housing and energy
05 Furnishings, household equipment and mtnance.	←	58 Household furnishings, equipment and mtnance.
06 Health	←	61 Health
07 Transport	←	62 Transportation
08 Communication	←	63 Communications
09 Recreation and culture	←	66 Culture and recreation
10 Education	←	67 Education
11 Restaurants and hotels	←	53 Restaurants and hotels
12 Miscellaneous goods and services	←	68 Other goods and services

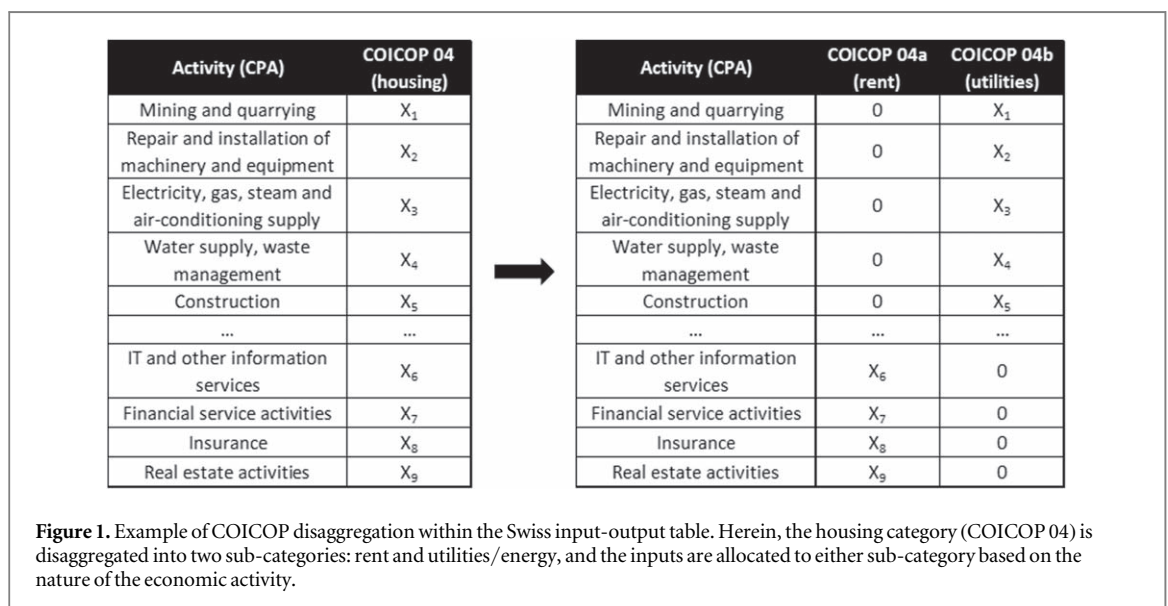


Figure 1. Example of COICOP disaggregation within the Swiss input-output table. Herein, the housing category (COICOP 04) is disaggregated into two sub-categories: rent and utilities/energy, and the inputs are allocated to either sub-category based on the nature of the economic activity.

Given our specific interest in the housing sector with respect to urbanization, category 57 (HBS)/COICOP 04 (IOT) was also disaggregated, again using HBS expenditure data at a lower level of aggregation to derive the two main components: rent and utilities. The utilities component encompasses all housing-related expenditures apart from rent, particularly energy expenditures. Similar disaggregation using more detailed HBS data was performed for transportation—category 62 (HBS)/COICOP 07 (IOT), in order to study household expenditure on ground and air travel separately.

Furthermore, household expenditures for each consumption category also had to be associated with each of the economic sectors in the IOT via the final use table. Each original COICOP column vector in the final use table was first scaled (between 0–1), and then the household expenditure corresponding to that COICOP category was proportionally distributed across economic activities based on the scaled values. This process was repeated for all COICOP categories per household, and subsequently for all surveyed households.

2.1.2. Swiss input-output table (IOT)

We used the 2008, 2011, and 2014 IOTs from the FSO to estimate the CF for each of the three years [23]. The final use table lists 12 COICOP categories as defined by the United Nations Statistics Division [24]. Since these COICOP categories must be compatible with the consumption categories considered in the HBS, COICOP 04 in the final use table was also disaggregated into the rent and utilities sub-categories as described above. In order to disaggregate a COICOP vector, the inputs from each economic activity must be considered individually and allocated to either sub-category based on the nature of the activity. A simplified representation of this disaggregation process is presented in figure 1.

2.2. National accounting matrix with environmental accounts (NAMEA)

NAMEA inventories report the annual volumes of GHG emissions linked to each economic sector [25]. The corresponding inventories were used to compute the CF estimates for 2008, 2011, and 2014. In order to incorporate these data into the CF model, the emission volumes were converted to emission intensity factors for each economic activity according to the sector's total output as reported in the corresponding IOT. The NAMEA emissions inventory also reports the total direct emissions of households for the housing and transportation COICOP categories.

2.3. Environmentally-extended input-output models

2.3.1. Estimating direct emissions

Direct emissions are associated with household consumption of fuels for transportation (ground) and housing (utilities). The estimates for household-level direct emissions were derived from the total volume of direct household emissions for transport and housing reported in the NAMEA air emissions inventory in several steps. First, each household's expenditure on combustibles for transport and heating was obtained from the HBS and summed as a function urbanity (i.e. total urban household expenditure and total rural household expenditure on combustibles). For this, each surveyed household was labelled either as 'urban' or 'rural' based on their municipality type indicated in the HBS (see section 2.3.1 for more details). These totals (urban and rural expenditure) were then used to compute a household-specific coefficient based on the household's individual expenditure on combustibles (i.e. coefficient for urban household A = household A expenditure/total urban expenditure). Next, the total volume of direct household emissions from the NAMEA emissions inventory was scaled accordingly according to the number of households surveyed in the HBS. Finally, to estimate the amount of direct emissions per household, the computed coefficients were multiplied by this scaled total emissions volume from the NAMEA inventory. The total urban and rural direct emissions were then obtained by summing the direct emissions of all urban and rural households respectively.

2.3.2. Estimating indirect emissions

Indirect emissions are induced by household final consumption of domestic and imported goods and services. Equation (1) presents the general EEIOA model used to estimate indirect domestic emissions in matrix form. Here, the total output sub-matrix from the IOT was used to estimate the impact of household consumption of domestically-produced goods and services.

$$\underbrace{\begin{pmatrix} ef_1 \\ \vdots \\ ef_n \end{pmatrix}^t}_e \underbrace{\left[\underbrace{\begin{pmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{pmatrix}}_{\text{identity matrix}} - \underbrace{\begin{pmatrix} z_{1,1} & \cdots & z_{1,n} \\ \vdots & \ddots & \vdots \\ z_{n,1} & \cdots & z_{n,n} \end{pmatrix}}_{\text{coefficients matrix}} \times \underbrace{\begin{pmatrix} 1/v_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1/v_n \end{pmatrix}}_{\text{coefficients matrix}} \right]^{-1}}_{[I-A]^{-1}} \\
 \times \underbrace{\left[\underbrace{\begin{pmatrix} c_1 \\ \vdots \\ c_n \end{pmatrix}^t}_{\text{household consumption}} \times \underbrace{\begin{pmatrix} y_{1,1} & \cdots & y_{n,1} \\ \vdots & \ddots & \vdots \\ y_{1,n} & \cdots & y_{n,n} \end{pmatrix}}_{\text{final use}} \right]}_Y \quad (1)$$

Equation (1): matrix formulation of EEIOA model coupled with household expenditure, where 'e' is the vector of emission intensities derived from the NAMEA air emission inventory and IOT, ' $I-A^{-1}$ ' denotes the Leontief's inverse matrix, and 'Y' is the final demand matrix based on a vector of household expenditure across final use categories. Within the matrices, 'z', 'v', 'c', and 'y', denote the transaction between activities (from IOT), total output (from IOT), household expenditure (from HBS), and final use (from IOT) values respectively, corresponding to each of the economic activities represented in the Swiss IOT.

In order to estimate the embodied emissions in import (EEI), the general CF model was slightly modified (see equation (2)) in two steps [26]. First, we calculated a matrix of import coefficients—the ratio of total imports to the total supply as reported in the IOT. Next, the vector of emission intensities had to be updated; given its largely service-oriented economy and the nature of its production systems, assuming domestic emission factors for imported products is highly unrealistic for Switzerland. Moreover, no appropriate or representative Swiss data is available for imported non-competing goods. Given that 80% of all Swiss imports are of European origin [27], this study used a set of average EU emission factors to more adequately quantify the EEI; particularly since the already large share of imported semi-finished and finished products in the Swiss economy continues to grow.

These average EU emission factors per economic activity were derived from the emission intensity (kg/€) data of each EU country [28].

$$\underbrace{\begin{pmatrix} ef_1 \\ \vdots \\ ef_n \end{pmatrix}^t}_{\text{EU emission factors}} \underbrace{\begin{pmatrix} Im_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & Im_n \end{pmatrix}}_{\text{import coefficients}} \times \begin{pmatrix} \frac{1}{x_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{1}{x_n} \end{pmatrix} \left[\begin{matrix} I & - & A \\ \text{identity} & & \text{coefficients} \\ \text{matrix} & & \text{matrix} \end{matrix} \right]^{-1} \begin{bmatrix} Y \\ \text{final} \\ \text{demand} \\ \text{matrix} \end{bmatrix} \tag{2}$$

Equation (2): Matrix formulation of modified EEIOA model to estimate embodied emissions in import trade. The coefficients matrix A in the Leontief’s inverse $I-A^{-1}$ employs the total supply instead of total output from the IOT, and final demand matrix Y is unchanged. Within the matrices, ‘Im’, ‘x’, ‘c’, and ‘y’, denote the imports (from IOT), total supply (from IOT), household expenditure (from HBS), and final use (from IOT) values respectively, corresponding to each of the economic activities represented in the Swiss IOT.

2.4. Carbon footprint regression models

As elucidated in equation (3), the total CF of household consumption was obtained by summing the direct emissions, indirect domestic emissions, and indirect import-related EEI described above. Hereafter in this letter, ‘carbon footprint (CF)’ always refers to this overall sum. Only CO₂ (fossil), CH₄, and N₂O are considered.

$$\text{Carbon Footprint (CF)} = \text{Direct emissions} + \text{Indirect emissions} + \text{EEI} \tag{3}$$

Equation (3): Definition of the total carbon footprint.

The CF estimate of the transportation category (COICOP 07) was disaggregated to yield the CFs of ground transport and air transport according to the ratio of household expenditure on those two categories, thus resulting in the analysis of 14 total consumption categories. The CF estimates per household generated by the EEIOA model were first normalized according to their respective household sizes to obtain per capita CF estimates, which were then aggregated to produce national, urban, and rural averages. Thereafter, multilinear ordinary least squares (OLS) regression models of the per capita CF and five explanatory variables was performed for 2008, 2011, and 2014 (model equation: CF per capita ~ Income + Urbanity + HHType + HHSize + Region). For each of these years, three regression models were considered: (i) M1–Total CF; (ii) M2–Indirect emissions only; and (iii) M3–Direct emissions only. Input data were all log-transformed to approximate a normal distribution and each model was checked for multicollinearity by evaluating its variable inflation factors (VIFs). Variables would be removed from the model if their VIF > 5 [29].

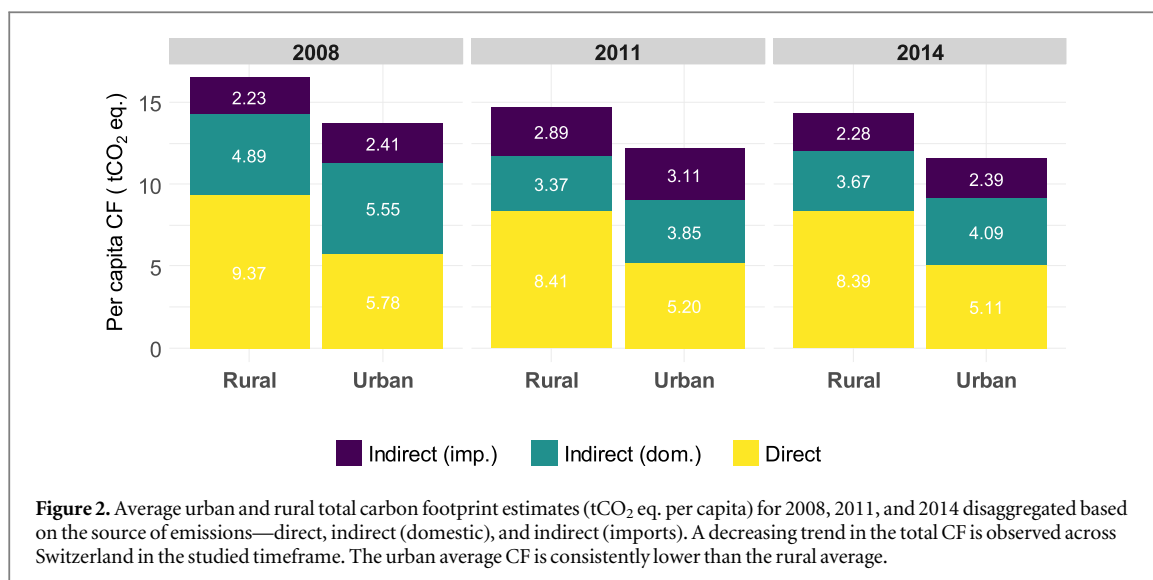
2.4.1. Explanatory variables

The five explanatory variables examined in this study are income, household size, household type, region, and urbanity. Income and household size data were directly obtained from the HBS whilst the remaining three variables were derived from HBS data.

A range of demographic data such as number of children, age of household members etc is reported in the surveys. From this, we defined six classes of household types, ranging from single-parent families to flat-shares: 1 P (one-person household); 2 P (two-person household); 1 F (one-parent family); 2F2 (two-parent family with 1 to 2 children); 2F2 + (two-parent family with more than two children); and O (other household types). Refer to the Supplementary Material (Annexe I) for more details.

We classified each surveyed household as urban or rural according to a typology of municipalities developed by the Swiss Federal Office of Spatial Development. Among the nine classes of municipalities defined in the typology, three were considered urban (centres, sub-urban, and high revenue municipalities) and the rest were categorized as rural (peri-urban, touristic, industrial and tertiary sector, rural commuter, mixed agricultural, and peripheral agricultural municipalities) [30].

Region represents an aggregation of linguistic, cultural, physical and socioeconomic characteristics of the cantons (i.e. states) that make up each regional unit and refers to the seven major regions in Switzerland [31]: 1. Lake Geneva region (VD, VS, GE); 2. Espace Mittelland (BE, FR, SO, NE, JU); 3. Northwest Switzerland (BS, BL, AG); 4. Zurich (ZH); 5. East Switzerland (GL, SH, AR, AI, SG, GR, TG); 6. Central Switzerland (LU, UR, SZ, OW, NW, ZG); and 7. Ticino (TI). Out of these seven regions, the Lake Geneva, Northwest Switzerland, and Zurich regions contain the key urban city centres of the country; namely Geneva, Lausanne, Basel and Zurich. Together with Espace Mittelland region, this collective area is referred to as the Swiss central plateau where most of the population resides and most economic activities take place [32]. The Eastern and Central Switzerland regions comprise largely rural settlements.



Descriptive statistics of each of the explanatory variables for all three years are presented in the Supplementary Material (Annexe II).

3. Results

The average total CF of Switzerland has decreased from 2008 (14.8 t CO₂ eq. per capita) to 2014 (12.7 t CO₂ eq. per capita). We also observe for each an overall decreasing trend in the average urban and rural total CFs from 2008 to 2014 (figure 2). For all the three years, the overall rural emissions were around 20% higher than the urban emissions. This is due mostly to the direct emissions, of which the rural areas had nearly twice as much CO₂ equivalent emissions than the urban areas. This trend is reversed in the case of indirect emissions, of which urban areas had slightly higher volumes—approximately 10% and 5% higher for domestic and imported emissions, respectively.

A deeper examination of the specific consumption categories shows that transport, housing, and food and non-alcoholic beverages have the largest contribution to CO₂ emissions (figure 3(A))². If we consider the direct and indirect components of the total CF separately from each other, we find that the housing-related direct emissions are almost three times larger for rural than urban households (figure 3(B)), and the volume of direct emissions for ground transportation is also larger for rural households. Conversely, most consumption categories report larger indirect emissions volumes for urban households compared with their rural counterparts. Only the housing utilities and ground transportation categories show smaller urban volumes of indirect emissions (figure 3(B)).

3.1. Drivers of the carbon footprint

The multilinear regression analysis performed in this study expands on existing household carbon footprint research [4–6, 8]. We disaggregated the overall total CF to separately analyse indirect and direct household carbon emissions and the effect of each variable on emissions through three regression models. All variables were retained in the models as their VIFs < 5. The full summaries for all three models and years are presented in the Supplementary Material (Annexe IV).

Looking first at the overall total CF regression model (see table 1, model M1—Total CF), income, urbanity, and two-person (2 P) or family (2F2 and 2F2+) household structures have the largest effect on total emissions. Income ($\beta_{\text{Income}} = 0.70$) increases the size of the per capita CF in Switzerland; however, an urban neighbourhood appears to offset this effect by lowering the volume of emissions ($\beta_{\text{UrbanityU}} = -0.45$). Across all household types, a two-person household structure results in the largest CF per capita; however, the volume of emissions decreases with increasing family size. Furthermore, among all the considered regions, Ticino (region 7) is the most impactful in terms of increasing the total CF ($\beta_{\text{Region7}} = 0.19$). Regions with a negative beta coefficient—living in these regions lowers one's per capita CF—correspond to areas with larger urban centres such as Zurich, Bern, and Basel.

² For ease of interpretation, since the overall trends and conclusions drawn for each of the three years were comparable, with the exception of those illustrating a temporal trend from 2008 to 2014 (e.g., figure 2), only the results from 2014 will be presented. The figures corresponding to the results of 2008 and 2011 are reported in the Supplementary Material (Annexe III).

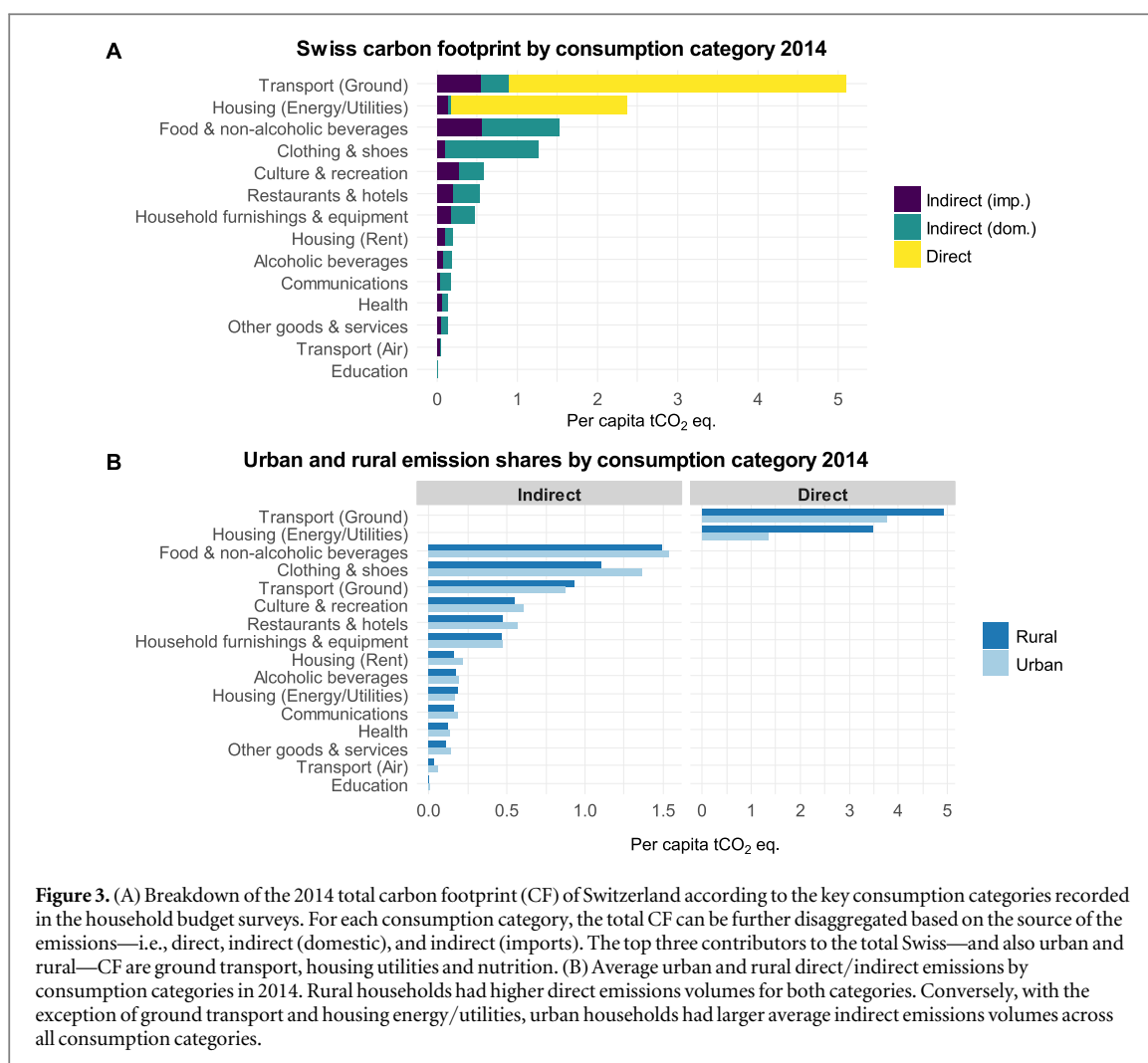


Figure 3. (A) Breakdown of the 2014 total carbon footprint (CF) of Switzerland according to the key consumption categories recorded in the household budget surveys. For each consumption category, the total CF can be further disaggregated based on the source of the emissions—i.e., direct, indirect (domestic), and indirect (imports). The top three contributors to the total Swiss—and also urban and rural—CF are ground transport, housing utilities and nutrition. (B) Average urban and rural direct/indirect emissions by consumption categories in 2014. Rural households had higher direct emissions volumes for both categories. Conversely, with the exception of ground transport and housing energy/utilities, urban households had larger average indirect emissions volumes across all consumption categories.

Table 1. Regression results for OLS models M1, M2, and M3 for the year 2014. For each model, the regression estimates (standardized beta coefficients) are presented along with the significance code of each explanatory variable. Models were checked for multicollinearity using VIF; all variables had VIFs < 5 and were retained in the model. Refer to section 2.3.1 for details on the explanatory variables.

2014 (n _{obs} = 9367)							
	M1—Total CF (tCO ₂ /capita)		M2—Indirect emissions (tCO ₂ /capita)		M3—Direct emissions (tCO ₂ /capita)		
Variables	β-coeff.	t-value	β-coeff.	t-value	β-coeff.	t-value	
(Intercept)	4.2321	55.66***	1.8241	73.4***	1.6824	30.38***	
Income	0.7040	47.98***	0.2741	57.16***	0.2395	22.41***	
UrbanityU	-0.4502	-16.36***	-0.0199	-2.21*	-0.4116	-20.53***	
HHType1P	-0.1007	-0.87	-0.0590	-1.55	-0.0119	-0.14	
HHType2F2	0.2863	3.51***	0.0676	2.54*	0.1829	3.08**	
HHType2F2+	0.2763	2.19*	0.0926	2.24*	0.1273	1.38	
HHType2P	0.3954	5.33***	0.0602	2.49*	0.2853	5.28***	
HHTypeO	0.0551	0.57	-0.0570	-1.79.	0.1412	1.99*	
HHSize	-0.0906	-1.59	-0.0658	-3.54***	0.0113	0.27	
Region2	-0.1110	-2.56*	-0.0016	-0.12	-0.1039	-3.29**	
Region3	-0.1061	-2.15*	0.0086	0.53	-0.1128	-3.14**	
Region4	-0.1461	-3.17**	0.0316	2.09*	-0.1970	-5.86***	
Region5	0.0138	0.28	0.0102	0.63	0.0001	0	
Region6	-0.1349	-2.56*	0.0148	0.86	-0.1551	-4.04***	
Region7	0.1877	3.45***	0.0027	0.15	0.1901	4.8***	
Adj. r ² :	0.2968		0.3339		0.1175		
p-value:	<2.2e-16		<2.2e-16		<2.2e-16		

Significance codes (Pr(>|t|)): 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

In model M2—Indirect emissions, we see that income stands out as the single most important driver ($\beta_{\text{Income}} = 0.27$). In contrast to model M1—Total CF, urbanity plays a negligible role and does not offset the effect of income; however, household size is a significant, albeit weak ($\beta_{\text{HHSize}} = -0.07$) predictor variable of indirect emissions, such that larger households correspond with lower per capita indirect emissions volume. The other explanatory variables also have a weak relationship with indirect emissions and are mostly insignificant predictors ($p > 0.01$), as indicated by their near 0 beta-coefficients.

Finally, in model M3—Direct emissions, we observe that urbanity ($\beta_{\text{UrbanityU}} = -0.41$) is the strongest significant predictor in terms of lowering the per capita emissions volume. Across the various regions, the regression results associate largely urban regions (i.e., regions 2, 3, and 4) with decreased volumes of direct emissions. However, other important explanatory variables such as income ($\beta_{\text{Income}} = 0.24$) and a two-person ($\beta_{\text{HHType2P}} = 0.29$) household structure offset the effect of urbanity and increase the per capita direct emissions.

4. Discussion

This paper presents a consumption-based emissions model to quantify the household CF in Switzerland and provides clearer insight into the normally vague process of relating consumption and production in CF modelling. The estimates were then used to investigate the impact of urbanity and other household socioeconomic variables on the Swiss household CF, and also the role played by specific local features across Switzerland in shaping the relationships gleaned from the regression models.

4.1. Role of urbanity in determining the Swiss carbon footprint

Our regression model revealed that income is overall the most relevant driver (table 1, model M1); but with the second most important beta coefficient, urbanity still plays a key role. Moreover, our results presented in table 1 show that urbanity has varying impacts on direct and indirect emissions, both in terms of its significance and beta coefficient. Urbanity is in fact the most important driver of direct emissions, and this variable appears to reduce household GHG emissions with its negative beta coefficient (table 1, model M3). However, as direct emissions are only relevant to two of the 14 consumption categories, the contribution of urbanity is still outweighed by that of the socioeconomic variables when the total CF is considered. These results suggest that urbanity does play a significant role in lowering the per capita CO₂ emissions; however, the large, opposing influence of income offsets its effect (see table 1, model M1). These results are in line with similar studies concerning other European cities [4, 5], thus suggesting that they are generalizable, at least to countries with a similar economic profile.

The differences observed in the indirect and direct emissions models reflect the significance of the source of emissions when evaluating the role of urbanization. Each has a different focus when used as a metric to evaluate the environmental impact of household consumption. Direct emissions are particularly useful when the study is interested in infrastructural aspects of human settlements that precisely concern the consumption of fuels, such as for buildings and vehicles. Although we are not implying that income and urbanity are mutually independent, consumption linked to direct emissions tends to be more ‘necessity-based’ (e.g. for heating and petrol) and are thus less likely to fluctuate with income and lifestyles. Rather, they are usually indirectly related to the state of physical infrastructure and the degree of urbanisation in the urban system. In contrast, if one were keener on exploring the environmental impact of consumption patterns, indirect emissions would be a more adequate indicator, as they encompass the whole spectrum of consumer goods and services and can better reflect the impact of the various consumer trends and lifestyle choices.

Since this study focusses on household consumption patterns and their associated GHG emissions, the indirect component of the total CF is of greater interest. From regression model M2 (see table 1), urbanity is a much weaker driver of indirect emissions compared to other socioeconomic variables such as income and household size. Moreover, urban and rural households are characterized by comparable structures of consumption (see figure 3)—i.e., the proportion of each consumption category’s share of the total indirect emissions. Thus, the larger volume of indirect emissions associated with urban households is solely explained by their higher rates of consumption. This suggests that Swiss residents across the country have relatively similar lifestyles and consumption habits, and are constrained only by their financial resources. More specifically, Swiss urban and rural lifestyles show convergence, and this homogeneity in lifestyle archetypes is a reflection of the relative uniformity across the country in terms of its physical and social landscape.

Switzerland has a unique structure with respect to the organization of its human settlements. In the key areas of habitation (e.g., the Swiss central plateau), a continuous metropolitan region exists where there is not always a clear divide between cities and the surrounding areas [32, 33]. This phenomenon can be observed in the regression results (see table 1 model M2—Indirect emissions) where none of the *region* variables, with the exception of region 4 (Zurich), were found to be significant predictors of the indirect emissions; indicating that

household consumption patterns and lifestyles are not significantly differentiated across the country. We therefore argue that drivers of any differences in consumption patterns across Switzerland would typically be socioeconomic, rather than geographical or physical in nature.

On direct emissions, our findings reveal that for the housing sector, the average urban estimate is smaller than the rural average, which reflects the positive impact of urban design—for example, smaller unit sizes and the use of more efficient energy systems—on the carbon load of buildings in Switzerland [34–36]. For transportation, the average urban volume of direct emissions linked to ground travel is consistently smaller than that of rural areas, implying that urban residents travel less with private vehicles. Using a different accounting approach, Froemelt *et al* obtained similar results for Switzerland: rural households have larger transport-related emissions per capita than those in urban areas due to greater mobility demands and a larger extent of car-kilometres travelled [37]. Therefore, the trends in household direct emissions across Switzerland are coherent with other studies showing that efficient public transportation networks and soft mobility initiatives can significantly reduce residents' travel demand via private vehicles [34, 36].

Conversely, urban households have consistently larger volumes of indirect emissions deriving from air travel. This result aligns with findings of recent studies showing that urban residents typically engage more in flight-based long-distance leisure travel due to various factors, such as having more geographically-dispersed social networks and more vibrant and cosmopolitan lifestyles [38]. Due to data constraints, the GHG emissions associated with flights can only be indirectly quantified via household expenditure data on flight tickets reported in the HBS and is likely to have been underestimated herein due to limitations of the HBS (see section 4.3). However, even accounting for direct emissions of aviation, the true environmental impact of aviation has been posited to be significantly larger than the estimated volume of direct CO₂ equivalent emissions [39]. A comprehensive assessment of the environmental impacts of aviation reported various ways that this activity can alter the composition of the atmosphere, including affecting radiative forcing and driving ozone depletion and climate change [39]. Despite this likely underestimation, our findings are still adequate from a comparative perspective to evaluate the differences between urban and rural lifestyles with respect to air travel.

All in all, although urbanization does appear to significantly reduce direct emissions and can be justified from other environmental or social perspectives [4], this should not be the first course of action toward reducing the household consumption CF in Switzerland. Among other studies, Jones and Kammen illustrated significant limitations and unanticipated trade-offs associated with increasing urban density to better manage the level of GHG emissions [6]. Rather, the identification of priority areas with respect to either direct or indirect emissions is necessary to design local level consumer-centric initiatives to encourage behavioural changes and achieve sustainable lifestyles.

4.2. Effect of other household structural features on the Swiss carbon footprint

Apart from urbanity, our regression models also draw attention to the effect of other variables—namely household size and type—on the Swiss household CF that arise due to specific local features in Switzerland. Table 1 suggests that direct emissions from potentially 'shared' goods such as cars and heating are not reduced with larger households since household size is neither a significant predictor of direct emissions (model M3) nor the total CF (model M1). For the case of Switzerland, household type, rather than size, would be a more suitable variable through which the effect of sharing can be observed since the structure of a conventional household unit is captured in the type variable. This could possibly also explain the difference in results obtained in another study [7] where household size was found to be a significant predictor of direct GHG emissions in Germany. The household size variable (ranging from 1 to 4 household members) in Gill and Moeller (2018) more closely correspond to the household type variables in this study, that were similarly found to be significant predictors of direct GHG emissions in Switzerland. In addition to the convergence in urban and rural consumption patterns in Switzerland, high rents in urban areas has led to the growing popularity of the 'co-living' concept where the composition of households changes to multiple individuals, couples and even families sharing the same housing unit [40–43]. Pooling the revenues can lower the rent but also give access to more luxurious housing. Outside of rent, other expenditures rise and the sharing of transport and/or energy goods would no longer be the case.

In light of these findings, household composition should therefore be a focal point when studying household carbon saving strategies because the way in which they are organised—co-living ones in particular, could have an important impact on household consumption patterns and consequently their GHG emissions. Moreover, recent research has also highlighted the important role of environmental attitudes and concern in influencing emissions [44] and energy consumption [45]. Such subjective variables (see also [12]) share a bidirectional relationship with household composition and together shape consumption patterns.

From the Swiss perspective, one can conclude that household CF mitigation strategies should prioritise the shift in consumer behaviour and attitudes at the individual or household-level. Sustainable lifestyles and consumption patterns are local scale concepts that must be tailored based on local circumstances, social norms,

and the physical environment. In this context, although urbanization can be effective in creating adapted physical environments to encourage more sustainable lifestyle choices, this in itself is insufficient. Normative perceptions and the effect of peer pressure must also be targeted in order to stimulate changes in individual behaviour [46].

4.3. Consumption-based model to estimate the household carbon footprint

Another objective of this study was to incorporate household consumption data (HBS) into an EEIOA model to estimate the household CF of Switzerland. Our estimates are all larger than the reported figures presented in official Swiss GHG emission accounts based on a production approach (refer to [47]). This distinction corroborates existing claims that production-based emissions accounts underestimate the true impact of household consumption in highly import-dependent areas (e.g. [5]). In addition, the size of our CF estimates align with other consumption-based estimates produced by the FSO using similar methods [48]. Finally, the top contributors to the total CF identified in our study, namely transportation, housing and nutrition, were similarly identified in other, comparable studies of European cities [37, 49, 50].

A second objective was to provide a thorough account of how consumption was associated with production in order to shed light on this relatively obscure process. In order to map consumption data such as budget surveys to intermediate production data available in IOTs, the first step required all data sources to be standardized in terms of their structure relating to the economic sectors. It was also necessary to ensure the compatibility of consumption categories reported in the HBS with the final use categories presented in the IOTs. In section 2, we provided a detailed account of how consumption categories (COICOP) were (dis)aggregated in the HBS and IOT, and the specific process of proportionally allocating consumption data (household expenditure) to the production data (economic sectors) was made more transparent. These actions contribute to the clarification of an important procedure that has thus far remained ambiguous [21].

4.4. Key limitations

The most important limitation of our method would be basing the EEIOA model solely on expenditure. This leads to possible overestimation of the actual impact of marginal consumption, as Girod and de Haan argued that CF models based solely on monetary units typically ‘neglects the potential of decoupling income and environmental impact by consuming better instead of more’ [51]. Therefore, in reality, the relationship between income and environmental impact may not be as linear as it currently appears.

Apart from the problems associated with expenditure-based CF models, there exists other methodological limitations. Unlike most other studies that have estimated the GHG emissions of consumption using aggregated, national-level consumption data, the input data herein was derived from household budget surveys, which has several implications. First, response bias is likely to occur in the household budget surveys, thus leading to potential underreporting of expenses for more sensitive indicators or consumption categories such as income and transportation expenditure [52, 53]. Moreover, the Swiss HBS is conducted on a monthly basis, and the expenditures were scaled up to obtain the annual expenditure values for each consumption category. Clearly, this could have significant impact on the accuracy of the results given that consumption patterns of households could vary significantly throughout the year. For example, a household surveyed during the winter months would likely result in an overestimation of their annual expenditure on heating. Similarly, air travel expenses are likely to be underestimated in the household was surveyed for a month where there was no travel abroad by plane.

5. Conclusions

To conclude, this study calls attention to the important effect of income, rather than urbanization, on the overall CF of household consumption. The results highlight important differences between direct and indirect emissions in their relationship with urbanity. Whereas urbanity plays an important role when we only examine direct emissions, socioeconomic drivers that more directly influence consumption patterns outweigh these carbon-savings effects when the total CF is considered. This finding implies that mitigation priorities must also emphasize measures to increase awareness of sustainable consumption and subsequently induce lifestyle changes at the individual-level. Being largely service-oriented, Switzerland relies heavily on its global hinterlands to meet domestic consumption demand. Thus, a consumption-based accounting approach is imperative for effective climate change action and mitigation. This study is the first to use household budget survey data coupled with input-output analysis to estimate the CF of consumption in Switzerland, and it also explicitly details the mapping process between the HBS and IOT to relate consumption and production in CF modelling. Finally, unique local features and their impact on the drivers of household emissions in Switzerland have also been discussed; identifying household composition as the direction in which further study should be taken.

Acknowledgments

All data with the exception of the household budget surveys are publicly available as listed in the References.

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