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Towards a More Sustainable Urban Food System

Carbon Emissions Assessment of a Diet Transition with the FEWprint Platform

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Towards a More Sustainable Urban Food System—Carbon Emissions Assessment of a Diet Transition with the FEWprint Platform

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Abstract: The production, processing, and transportation of food, in particular animal-based products, imposes great environmental burden on the planet. The current food supply system often constitutes a considerable part of the total carbon emissions of urban communities in industrialised cities. Urban food production (UFP) is a method that can potentially diminish food emissions. In parallel, a shift towards a predominantly plant-based diet that meets the nutritional protein intake is an effective method to curtail carbon emissions from food. Considering the high land use associated with the production of animal-based products, such a shift will prompt a community food demand that is more inclined to be satisfied with local production. Therefore, during the design process of a future low-carbon city, the combined application of both methods is worth exploring. This work introduces, describes, and demonstrates the diet shift component of the FEWprint platform, a user friendly UFP assessment platform for designers that is constructed around the broader three-pronged strategy of evaluation, shift, and design. For three neighborhoods, in Amsterdam, Belfast, and Detroit, the contextual consumption and country-specific environmental footprint data are applied to simulate a theoretical community-wide diet shift from a conventional to a vegan diet, whilst maintaining protein intake equilibrium. The results show that in total terms, the largest carbon mitigation potential awaits in Detroit (-916 kg CO_2eq/cap/year), followed by Belfast (-866 kg) and Amsterdam (-509 kg). In relative terms, the carbon reduction potential is largest in Belfast (-25%), followed by Amsterdam (-15%) and Detroit (-7%). The FEWprint can be used to generate preliminary figures on the carbon implications of dietary adaptations and can be employed to give a first indication of the potential of UFP in urban communities.

Keywords: diet assessment; carbon accounting; sustainable cities; FEW nexus; diet transition; sustainable urban planning; protein intake; CO_2 emissions; plant-based diet

1. Introduction

Throughout the various agricultural revolutions, crop yields kept pace with the increasing food demand of populations [1,2]. Maintaining sufficient food yields for a growing demand imposes a great environmental burden on the planet, for example, freshwater depletion, eutrophication, acidification, pollution, biodiversity reduction, and the emissions of greenhouse gasses. Research estimates that in 2015, the agriculture sector was responsible for about a third (range 24–42%) of the global greenhouse gas (GHG) emissions (Estimations are different between research institutes due to different analysis methods, taxonomy, and/or scopes. In addition, the estimation can vary between years, partly due to developments in the other sectors (e.g., transportation or energy) [3]. During the course of the 20th and early 21st century, subsidence agriculture is shifting towards highly optimised and resource-intensive bio-industry, thus driving the emissions of greenhouse

gasses [2,4]. In addition, populations increasingly rely on international food trade, a trend that is expected to continue in especially developing nations [5]. This increases the distance between the food producers and consumers and is in the carbon accounting discourse often described as *food miles* [6]. At overseas farms, but mainly in tropical areas [7], cropland is increased at the expense of forest land [8]. This is commonly referred to as land-use/land-use change and is a common method to boost food yields, leading to the large-scale atmospheric deposition of carbon dioxide emissions and the loss of soil organic carbon stocks. As the global demand for animal-sourced protein is rising [9], a large portion of the global GHG emissions can be assigned to the livestock sector.

The meat, dairy, and fishery industries are responsible for more than half of the food sector's global environmental impact [10]. In addition to playing a considerable role in global land-use change [9], the livestock sector also contributes to the global greenhouse gas problem by emissions through enteric fermentation and manure management. Enteric fermentation mainly applies to ruminant livestock, i.e., the beef, dairy, and mutton sector, and is the result of microbes breaking down feed and releasing the strong GHG methane (CH_4) in the process [11]. Anaerobic breakdown of organic matter during manure storage mainly leads to methane emissions, and manure application to farmland leads to the release of various greenhouse gasses (mainly N_2O, nitrous oxide).

Greenhouse gas emissions, also referred to as carbon dioxide equivalent (CO_2eq) emissions throughout this work, caused by the consumption of food, can constitute a significant part of the total emissions of an urban dweller. In a preceding study, that introduced a carbon assessment approach for neighbourhoods, the carbon emission profiles for various urban communities around the world were produced [12]. These carbon profiles have been coined *FEWprints*, or Food Energy & Water carbon emission footprints, named after the platform specifically developed for this carbon assessment. The profile incorporates emissions associated with the management of throughput resources commonly used at the household level, which are thermal energy demand, electricity demand, fuel demand for personal mobility, water provision, water treatment, rainwater management, the processing of domestic waste, and food consumption (see Figure 1). This work only focuses on food-related emissions.
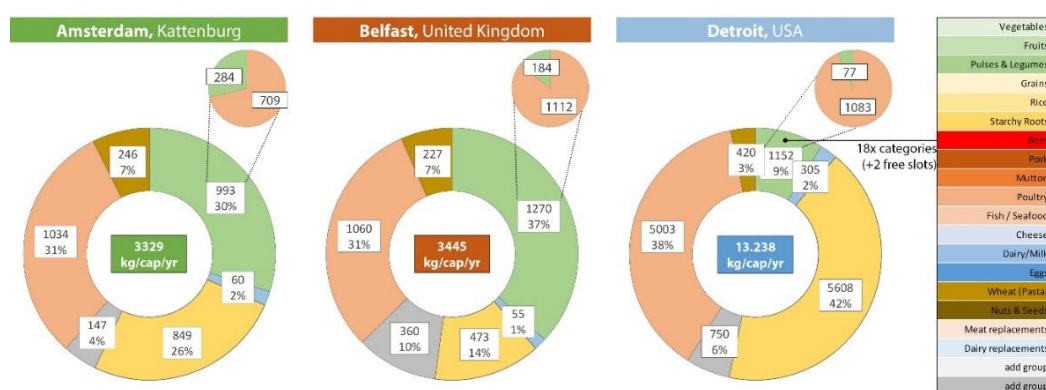
Figure 1. Based on the results in Caat et al. (2022). The FEWprint of the Kattenburg community (Amsterdam, AMS), the Inner-East community (Belfast, BEL) and the Oakland Avenue Farming Community (Detroit, DET). Values are expressed in kg CO_2eq/capita/year. The secondary graph shows the animal (pink) and plant based (green) emissions.

FEWprint assessment of an urban community in the neighbourhood of Kattenburg (Amsterdam), Inner-East (Belfast), and Oakland Avenue (Detroit) has revealed that food-related emissions are responsible for respectively 30%, 37%, and 9%, or 993, 1270, and 1152 kg/capita/year. The assessments are based on contextual resource demand and country-specific (or at a more granular level when available) carbon footprint indicators. The food sector emissions are estimated based on national food consumption survey data combined

with country specific emission factors. Only non-processed food items/groups—subdivided into 18 food categories—were added to the food assessment scope. The relative impact of food [% of total emissions] is often dictated by the impact of the other sectors recorded in the carbon profile, hence leading to a considerable range (9–37%).

In essence, food sector emissions can be brought down by making improvements to the supply chain or by altering the demand on the consumer's side. One alternative strategy to the conventional food supply chain is urban food production (UFP): the production, processing, and marketing of food products in urban centres or in the urban periphery. This can potentially offer various ecological benefits [13], environmental benefits when managed sustainably [14,15], and deal with various other challenges in the urban setting [16]. A collective dietary change at the consumer level can bring about environmental benefits on a scale that is difficult to achieve by the producers of the food [10].

The greenhouse gas emissions related to food consumption have been studied extensively in the past decades, and so has been the impact of a diet change to mitigate food sector emissions [17–20]. In general, it can be stated that the scientific community is in consensus on the lower environmental impact of adopting a diet that predominantly consists of plant-based food categories [21], and the World Resource Institute has included this as one of the key steps to achieved sustainable food security in the future [22]. Also, when calculated at the community level, changing food consumption patterns is expected to bring about carbon emissions benefits. However, due to the variation in sectoral emissions between communities, it is likely that a dietary shift from animal-based to plant-based protein would impact the FEWprints to a different extent in each community, which is tested in this work.

Urban food production is increasing in popularity among the general public, architects, urban designers, and policymakers in urban centres [15], quite often driven by the claim that *local* is inherently better for the environment [23]. However, the carbon emissions-reducing impact of UFP strategies is difficult to holistically quantify as food production is a complex and multi-faceted system and a comparison between a local and an imported product is not easily drawn. Local food production, especially in a dense inner-city location, often operates at a smaller capacity. This leads to a decreased energy efficiency per unit of food output and an increased footprint, a concept coined the *ecology of scale* [24]. Considering the inverse relationship between farm-scale and impact per unit of food, UFP should not be approached as merely the relocation of farming to an urban context, which effectively only shortens food miles and reduces food waste, but rather as the integration of a food system within the urban resource infrastructure. This could disclose an array of opportunities for symbiotic resource management between the two systems, a potential that is discussed more often in literature [16,25–27].

In the contours of urban design practice that is in pursuit of self-sufficiency, resiliency, and the decarbonisation of a neighbourhood or city, food demand, and UFP design are at interplay with each other, particularly during the conceptual stage of the design process. Community-wide food consumption patterns determine the food demand. A combination of UFP and conventional food imports are responsible to meet this demand. In view of the high land use associated with animal-based protein [10,28], diets that are inclined towards plant-based food offer more potential in space-limited urban centres or peripheries. As such, a dietary intake shift could play a determinative role in the ratio between locally produced protein and imported protein. With our research, we intend to provide a strategy and framework for non-agriculturist (e.g., urban planners and designers) and support the UFP design process with instant preliminary figures on food yield, resource demand, and environmental impact after design moves. To achieve this, the FEWprint operates as an integrated UFP assessment platform and has been constructed around the three-pronged strategy of (1) *evaluation*, (2) *diet shift*, and (3) *design*.

This work introduces and describes the *diet shift* component of the FEWprint platform. The component is demonstrated by employing it to determine the theoretical impact on the carbon equivalent emissions of the three aforementioned case study communities

when animal-based protein is gradually replaced by plant-based protein. Protein intake is used as the functional unit, and Section 2.1 further elaborates on securing a protein intake equilibrium during diet transition. The first objective of this study is to see the extent to which the community's food sector emissions are diminished throughout a series of drastic diet scenarios. The second objective is to see how the daily food intake pattern changes as a consequence of maintaining a protein intake balance throughout these diet scenarios. The preceding FEWprint *evaluation* component has been discussed in Caat et al. [12] and the successive UFP *design* component will be discussed in future disseminations. An empty FEWprint platform template and example assessments can be found in the Supplementary Materials Documents S1–S4 of this article.

2. Materials and Methods

2.1. Dietary Quality Indicator: Protein

Protein is a macro-nutrient that is composed of long chains of various types of amino acids. Dietary protein supplies the human body with the full range of essential or indispensable amino acids, i.e., the types of the body cannot synthesize on its own. By breaking down the dietary protein during digestion, the body is able to self-compose various other amino acids important to sustain bodily functions, also referred to as the non-essential amino acids [29]. Briefly: amino acids are vital components for growth, metabolic interactions, and maintenance of the body. Parts of the amino acids are further broken down to produce energy for the body. The recommended daily protein intake is different among individuals and depends on age, gender, physical condition, or sports activity. For the general population, the world health organisation recommends a minimum safe level of daily protein intake for adults (male + female) of 0.83 g/kg of body weight [30]. Long-term deficient intake of protein can affect vital organs and the immune system, making protein content and protein quality of food products and/or diets an important criterion of adequate nutrition [29]. This study applies the daily protein intake [$gram_{prot}$/day] as the currency of nutritional quality of the alternative diet, a method that has been used more frequently in the past [31,32].

Both animal-based and plant-based food contain protein. It is however animal products that are considered as the typical source of protein in current diets [33]. Animal-based protein contains, in higher quantities, the full range of essential amino acid combinations required by the body, which can be an essential component to close nutrition gaps in especially developing countries [34]. Plant products contain a lower amount of proteins and plant protein contains fewer amino acids or they are present in non-optimal proportions, making them harder to break down [35]. Even though total protein consumption or protein content of food items is popularly used as an umbrella unit, nutritional quality of a diet should be assessed at the level of the individual amino acid intake [36–38]. This is underlined by Bohrer by stating that "plant derived proteins usually have large amounts of some to most essential amino acids, but have little or no amounts of some essential amino acids" ([35], p. 105), meaning shortages of specific amino acids can be bypassed through variety in plant-protein. Various studies have shown that a healthy amount of indispensable amino acid intake can be achieved by consuming only plant-based protein [35,36,39,40].

2.2. Maintaining a Healthy Protein Intake

An inconsiderate transition towards a (partly) plant-based diet could lead to an abatement of total protein intake, even when the amount of food consumed in terms of weight is kept equal by consuming substituting plant-based products. The size of such emerging protein-gap depends on various factors, namely the current reliance on meat and dairy for protein intake, the present consumption of the other food groups, the extent of the assessed diet shift, and the applied protein content indicators for the various food

groups. But as argued, a considerate consumption of plant-based amino acids can avoid such a risk of protein deficiency.

On a single source basis, plant products offer reduced protein intake with a lower bioavailability compared to their meat analogues [35]. However, a combination of various plant proteins, extracted from a range of crop types, can be fully adequate to provide the necessary diversity of indispensable amino acids [39]. The EAT-Lancet committee recommends diversity within a largely plant-based diet, with a modest amount of animal sources [41]. When only plant-based food products are consumed, variation remains an essential aspect and will secure an adequate diet [42,43]. Therefore, in this study, a varied selection of plant-based groups that are generally high in protein are added to the diet in order to close the emerged protein gap. These are legumes and pulses, grains (cereals), nuts and seeds, and meat replacers (soy-based). Dairy (includes milk and yoghurt) is substituted with soybean-based dairy replacers.

The FEWprint platform can be used to compose a new and less impactful diet, whilst maintaining protein intake equilibrium with the current diet. In order to produce a meaningful evaluation of nutritional quality with regard to the protein intake of a new diet, it should preferably be evaluated at the amino acid level, where each amino acid combination is quantified separately. However, as each food product contains a different composition and quantity of essential amino acids, it would complicate the mechanics and data requirements of the platform considerably. Since the platform has been developed on the values of inter-component integration and scope comprehensiveness, whilst securing simplicity and functionality [12], it, therefore, simplifies the assessment by only considering the total protein intake [gram$_{prot}$/cap/day].

A holistic assessment and comparison of conventional diets with alternative low-impact plant-based diets on the dimensions of sustainability and nutritional quality is a complex task as it requires indicators for both aspects and the possibility to link them [44]. The protein content of food [gram$_{prot}$/100 gram$_{food}$] is such a factor when (re)establishing the protein intake equilibrium between two diets. Both extensive, as well as aggregated lists of protein content of numerous retail food products/categories, can be retrieved from online public databases, however, protein content data shows a lot of variabilities [42]. This can also be observed in Table A5, where the protein content of food groups, retrieved from national databases for the Netherlands, the United Kingdom, and the USA, is tabulated in grams of protein per 100 g (retail weight). This study applies the global average FAO values for the assessment [45], which are based on a combination of various items within a group, and only products that are considered a customary staple food for daily consumption are included, see Appendix C for more information.

2.3. Diet Shift: Framework of Diets and Diet Shift Component

The platform applies five commonly followed diet types to frame a community-wide transition towards a plant-based diet: *pesce-pollotarianism* (*PPT*), *pescetarianism* (*PT*), *vegetarianism* (*VT*), *ovo-vegetarianism* (*OV*), and *veganism* (*VG*). Since formal definitions of these terms may differ depending on the addressed source or context, this study applies elementary definitions that are based on the ADA descriptions [40]. In the pesce-pollotarian diet, red meat is removed from the menu, which is beef, pork, and lamb/mutton. In a pescetarian diet, red meat and poultry are not eaten whilst the consumption of fish and seafood is still allowed. In a vegetarian diet, all red meat, poultry, and fish and seafood groups are removed. People who follow an ovo-vegetarian diet additionally remove dairy and cheese from the menu, but the eggs are still allowed. This is a very uncommon diet in reality but is added to the selection as it can be a relevant in-between step when designing an urban food production strategy. Finally, all animal-based food groups are removed in the vegan diet.

Figure 2 displays a screenshot of the *diet shift* component of the MS Excel based platform that consists of steps 3a to 3d. The dietary transitions are inserted in step 3a. The percentages, noted by r_{1-5}, represent the fraction of the total community that follows a

specific diet. The dietary levels follow a hierarchy according to increasing removed food groups, and each broader restriction contains the lenient one (e.g., a vegan must by definition also be a vegetarian, but a vegetarian is not necessarily a vegan). This means that the inserted value of a diet tier can therefore never be higher than the preceding tier. In step 3b, substitution food is selected and quantified to maintain consumption balance based on weight. Step 3c is used to manually reinstate protein intake equilibrium with plant-based products after diet shift. Step 3d can be used to manually adjust the diet according to the users' preferences.

2.4. Diet Scenarios

For all three assessed communities, four alternative diet scenarios and their impact on the community's total carbon footprint are calculated and compared with the baseline. The scenarios are in order of removed animal products, illustrating a gradual transition towards a vegan diet. Substitution factors are presented in Table 1. In each scenario, discussed animal food group(s) are completely removed from the diet. The equation framework and parameters used to assed the transition are further discussed in Section 2.5.

The five scenarios:

1. *Business as Usual (BAU)* represents the current situation without any dietary changes. Food consumption is based on national survey data.
2. *Pesce-Pollotarian diet—animal substitution* (PPTA, $r_1 = 1.00$). For all people in the assessed community, the beef, pork and mutton food groups (red meat) are completely removed from the diet and replaced with animal-based substitutions: poultry $(r(poultry)_{sub1} = 0.5)$ and fish, $(r(fish)_{sub\,1} = 0.5)$.
3. *Pesce-Pollotarian diet—plant substitution* (PPTP, $r_1 = 1.00$). For all people in the assessed community, beef, pork, and mutton food groups (red meat) are completely removed from the diet and replaced by plant-based alternatives. Substituting food groups and values are listed in Table 1.
4. *Vegetarian diet* $(r_{1-3} = 1.00)$. For all people in the assessed community, the food groups beef, pork, mutton, poultry, and fish are completely removed and replaced with plant-based alternatives according to the values listed in Table 1.
5. *Vegan diet* $(r_{1-5} = 1.00)$. For all people in the assessed community, all animal-sourced food groups are removed and replaced by plant-based food according to the substitution values listed in Table 1.

Table 1. Substitution values $r(n)_{sub}$ used for the diet scenarios (scen.) in this study. $\times$ = removed from diet in that tier.

Weight and Protein Compensation [1]	Scen.	Eq.:	1 Vegetables	2 Fruits	3 Leg. & Pulses	4 Grains	5 Rice	6 Starchy Roots	7 Beef (&veal)	8 Pork	9 Sheep/Goat	10 Poultry	11 Fish & Sea food	12 Cheese	13 Dairy (other)	14 Eggs	15 Pasta (durum)	16 Nuts & seeds	17 Meat replacers	18 Dairy replacers	Total
business as usual (BAU)	(1)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
pesce-pollotarianism -animal substitutes (PPTA))	(2)	[1]	-	-	-	-	-	-	$\times$	$\times$	$\times$	½	½	-	-	-	-	-	-	-	1
pesce-pollotarianism -plant substitutes (PPTP)	(3)	[1]	-	-	¼	¼	-	-	$\times$	$\times$	$\times$	-	-	-	-	-	-	¼	¼	-	1
pescetarianism (PT)	n.a.	[2]	-	-	¼	¼	-	-	$\times$	$\times$	$\times$	$\times$	-	-	-	-	-	¼	¼	-	1
vegetarianism (VT)	(4)	[3]	-	-	¼	¼	-	-	$\times$	$\times$	$\times$	$\times$	$\times$	-	-	-	-	¼	¼	-	1

| ovo-vegetarianism (OV) | n.a. | [4] | - | - | - | - | - | - | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ | - | - | - | - | ¼ | 1 |
| veganism (VG) | (5) | [5,6] | - | - | ¼ | ¼ | - | - | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ | | - | ¼ | ¼ | - | 1 |

[1] Please note: in this study, the substitution factors used to maintain equal food intake and the surplus consumption to maintain protein intake equilibrium are in the same proportion within a scenario and are therefore presented in the same overview.
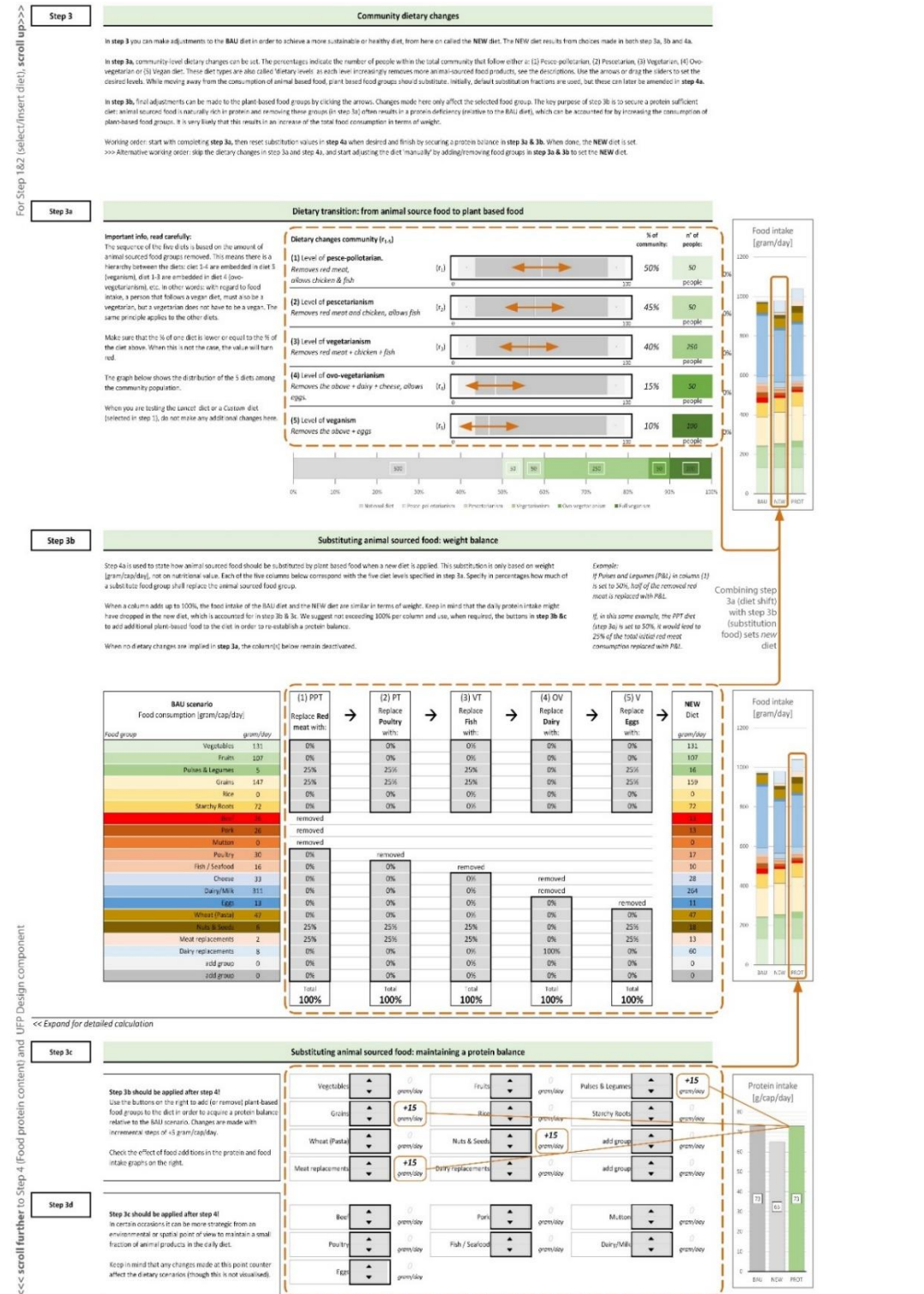

Figure 2. Screenshot of the FEWprint tool interface. Step 3a: The sliders used to set the values (r_{1-5}) for the various diets. The graph shows the NEW diet (=weight balanced) and PROT diet (=protein balanced) Step 3b: Substitution values should be inserted for each of the five-diets tier, or default

values can be used. Step 3c & 3d: Increase or recompose the food intake of plant based or animal-based food groups to account for the protein deficiency. Displayed values are exemplary.

2.5. Equations Framework

A new and community-wide diet scenario is simulated by inserting the fraction of the community that will follow an intended alternative diet. Equations (1)–(6) are used to determine how removed animal-based food categories are substituted throughout the five dietary levels with plant-based food groups in order to maintain an equal food intake in terms of weight. The various values applied in this study are similar to the default values used in the FEWprint (listed in Table 1) and aim towards a lower-emission alternative diet with increased consumption of varied plant-based food groups that are naturally high in protein content.

$$PCC(7,8,9)_{new} = PCC(7,8,9)_{ctx} \times (1 - r_1) \tag{1}$$

$$PCC(10)_{new} = (PCC(10)_{ctx} + (PCC(7,8,9)_{ctx} \times r_1 \times r(10)_{sub\,1})) \times r_2 \tag{2}$$

$$PCC(11)_{new} = (PCC(11)_{ctx} + \sum(PCC(7,8,9,10)_{ctx} \times r_{1,2} \times r(11)_{sub\,1,2})) \times r_3 \tag{3}$$

$$\begin{aligned} PCC(12,13)_{new} = \;&(PCC(12,13)_{ctx} \\ &+ \sum(PCC(7-11)_{ctx} \times r_{1-3} \times r(12,13)_{sub\,1-3}) \times r_4 \end{aligned} \tag{4}$$

$$PCC(14)_{new} = (PCC(14)_{ctx} + \sum(PCC(7-13)_{ctx} \times r_{1-4} \times r(14)_{sub\,1-4})) \times r_5 \tag{5}$$

$$PCC(n)_{new} = PCC(n)_{ctx} + \sum(PCC(7-14)_{ctx} \times r_{1-5} \times r(n)_{sub\,1-5}) \tag{6}$$

All calculations start with the (contextualised, ctx) present food intake of a food group, denoted by the Per Capita Consumption, $PCC(n)_{ctx}$ [g/cap/day], where n refers to the food group represented by its listing number 1–18 in Table 2. The new per capita food consumption is noted by $PCC(n)_{new}$ [g/cap/day]. A dietary shift towards a PPT, PT, VT, OV, and VG diet are respectively simulated with the factors r_1, r_2, r_3, r_4, and r_5, where the number refers to the diet tier. The r value sits between 0% (no people in the community will follow that specific diet) to 100% (everybody) and since the lower-tier diets are contained in the higher ones, the constraint $r_{n-1} \geq r_n$ applies. The substitution percentages are represented by $r(n)_{sub\,1}$ to $r(n)_{sub\,5}$, where the *sub* number corresponds with the diet tier. For example, $r(10)_{sub\,1} = \frac{1}{2}$ implies that half of the removed red meat after the BAU to PPT shift is replaced with poultry (group 10). Within one diet tier, the total of all $r(n)_{sub\,x}$ values should add up to 1.0 to secure an equal food weight intake. The aforementioned factors are displayed in Figure 3 for clarity. The combined effect of applied r_{1-5} and $r(n)_{sub\,1-5}$ values in one tier trickle down to all the lower diet tiers, as is visualised in Figure 4. Equations (1)–(6) and the default values are embedded in the *diet shift* component of the FEWprint platform to streamline the simulation.
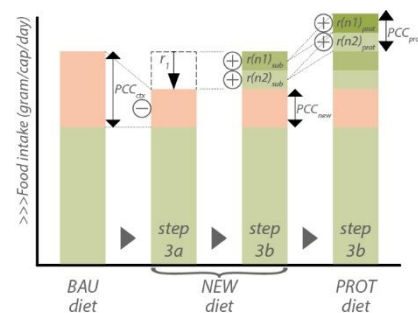

Figure 3. Various factors used in diet shift simulation.

As mentioned in Section 2.2, the animal-based food that is removed by a diet shift, is substituted with four different plant groups: (1) Legumes and Pulses, (2) Grains, (3) Nuts and Seeds, and (4) Meat replacers. These products are used both to maintain equilibrium

in terms of weight (step 3b) as well as securing a protein intake equilibrium (step 3c). In order to maintain a protein equilibrium, the above products are repeatedly added in steps of 5 g in the same sequence as listed above, until a similar protein intake as the baseline situation is achieved, which is called the PROT diet. In addition to the ability of starting with a fully customisable diet, all the diet transition levels (r_x), substitution ratios ($r(n)_{sub\,x}$), and plant alternatives used as protein replacers can be specified according to the user's priority in the platform.

Figure 4 depicts the diet hierarchy applied in the FEWprint platform and shows how changes on one level trickle down to affect the dietary composition on successive levels. Community-wide dietary changes throughout tier 1 to 5 are based on the contextualised diet, i.e., the national diet adjusted to the local context by accounting for halal diets and the meat lover population. Finally, the consumption of plant-based food groups can be adjusted to re-establish protein equilibrium in step 3c. In addition, any other dietary changes the user wishes to simulate, for example, an increase in fruit consumption, can be inserted in steps 3c and 3d.
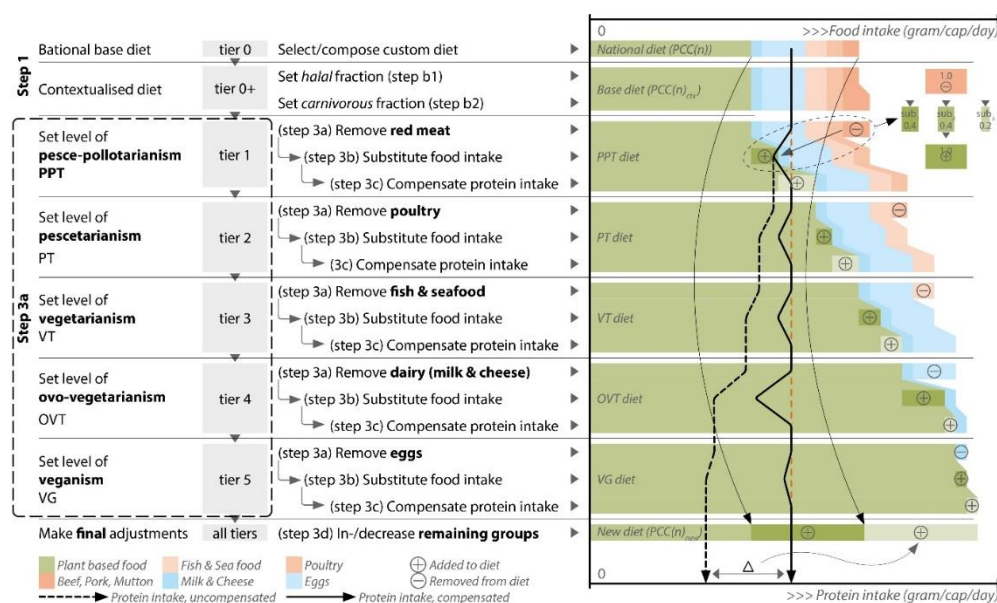
Figure 4. FEWprint diet and calculation hierarchy. Step 3a to 3c correspond with the FEWprint steps shown in Figure 2 and are used to establish the new diet. The dashed lines indicate the protein intake without supplementary food for protein balance, the straight line represents the balanced intake.

2.6. Urban Case Studies: Amsterdam, Belfast & Detroit

Three urban communities have been selected for a continued analysis on the role of food and a diet transition with regards to their FEWprint carbon profile. The first case is the residential neighbourhood of Kattenburg in Amsterdam, which holds a population of about 1700 people. The second case is Inner-East in Belfast, where about 32,000 people live. The third case is the smaller Oakland Avenue Farm community in Detroit, where currently 427 people are living. The three cases, their consumption of FEW resources, and the relevant carbon emission indicators are more thoroughly discussed in Caat et al. [12]. Table 2 lists the dietary intake [gram/cap/day], country-specific carbon footprint data [kg CO₂e/kg food] and protein contents [g/100g_food] applied in this study.

Table 2. Dietary intake of the 18 food groups, *PCC(n)* [gram/cap/day] + applied contextualization parameters r_{hal}, r_{car}, and r_{add} [%]. N.d. = no data available or not mentioned as an individual food group but logged under other group. Consumption values only contain non-processed food items. Protein content of food groups. FAO data is used for further assessment and values represent the average protein content of an extensive list of products. Protein content values apply to retail weight.

	Food Category	Food Intake [g/cap/day]			Carbon Footprint [kg$_{CO2}$/kg$_{food}$]			Protein Content [g/100 g$_{food}$]
	Food Groups (*n*)	AMS [3]	BEL [4]	DET [5]	AMS [6]	BEL [7]	DET [8]	FAO [9]
	r_{hal} [%]	15%	0%	3%	-	-	-	-
	r_{car} [%]	25%	20%	22%	-	-	-	-
	r_{add} [%]	15%	15%	15%	-	-	-	-
1	Vegetables	131.0	92.0	99.7	1.82 (31)	1.77 (3)	0.48 (57)	1.90 (29)
2	Fruits	113.8	114.0	77.5	1.53 (18)	0.90 (1)	0.57 (32)	0.70 (37)
3	Legumes & pulses	4.5	3.0	11.6	2.53 (3)	3.40 (2)	0.80 (18)	24.2 (12)
4	Grains & Cereals	138.3	106.0	150.8	1.32 (12)	1.00 (2)	0.46 (14)	14.0 (12)
5	Rice	n.d.	15.0	n.d.	1.71 (2)	3.90 (1)	1.73 (4)	6.70 (7)
6	Starchy roots	72.2	93.0	57.7	0.92 (1)	0.40 (1)	0.25 (3)	2.10 (16)
7	Beef (& veal)	12.6	21.0	51.8	30.82 (6)	68.8 (1)	32.85 (1)	16.4 (?)
8	Pork	13.0	31.0	39.4	13.73(4)	7.90 (1)	5.56 (1)	13.1 (?)
9	Sheep & Goat (+lamb)	0.6	5.0	0.7	n.d.[12]	64.2 (1)	34.75 (1)	13.5 (?)
10	Poultry & Turkey	16.6	36.0	75.1	12.21(2)	5.40 (1)	3.20 (3)	15.2 (?)
11	Fish & Seafood	12.9	22.0	8.2	8.61 (19)	5.40 (1)	7.70 (6)	13.5 (?)
12	Cheese	32.6	18.0	34.2	11.28 (5)	4.50 (1)	9.97 (1)	17.0 (?)
13	Dairy (Milk & Yog.)	254.3	262.0	138.6	2.31 (11)	1.90 (2)	1.33 (2)	8.30 (?)
14	Eggs	12.7	15.0	27.3	4.32 (1)	4.90 (1)	3.75 (1)	10.7 (?)
15	Pasta (durum wheat)	47.1	14.0	n.d.	1.52 (1)	1.00 (1)	n.d.	11.8 (?)
16	Nuts & Seeds	6.3	5.0	13.9	4.16 (8)	2.00 (1)	1.93 (12)	13.0 (13)
17	Meat replacements [1]	1.5	n.d.	n.d.	n.d. [10]	n.d. [10]	n.d. [10]	13.0 [1]
18	Dairy replacements [2]	8.4	n.d.	n.d.	0.76 (1)	n.d. [11]	0.53 (2)	3.0 [2]
	total [g/cap/day]	878	852	787				

[1] Retail product assumed for meat replacer: Tofu, uncooked (33% water), 13 g protein/100 g product. [2] Retail product assumed for dairy replacer: Soy Drink, natural, 3.0 g protein/100 mL of product. [3] Source:[46], [4] Source: [47]. [5] Source: [48], an extensive breakdown of the 18 food categories into individual food items or subgroups can be found for all three cases in Caat et al. [12]. [6] Source: [49], data is based on Life Cycle Inventory studies and reflects cradle-to-consumption greenhouse gas emissions factors. Dataset is in Dutch. [7] Source: [19], data is based on Life Cycle Inventory studies and reflects cradle-to-retail distribution centre [50]. Note source: values are weighted for production in the UK, imports from the EU, and imports from outside the EU. [8] Source: [51]. [9] Source: [45], see Appendix C for more information about the data sources for all three cases and dataset processing. [10] Food group not specified in source, assumed value applies: 2.0 kg CO_2eq/kg$_{food}$. [11] Food group not specified in source, global value applies (provided by Poore & Nemecek [10]: Mutton = 24.00 kg CO_2/kg, Dairy repl. = 0.90 kg CO_2eq/L).

3. Results

Five diet scenarios were assessed with the FEWprint platform for an urban community in Amsterdam, Belfast, and Detroit. The first objective is to assess the theoretical carbon emission mitigation potential of a diet shift towards a plant-based diet (Section 3.1). The second objective is to see how the average food intake changes during the diet shift when a protein intake equilibrium is maintained (Section 3.2).

3.1. Carbon Implications

The *business as usual* (BAU) and the four theoretical diet scenarios have been assessed based on their total [kg/cap/y] and relative impact [%] on the overall carbon equivalent footprint of the community (Figure 5). The substitution factors ($r(n)_{sub}$, Table 2), diet shifts, and assumed amount of protein contained within a food item/category are similar

for each of the cases during the simulations. In addition, the scope of assessed food consumption is aligned between cities as much as possible so that for each community, the same food items are accounted for in this carbon assessment [12].
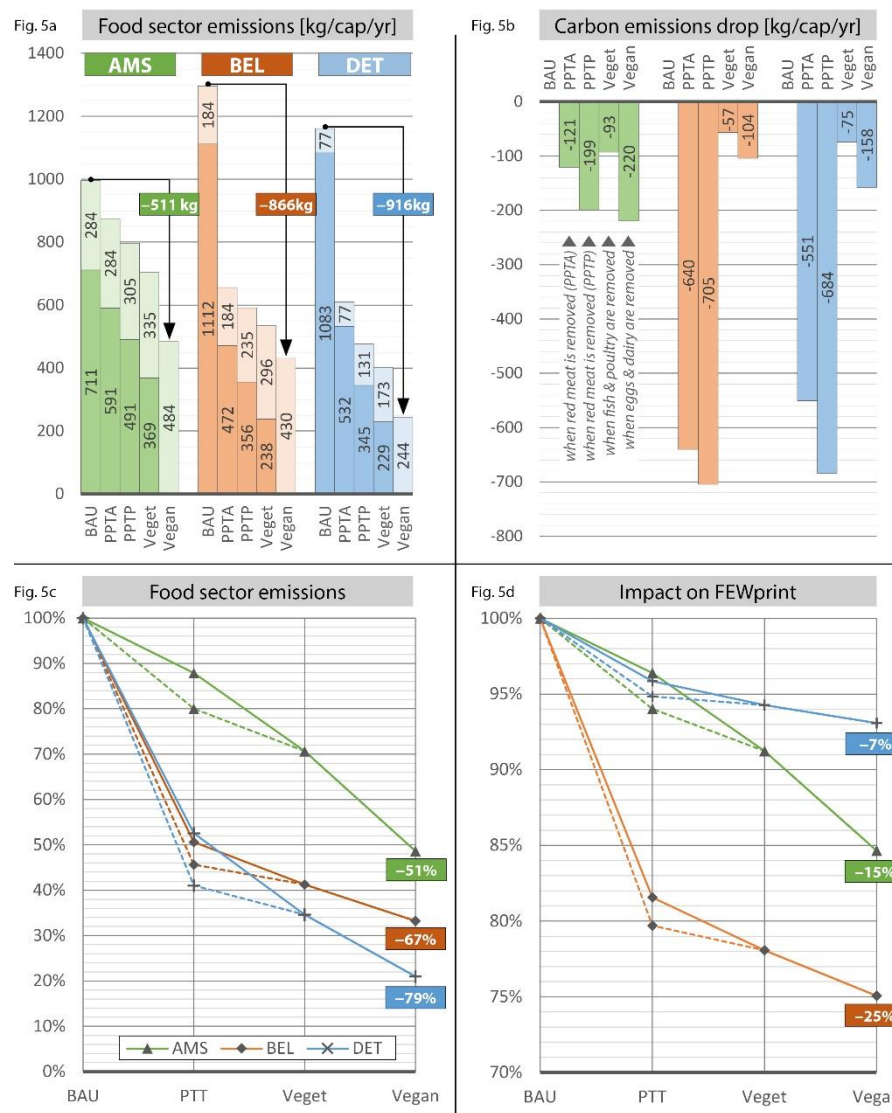

Figure 5. Carbon emissions of the food sector (dark color = animal products, light color = plant products. (**a**): [top left] Food sector emissions (AMS, BEL & DET) for the 5 diets [kg/cap/year]. (**b**): [top right] Carbon reduction per removed food categories (**c**): [bottom left] Relative impact of a dietary change on the food sector emissions [%]. The PPTA and PPTP diet has been split in two nodes, where the PTTP (plant alternatives) diet is represented by the dashed line. (**d**) [bottom right] Relative carbon emission reduction of a diet shift on the total FEWprint of a community.

Figure 5a shows the absolute impact of diet change on food-related emissions. Removing animal-sourced food categories and replacing them with plant-based alternatives predictably leads to a drop in the food-related emissions for all three communities. However, the carbon emissions mitigation potential of such diet transition varies considerably per country. The largest carbon mitigation potential, i.e., the difference between the present situation and the vegan scenario, awaits in Detroit (−916 kg CO_2eq), closely followed by Belfast (−866 kg CO_2eq) and then Amsterdam (−511 kg CO_2eq). The red meat categories dominate a significant part of the emissions in the Belfast and Detroit cases, which is evidently visible in the graph. In Amsterdam, the largest drop in emissions can be seen when cheese and dairy are removed from the diet.

Figure 5c,d shows the relative impact throughout the four alternative diets for respectively the food sector and the total FEWprint of the community. In Amsterdam, Belfast, and Detroit, the food sector initially constitutes respectively 30% (993 kg CO₂eq) 37% (1270 kg CO₂eq), and 9% (1152 kg CO₂eq) of the total emissions. Even though the largest reduction is in absolute numbers theoretically achievable in Detroit (−916 kg/cap/y, Figure 5a), when a vegan diet is maintained, in relative terms, the impact sits just below 7%. In comparison, a vegan diet in Belfast would reduce the total carbon emissions of a community by about 25%—the highest reduction potential of the assessed case studies.

Figure 5c,d show two curves for each case study. For all three cities, the upper node in the PPT column represents the scenario where the red meat category is substituted with animal-sourced alternatives (PPTA). The bottom node represents the scenario in which red meat is substituted with plant-based food (PTTP). Substituting red meat with plant alternatives instead of meat alternatives leads to lower emissions in all three cases, with the Detroit case showing the largest difference (132 kg CO₂e/y).

3.2. Food Intake Shift

When transitioning through the diet alternatives, removed animal-based food products are equally substituted in weight equivalents according to the substitution factors listed in Table 2. In addition, as a result of securing a protein intake equilibrium relative to the current situation, surplus plant-based food that is naturally high in protein content should be consumed.

When comparing the present diet with the vegan diet in each case study, most surplus food is required in Amsterdam (+80 g/cap/day), followed by Detroit (+75 g) and Belfast (+65 g), shown in Figure 6. All communities show a steep drop in protein intake when dairy and eggs are removed from the diet, resulting in a considerable increase in surplus consumption to compensate. This can be attributed to the combined effect of relatively high consumption of dairy (AMS: 254, BEL: 262 and DET: 139 g/day) and high protein content of dairy (8.30 g/100g_food), that is fully substituted with a soy-based alternative with a lower protein content (3.0 g/100g_food), hence requiring more consumption from the other categories to level the intake.
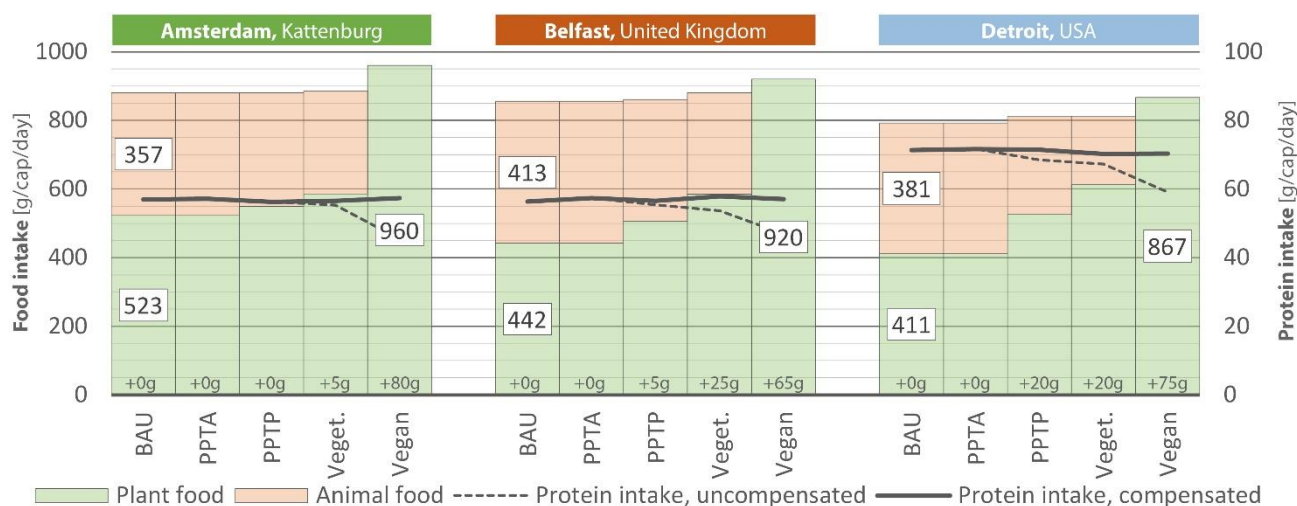
Figure 6. Change of food intake throughout the five diets, subdivided in animal and plant-based products [left vertical axis, gram/cap/day]. The dashed line shows daily protein intake [right vertical axis, g/cap/day] when protein deficiency would not be compensated with surplus food. The values right above the horizontal axis show the surplus food intake relative to the BAU situation. Due to roundups/decimals, the compensated protein intake line is not fully straight.

3.3. Interpretation

A dietary transition from a conventional diet to a full-vegan diet has a different impact on a community's FEWprint in each of the three cities. With regards to the food sector emissions only, the differences in outcome between cities can be ascribed to the effect of combining two key variables: the community-specific food intake (PCC_{ctx}) and the country-specific (LCA based) global warming potential of food groups ($ef(n)$). With regard to the total FEWprint, inter-city differences are also caused by the -sometimes domination-role of the other sectors.

When simulating a pesce-pollotarian diet (removes red meat), a considerable drop in emissions is observed for Belfast and Detroit, whereas in Amsterdam, the drop is less significant during this diet shift. This can be explained by the considerable differences in initial red meat intake of the communities (AMS: 26.2 g, BEL: 57.0 g & DET: 91.9 g) and the higher carbon emission factors applied to red meat in Belfast, see Table 2. A similar observation can be made when a fully vegan diet is simulated and eggs and dairy are removed, resulting in the largest emission drop in Amsterdam. Consuming additional plant-based food to secure protein intake equilibrium has a counteractive effect on the carbon emissions drop caused by the initial diet shift. These surplus emissions are however in a lower order of magnitude than the avoided emissions associated with the diet shift, also see Appendix A.

4. Discussion

4.1. Robustness of Outcomes

In order to obtain accurate output figures, resource consumption data should be collected/measured at the lowest possible data aggregation scale. Data collected at higher scales will increasingly lose its relatedness with the considered community. Protein content should be based on the actual food commodities that are consumed by the community. Finally, environmental footprint indicators should be based on, (a) Life Cycle Inventory assessments and (b) the actual resources/products/services used or consumed in the considered urban context. However, situational consumption data may not always be readily available, and producing this relevant context-based data is resource-intensive. As the platform is intended to support non-experts during urban design concept explorations –for which highly accurate output is not essential—certain simplifications are permitted to grasp the situation. Naturally, this leads to compromises surrounding the robustness of the output.

This study makes use of Life Cycle Inventory based GHG emissions factors for food that have been retrieved from peer-reviewed literature (Belfast and Detroit) or independent consultants (Amsterdam). It is likely that outcomes will be different when different carbon footprint databases are addressed, when different values are assumed for the protein content of food categories or when a more comprehensive food scope is used. In previous research, it was revealed that between developed cities, consumption data is often collected/measured at very different scales [12]. We recommend platform users to search, study and insert contextual data when available, before resorting to data collected at, for example, the national level.

4.2. FEWprint Application Potential

The parametric FEWprint *diet shift* component demonstrated in this study is part of a three-pronged urban food production assessment strategy. The component can be used to generate an estimation of the role of food consumption to the total FEWprint of a community and how the food sector emissions compare to the other sectors. This insight gives a preliminary idea on which resource sector to emphasise when exploring an urban redesign strategy or any other city decarbonisation effort (Section 3.3). The rigorous and rather optimistic diet transition scenarios applied here remain particularly hypothetical (also see Section 4.3.4). However, the impact assessment of such community-wide behavioural

changes could instil inspiration and incentivise a movement to further explore opportunities for urban farming design, which could be of great value in the process of future urban design.

From a technical perspective, a diet shift could increase the potential of urban food production in terms of self-sufficiency. This is especially relevant when a UFP strategy is designed as part of a long-term strategy that takes into account projected or speculative developments surrounding (local) food culture. The agricultural output of an urban food system could be expressed in protein availability per community member and the extent of meeting the lower threshold level for an average person (0.83 g/kg body weight) can be articulated as a self-sufficiency fraction. Considering the high space demand for animal husbandry resulting from grazing and feedstock production, maximising self-sufficiency in space-constrained (peri-) urban contexts could be more feasible if the community demand for plant-based protein is increased at the expense of animal protein. This is however a context-dependent challenge as each urban environment offers a unique canvas for a food production design. Hybrid plant-animal protein solutions are likely more feasible in terms of protein provision and more space-efficient when resource loops are closed, for example by applying high-density livestock with higher food conversion ratios (poultry, fish, eggs) or using neo-food products like insect protein.

The FEWprint platform embeds evaluation, diet shift, and UFP design into an iterative process. The *diet shift* component is linked with the *design* component of the platform and it can be granted a *determinative* or a *responsive* role. In a *determinative* role, it can translate the community's food demand into concrete targets for agricultural output, according to which a system should be composed and designed. In a *responsive* role, a new diet can be configured around the agricultural capacity of a UFP strategy and translated into a daily food intake, i.e., a per capita daily availability of local production.

4.3. Limitations

Several limitations arose during the research and development of the platform. Most limitations revolve around data availability and food composition data.

4.3.1. Protein Content

The macronutrient content between similar food products can vary significantly because of climate, geography, agricultural practises, crops genetics, or processing influences during the food production and preparation stages [52]. In addition, food consumption patterns lead to country-specific foods, recipe compositions, and food brands. For a representative output, each diet simulation and UFP strategy should be conducted with local data that has been collected and processed according to international standards for comparability [53]. However, research for this study revealed discrepancies between countries when comparing protein content for individual food items and aggregated values used for food groups (Table A2 and Figure A4).

In line with the user-friendly aspect of the platform, this study uses datasets that are publicly available. The Dutch online dataset consists of 2152 food items and nutritional values that are derived from chemical analysis in accredited laboratories. Before values are recorded, a quality check is conducted surrounding the description of the food item, sampling procedure, and method of analysis [54]. The Belfast dataset is provided by the British Nutrition Foundation and consists of pre-aggregated protein indicators for food groups [55]. No further information is provided on the origin of the data nor the sub-products contained within the values. The Detroit values are provided by the US Food and Nutrition Information Centre [56]. Despite providing an elaborate list of well-described food items, values are expressed in household units (e.g., cups, slice, serving) making it difficult to determine reliable protein content values. Only meat items are consistently expressed in ounces (~28.4 g) and are therefore submitted to Table A2. The FAO [45] provides an extensive dataset of *as purchased* protein values and claims to be suitable for international use, however, no further information is provided about the data's origins.

The protein content of food categories determines the composition of the new diet. Variation of protein factors between cases would influence the way a new diet is formed during the transition and subsequently affect the emissions associated with that resulting diet. In order not to include a third variable in the equation and decrease the comparability between case studies, this study applies the universal FAO food balance sheets to all three cases, despite the considerable differences with the national values for certain food categories. A graphical and tabulated overview of the protein data is provided in Appendix B.

4.3.2. Food Scope and Aggregating Indicators

The FEWprint uses 18 food categories to frame UFP design and assessment. To secure inter-component integration, the platform's food scope is limited to unprocessed and minimally processed food products, while drinks, with the exception of milk products, have been excluded [12]. Therefore, the range of food products provided by the datasets has to be transformed and aggregated (or disaggregated) into a single representative indicator per category. This process of data clustering applies to all three key factors (food intake, carbon impact, and protein content) as none of the source's scopes aligns seamlessly with this study's food scope. In addition, the three factors are provided by different institutions that do not align on their scopes and/or nomenclature among each other, thus compromising the comparability between the case studies. Combined with the aforementioned uncertainties around the institution's data collection methods, the accuracy of the output in this study comes with a degree of uncertainty, affecting the comparability.

4.3.3. Animal vs. Plant Products: Mutually Substitutable?

In Section 2.1 it was mentioned that for a meaningful and accurate assessment, the protein quality of a plant-based diet should be considered at the amino acid level (AA). The quality of food-borne protein depends on the digestibility of the protein and the composition and bioavailability of essential amino acids in the food [30]. To account for protein quality at the product or diet level, the *Digestable Indispensible Amino Acid Score* (DIAAS) factor was developed, a successor to the PDCAAS indicator [37]. This index considers amino acids as individual nutrients and applies a more accurate measuring method. The nutritional quality score of protein, a food product, or a dish is dictated by considering the least digestible amino acid within that item. An extensive catalogue of DIAAS values for various human food products is still unavailable, but first publications show that the DIAAS factors of animal-based products (groups) are superior to their plant-based siblings [38,57]. This insinuates that animal and plant products are not mutually substitutable merely on the basis of protein quantity and suggests that, after compensating for the total protein content at the product level, also the quality difference at the protein level should be accounted for.

Plant proteins are often limited by the lack of one or two key amino acids, leading to a reduced DIAAS index [36]. Cataloguing the digestible indispensable amino acid contents of food groups and/or individual products can inform the combination and ratio of plant-based food mixtures, where one product compensates for the AA deficits of the other on the plate. Herreman demonstrates this for a rice-peas mixed dish, where rice, as a sole-source would have a DIAAS of 47 due to the poorly available amino acid *Lysine*, and peas have a DIAAS of 70 (limiting AA = *methionine* and *cysteine*). A rice-peas mix, however, in which rice constitutes 41% of the protein content, would lead to a DIAAS score of 84 [58]. Achieving a >100 DIAAS score for daily food intake, and subsequently, the community diet, could be achieved by a strategic combination of plant-based protein and minimal amounts of animal protein to close the gap, ideally with lower impact products like chicken and eggs.

Without the strategic combination method as described before, integrating the DIAAS quality correction factor to secure protein intake equilibrium could lead to an unreasonable surplus intake of plant-based food to compensate for the least digestible amino

acid. This subsequently puts an unnecessary high demand on the food system, especially in developed countries with an already varied diet. The authors acknowledge the reduced bioavailability of essential amino acids and the added value of working with DIAAS. However, we decided not to adjust for this gap in this research as it would overcomplicate this assessment with regard to its purpose, it would complicate the platform, and it would further increase the uncertainty of outcomes due to the current unavailability of suitable data.

To summarise, this study only adjusts for the lower protein content of crops at the product/group level to keep the platform comprehensible. We assume an adequate and heterogeneous intake of amino acids is achieved by adhering to the general recommendation to focus on variety within the new diet and replace animal protein with four plant-based categories (legumes, grains, nuts and seeds, soy products) in an equal proportion during the various simulations.

4.3.4. Radical Diet Scenarios

A near-future and community-wide abandonment of animal products for the purpose of decarbonisation is a rigorous and unrealistic scenario and therefore remains theoretical. National survey data reveals that the prevalence of the vegetarian-vegan population, in its purest sense, is still very low: for example respectively ±5% and ±0.4% in the Netherlands [59] and 5% and 3% in the USA [60]. Food consumption is deeply rooted in cultural behaviour or identity, people have been omnivorous for many generations and arbitrary impositions of dietary change on a community are unlikely to yield the intended desirable shift as food consumption remains a personal choice [61]. This study discusses the carbon reduction potential of changing a diet and does not consider the complex reality of bringing about such socio-cultural interventions, which goes beyond the technocratic nature of this research alone.

The arbitrary diet scenarios used in this study are culturally independent, non-geographical, and can be projected to any diet that is consumed in a locality. The assessed alternative scenarios are therefore also not based on context-based opportunities or agricultural potential but rather function as qualitative labels that are attachable to any conventional diet. The change to a more plant-based diet, as is simulated in this study, is usually a personal choice driven by intrinsic and external motivations; therefore, the community's engagement is very important. Consumer behaviour towards food consumption depends on a broad range of factors, and some simulated changes might not be considered reasonable or realistic within a community, possibly neglecting cultural acceptability [44]. Sustainable diet alternatives that are composed according to cultural aspects and local food management opportunities are likely more realistic and therefore more interesting to assess. The platform offers the framework for evaluating such diets, as long as the dietary recommendations can be translated into the 18 food groups used in the platform. In addition, two free slots are provided to insert food categories that are relevant to the considered context but that do not fit the 18 default categories.

4.4. Outlook

4.4.1. Data

In this study, we perform a comparative analysis between three urban communities. Comparative analysis requires harmonisation between sources on data gathering by measuring standardisations, scale level of data aggregation, scope alignment, coherence regarding units, and similarity in taxonomy. Life Cycle Inventory Analysis provides the framework to overcome the aforementioned challenges and is increasingly used to quantify the environmental impact of products and services. However, more work is required to integrate the LCI method in public datasets and –equally important– commutate the underlying calculation methods to the user. At last, we want to emphasise the importance of using independent and scientifically validated sources when assessing food.

4.4.2. Further Research

The parametric platform was developed based on the principles of the FEW nexus and informs the user during the conceptual and exploratory phase of UFP design. The diet shift component is demonstrated in this work and provides rapid feedback on the implications of a diet shift on the sectoral and total emissions of a community and calculates the food intake changes based on user-defined settings. The three components are interlinked with each other and are not completed in a linear fashion but rather facilitate an iterative process of design and evaluation that leads to a numerically supported UFP strategy (Figure 7). The *design* component of the platform will be discussed in future dissemination.
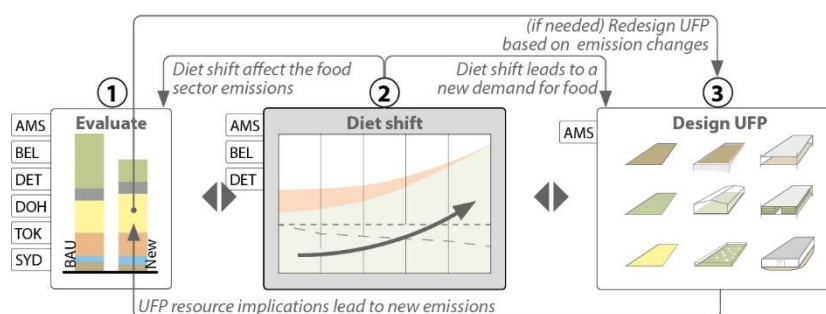

Figure 7. The FEWprint platform is composed of 3 components that correspond with the 3 key purposes of the FEWprint platform. The labels indicate the considered case study cities.

5. Conclusions

In industrialised nations, the consumption of food often constitutes a significant part of a community's total carbon emissions footprint. Animal-sourced food products are usually responsible for the largest share of the food sector emissions. Urban food production (UFP) is a strategy that could mitigate the carbon emissions from the producers' side; however, adequate design and assessment platforms for urban designers are lacking. A community-wide shift towards a plant-based diet is an effective way to reduce emissions from the consumers' side. When (re)designing neighbourhoods with the intention of food self-sufficiency and low-carbon impact, the combined application of both strategies is worth exploring. This article introduces and demonstrates the *diet shift* component of the FEWprint platform to simulate and assess, at the community level, the carbon emissions and food intake implications of a rigorous transition to a fully vegan diet, whilst maintaining protein intake equilibrium. As part of a larger UFP approach strategy, the FEWprint can be deployed to rapidly generate preliminary estimations on the carbon mitigation potential of dietary alterations. Three urban communities in the cities of Amsterdam, Belfast, and Detroit were studied, where consumption of a selection of 18 staple food groups currently emits respectively 993, 1270, and 1152 kg/capita/year, or 30%, 37%, and 9% of the total emissions. A dietary shift to a vegan diet would mitigate the emissions with 25% in Belfast (−866 kg CO_2eq), 15% in Amsterdam (−511 kg CO_2eq), and 7% in Detroit (−916 kg CO_2eq). The protein intake deficit that emerges during transition can be adjusted for with an estimated surplus consumption of +80 (AMS), +65 (BEL), and +90 g (DET) of various high-protein plant-based food categories. Future disseminations will demonstrate the design component of the platform and how UFP can further mitigate the food sector emissions.

Appendix A. Diet Simulation Results

Table A1. For each case study, 5 diet scenarios are assessed. Roundup errors may occur throughout this work. Diets are explained below.

Scenario		Food Intake [g/cap/day]				Protein Intake [g/cap/day]			Carbon Emissions [kg/cap/y]				FEWprint Impact [%]
Community	Diet	Animal Based	Plant Based	Surplus (Plant Based)	Total	Compensated	Uncompensated	Animal Based	Plant Based	Total (Animal + Plant)	Surplus (Plant Based)	
	BAU	357 (41%)	523 (59%)	0	880	57	57	709 (71%)	284 (29%)	995 (100%)	0	100%
AMS	PPTA	357 (41%)	523 (59%)	0	880	57	57	591 (68%)	284 (32%)	865 (−12%)	0	96%
Amsterdam	PPTP	331 (38%)	549 (62%)	0	880	57	56	491 (62%)	305 (38%)	796 (−20%)	0	94%
Kattenburg	VT	300 (34%)	586 (66%)	+5	885	57	55	369 (52%)	335 (48%)	704 (−29%)	+13	91%
	VG	0 (0%)	960 (100%)	+80	960	57	45	0 (0%)	484 (100%)	484 (−51%)	+175	85% (−15%)
	BAU	413 (48%)	442 (52%)	0	855	56	56	1112 (86%)	184 (14%)	1270(100%)	0	100%
BEL	PPTA	413 (48%)	442 (52%)	0	855	57	57	472 (72%)	184 (28%)	656 (−49%)	0	82%
Belfast	PPTP	355 (41%)	506 (59%)	+5	860	57	55	356 (60%)	235 (40%)	591 (−54%)	+17	80%
Inner-East	VT	295 (34%)	585 (66%)	+25	880	58	54	238 (45%)	296 (55%)	534 (−59%)	+59	78%
	VG	0 (0%)	920 (100%)	+65	920	57	47	0 (0%)	430 (100%)	430 (−67%)	+143	75% (−25%)
	BAU	381 (48%)	411 (52%)	0	792	71	71	1083 (93%)	77 (7%)	1152(100%)	0	100%
DET	PPTA	381 (48%)	411 (52%)	0	792	72	72	532 (87%)	77 (13%)	610 (−47%)	0	96%
Detroit	PPTP	287 (36%)	526 (64%)	+20	812	71	68	345 (72%)	131 (28%)	476 (−59%)	+26	95%
Oakland Avenue Farm	VT	200 (24%)	612 (76%)	+20	812	70	67	229 (57%)	173 (43%)	402 (−65%)	+26	94%
	VG	0 (0%)	867 (100%)	+75	867	70	59	0 (0%)	244 (100%)	244 (−79%)	+94	93% (−7%)

Explanation of diets (also see Section 2.4): BAU, *business as usual (or current diet)*, represents average food consumption of community. PPTA, *pesce-pollotarianism, animal substitutes*, removes red meat (beef, pork & mutton) from the diet and substitutes with poultry (50%) and fish & sea food (50%). PPTP, *pesce-pollotarianism, plant substitutes*, removes red meat (beef, pork & mutton) from the diet and substitutes with pulses & legumes (50%), nuts & seeds (25%), grains (25%) and soy products (25%). VT, *vegetarianism*, removes red meat, poultry and fish & seafood from the diet and substitutes as PPTP diet. VG, *veganism*, removes red meat, poultry, fish & seafood, eggs and dairy & cheese from the diet and substitutes as PPTP diet.
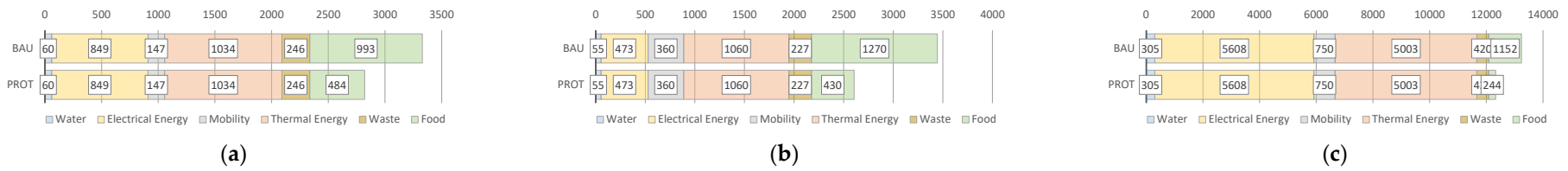
Figure A1. FEWprint profile of the community, before (top bar graph) and after a diet shift (lower bar graph). Labels show carbon equivalent emissions in kg/person/year. Cases: (**a**) Kattenburg (Amsterdam), The Netherlands (population = 1721), (**b**) Inner-East (Belfast), U.K. (population = 32.000), (**c**) Oakland Avenue Farms (Detroit), USA (population = 427). Carbon impacts of the non-food sectors come from [12].
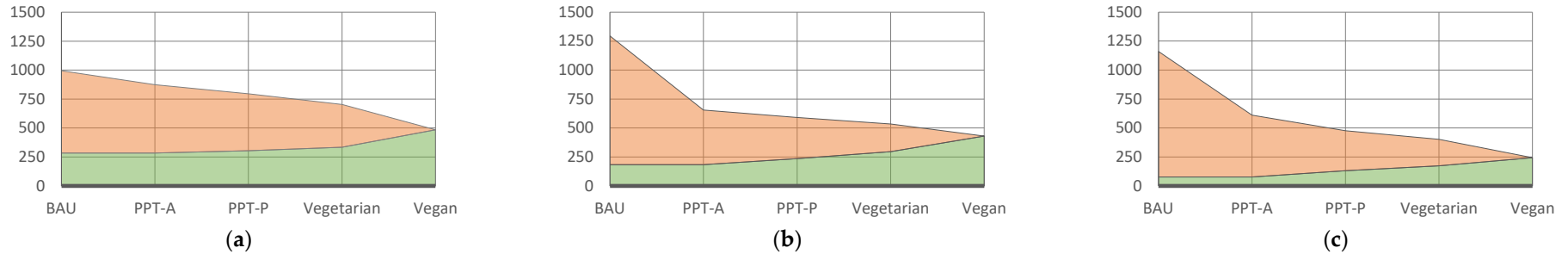
Figure A2. Food related carbon emissions [kg/cap/year] throughout the five diet scenarios, split up in emissions consequential to animal- and plant based food consumption. Cases:(**a**) Kattenburg (Amsterdam), (**b**) Inner-East (Belfast) and (**c**) Oakland Avenue Farms (Detroit).
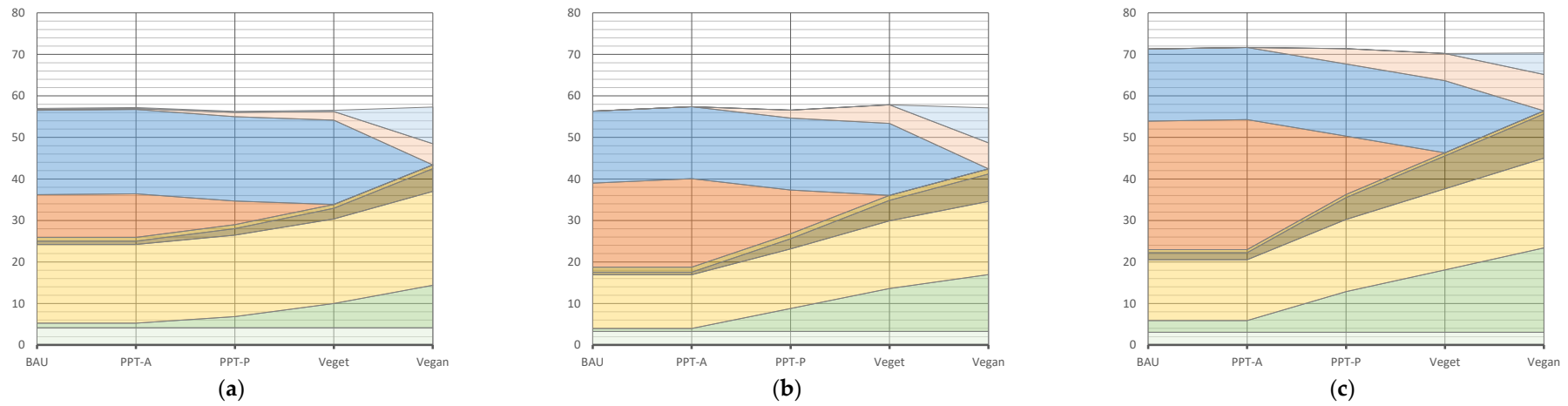
Figure A3. Daily protein intake [gram/person] throught the five diet scenarios, subdivided into various sub food groups within the diet. Cases:(**a**) Kattenburg (Amsterdam), (**b**) Inner-East (Belfast) and (**c**) Oakland Avenue Farms (Detroit).

Appendix B

Table A2. Knowing the protein content of food is relevant to calculate protein equilibrium after diet shift. For each case study, national datasets of protein content [gram$_{prot}$/100 g$_{food}$] have been collected. Where necessary, individual food products listed by the sources are combined or re-categorised in order to align with the 18 food categories applied in this study. Processed, non-staple food and drinks (except milk) are not included in this overview. As discussed in Section 4.3.2, a considerable deviation in values becomes evident after data cleaning, which is visualised in Figure A4. In order not to add an extra layer of variables and further compromise the comparability between the cities, the non-contextual FAO dataset is used for further assessment of the diet transition. Table A3 shows the processed FAO dataset. Values represent the average protein content of an extensive list of products, where (*n*) represent the number of aggregated individual items. The Detroit column only shows meat products as only these categories have been expressed in weight units (oz.) in the data source, whereas the (nearly) all other items are expressed in household unit that are difficult to convert (e.g., tablespoons, scoops). Values represent the retail weight of food. N.d. = no data. Food group 17–18 are not retrieved from the dataset but constitute assumed customary replacement products due to an unavailability of data.

|	Food Category	Protein Content [gram$_{prot}$/kg$_{food}$]			
	Food Group (*n*)	Amsterdam [3]	Belfast [4]	Detroit [5]	FAO [6]
1	Vegetables	1.9 (207)	n.d. (n.a.)	n.d.	2.3 (36)
2	Fruits	1.1 (111)	n.d. (n.a.)	n.d.	1.0 (50)
3	Legumes & pulses	11.9 (32)	7.0 (4)	n.d.	24.3 (11)
4	Grains & Cereals	10.3 (223)	9.9 (4)	n.d.	9.7 (24)
5	Rice	5.6 (9)	2.6 (1)	n.d.	6.7 (4)
6	Starchy roots	2.6 (45)	n.d. (n.a.)	n.d.	1.3 (11)
7	Beef (& veal)	28.5 (44)	31.0 (1)	24.5 (26)	20.9 (7)
8	Pork	26.6 (30)	31.6 (1)	23.1 (31)	13.9 (6)
9	Sheep & Goat (+lamb)	26.2 (6)	29.2 (1)	22.5 (38)	14.2 (4)
10	Poultry & Turkey	25.1 (6)	32.0 (1)	25.3 (21)	15.7 (11)
11	Fish & Seafood	22.8 (73)	19.8 (7)	21.2 (26)	20.9 (37)
12	Cheese	21.8 (77)	23.6 (3)	n.d.	24.5 (5)
13	Dairy (Milk & Yoghurt)	4.2 (138)	4.1 (5)	n.d.	4.3 (21)
14	Eggs	13.1 (12)	12.5 (1)	n.d.	11.1 (4)
15	Pasta (durum wheat)	6.9 (17)	6.6 (1)	n.d.	11.8 (3)
16	Nuts & Seeds	18.5 (36)	16.6 (3)	n.d.	12.4 (39)
17	Meat replacements [1]	11.1 (33)	8.1 (1)	n.d.	13.0 (n.a.) [1]
18	Dairy replacements [2]	2.5 (10)	n.d. (n.a.)	n.d.	3.0 (n.a.) [2]

[1] Retail product assumed: Tofu, uncooked (33% water), 13 g protein/100 g product. [2] Retail product assumed: Soy Drink, natural. 3.0 g/100 mL of product. [3] Data source:[54], [4] Data source: [55], [5] Data source: [56], [6] Data source:[45].
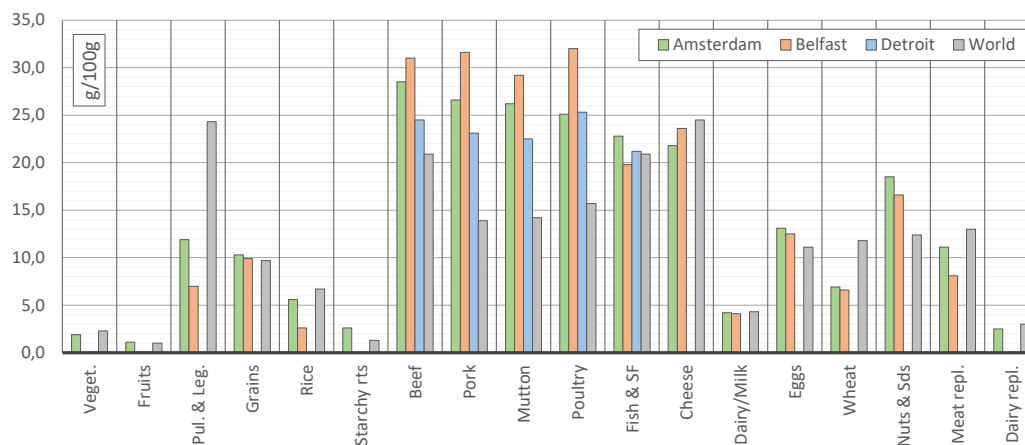
Figure A4. Visualisation of protein content [gram$_{prot}$/100 gram$_{food}$—4 data sources.

Table A3. Processing of FAO dataset.

Cereal and Products	g/100 g	Wheat (Pasta)	g/100 g
Wheat	12.2	Macaroni	11.0
Flour of wheat	Rem.	Quinoa	12.0
Bran of wheat	Rem.	Bulgur whole meal	12.3
Germ of wheat	Rem.	**Average:**	**11.8**
Bread	8.2	**Rice**	
Pastry	7.4	Rice paddy	6
Wheat starch	Rem.	Rice husked	7.5
Wheat gluten	Rem.	Rice milled	6.7
Barley	11.0	Rice broken	6.7
Pot barley	9.6	Rice flour	Rem.
Barley pearled	9.0	Rice gluten	Rem.
Barley flour and grits	Rem.	Rice starch	Rem.
Malt of barley	Rem.	Bran of rice	Rem.
Malt extracts	Rem.	**Average:**	**6.7**
Maize	9.5	**Roots, tubers and products**	
Germ of maize	Rem.	Potatoes	1.6
Flour of maize	Rem.	Flour of potatoes	Rem.
Maize gluten	Rem.	Potatoes frozen	1.2
Starch of maize	Rem.	Potato starch	Rem.
Pop corn	9.5	Potato tapioca	0.5
Rye	11.0	Sweet potatoes	0.7
Flour of rye	Rem.	Cassava	0.9
Oats	13.0	Flour of cassava	Rem.
Oats rolled	16.0	Cassava tapioca	0.5
Millet	9.7	Cassava dried	2.8
Flour of millet	Rem.	Cassava starch	Rem.
Sorghum	10.1	Yautia (cocoyam)	1.7
Flour of sorghm	Rem.	Taro (cocoyam)	1.5
Buckwheat	11.0	Yams	1.3
Flour of buckwheat	Rem.	Roots, tubers nes	1.6
Fonio	8.0	Flour of roots and tubers	Rem.
Flour of fonio	Rem.	Roots, tubers dried	Rem.
Triticale	11.6	**Average:**	**1.3**
Flour of triticale	Rem.	**Pulses**	
Canary seed	Rem.	Beans, dry	22
Mixed grain	8.0	Broad beans dry	23
Flour of mixed grain	Rem.	Peas, dry	23
Cereals nes	8.0	Chick-peas	20
Wafers	9.2	Cow peas dry	23
Flour of cereals	10.0	Pigeon peas	21
Breakfast cereals	7.4	Lentils	24
Cereals prepared nes	10.0	Bambara beans	18
Mixes and doughs	6.2	Vetches	32
Food preparations flour	7.5	Lupins	40
Treenuts		Pulses nes	22
Brazil nuts	6.9	Flour of pulses	Rem.
Cashew nuts	7.7	**Average:**	**24**
Chestnuts	1.8	**Meat replacers > custom product assumed**	
Almonds	8.0	Soybeans	n.a.
Walnuts	6.4	Cake of soya beans	n.a.
Pistachios	10.3	Soya sauce	n.a.
Kolanuts	9.0	Soya paste	n.a.
Hazelnuts	6.0	Soya curd	n.a.
Arecanuts	4.9	**Average:**	**n.a.**
Brazilnut shelled	14.3	**Vegetables and products**	
Cashew nuts shelled	15.3	Cabbages	1.0
Almonds shelled	20.0	Artichokes	1.1
Walnuts shelled	14.3	Asparagus	1.6
Hazelnuts shelled	13.0	Lettuce	1.1
Nuts nes	7.0	Spinach	2.1
Prepared nuts	15.5	Cassava leaves	5.8

Groundnuts in shell	18.7	Tomatoes	0.8
Groundnuts shelled	25.7	Tomato juice	Rem.
Cake of groundnuts	Rem.	Tomato juice concentrated	Rem.
Groundnuts prepared	26.8	Tomato paste	3.8
Peanut butter	24.3	Tomatoes peeled	0.9
Coconuts	1.7	Cauliflower	0.8
Coconuts desiccated	6.9	Pumpkins, squash, gourds	0.9
Copra	6.0	Cucumbers, gherinks	0.5
Oil palm fruit	0.3	Eggplants	0.9
Palm kernels	7.3	Chillies, peppers,green	1.1
Olives	1.3	Onions,shallots, green	1.7
Olives,preserved	1.1	Onions, dry	1.1
Karite nuts	6.8	Garlic	5.5
Sunflower seed	12.3	Leeks	0.7
Rapeseed	19.6	Beans, green	3.0
Safflower	9.7	Peas, green	2.1
Sesame seed	17.7	Broad beans,green	2.3
Cake of sesame seed	Rem.	String beans	1.6
Mustard seed	24.9	Carrots	0.9
Flour of mustard seed	26.4	Okra	1.6
Poppy seed	18.0	Green corn	2.1
Melonseed	18.2	Sweet corn frozen	1.8
Cottonseed	17.3	Sweet corn prepared	2.3
Linseed	18.0	Mushrooms	2.0
Oilseeds nes	14.7	Mushrooms canned	1.9
Flour/meal of oilseeds	Rem.	Mushrooms dried	9.6
Average:	**12.4**	Vegetables nes fresh	1.4
Fruits and products		Vegetables nes dried	11.2
Bananas	0.7	Vegetables nes canned	1.4
Plantains	0.8	Vegetables nes juice	0.6
Oranges	0.7	Vegetables dehydrated	Rem.
Orange juice	Rem.	Vegetables prepared by vinegar	Rem.
Orange juice concentrated	Rem.	Vegetables prepared nes	Rem.
Tangerines, mandarines, clementines	0.5	Vegetables frozen	3.3
Tangerines juice	0.5	Vegetables provisionally preserved	Rem.
Lemons and limes	0.6	Vegetables prepared or pres,frozen	Rem.
Lemon juice	Rem.	Homogenized vegetables prepared	1.2
Lemon juice concentrated	Rem.	**Average:**	**2.3**
Grapefruit and pomelo	0.3	**Beef**	
Grapefruit juice	Rem.	Beef boneless	18.5
Grapefruit juice concentrated	Rem.	Beef dried salted smoked	34.3
Citrus fruit nes	0.5	Meat extracts	Rem.
Citrus fruit nes juice	Rem.	Beef sausages	11.7
Citrus fruit nes juice concentrated	Rem.	Beef preparations	25.0
Apples	0.1	Beef canned	25.0
Apples juice	Rem.	Homogenized meat prepared	Rem.
Apples juice concentrated	Rem.	Liver preparations	13.6
Pears	0.4	Offals of cattle	18.4
Quinces	0.2	Buffalo meat	Rem.
Apricots	1.3	Offals of buffalo	Rem.
Sour cherry	0.9	**Average:**	**20.9**
Cherries	1.1	**Mutton**	
Peaches and nectarines	0.5	Mutton and lamb	13.5
Plums	0.7	Offals of sheep	14.6
Plum juice	Rem.	Goat meat	14.0
Plum juice concentrated	Rem.	Offals of goats	14.6
Stone fruit nes	0.9	**Average:**	**14.2**
Pome fruit nes	0.4	**Pork**	
Carobs	1.6	Pigmeat	11.0
Strawberries	0.6	Pork	13.4
Raspberries	0.9	Bacon—ham of pigs	13.1
Gooseberries	0.9	Pig meat sausages	11.7
Currants	1.4	Pig meat preparations	16.1
Blueberries	0.7	Offals of pigs	18.3

Cranberries	0.4		**Average:**	13.9
Berries nes	1.00		**Poultry**	
Grapes	0.5		Chicken meat	12.3
Grape juice	0.6		Chicken meat canned	21.8
Watermelons	0.3		Offal of chickens	18.0
Melons	0.4		Fat liver preparations	11.4
Figs	0.8		Duck meat	8.3
Mangoes	0.4		Offals liver ducks	18.7
Mango juice	Rem.		Goose meat	12.9
Mango pulp	0.5		Offals liver geese	16.4
Avocados	1.5		Turkey meat	16.1
Pineapples	0.2		Offals liver turkeys	20.0
Pineapples canned	0.4		Poultry meat	17.1
Pineapples juice	Rem.		**Average:**	**16**
Pineapples juice concentrated	Rem.		**Other meat products > not used**	
Persimmons	0.6		Pigeons other birds	n.a.
Cashewapple	0.8		Horsemeat	n.a.
Kiwi	0.9		Offals of horses	n.a.
Papayas	0.4		Meat of asses	n.a.
Fruit tropical nes	0.5		Meat of mules	n.a.
Fruit nes fresh	0.5		Meat of camels	n.a.
Fruit nes juice	Rem.		Offals of camels	n.a.
Fruit nes prepared	Rem.		Rabbit meat	n.a.
Flour of fruit	3.9		Meat of other rodents	n.a.
Fruit,nuts,fruit peel preserved by sugar	Rem.		Meat of other camelids	n.a.
Ruit cooked homogenized	Rem.		Offals of other camelids	n.a.
Dried fruits			Game meat	n.a.
Apricots dried	3.7		Meat nes	n.a.
Plums dried	2.3		Meat nes dried	n.a.
Raisins	3.2		Meat prepared nes	n.a.
Figs dried	3.0		Offals nes	n.a.
Dates	1.5		Snails not sea	n.a.
Fruit tropical nes dried	2.8		**Eggs**	
Fruit nes dried	2.8		Hen eggs	10.7
Average:	**1.0**		Eggs liquid hen	12.1
Fish and fisheries products			Eggs dry hen	Rem.
Freshwater diadromous fish fresh	10.9		Egg albumine	10.1
Freshwater diadromous fish fillet	20.3		Eggs excluding hen eggs	11.3
Freshwater diadromous fish cured	31.3		**Average:**	**11.1**
Freshwater diadromous fish canned	19.8		**Milk and cheese dairy/milk**	
Freshwater diadrom, fish prepared nes	26.9		Cow milk, whole fresh	3.3
Demersal fish fresh	8.3		Standardized milk	3.3
Demersal fish fillet	17.9		Cream, fresh	2.7
Demersal fish cured	37.9		Whole cow milk evaporated	6.8
Demersal fish canned	25.0		Whole cow milk condensed	7.9
Demersal fish prepared nes	25.0		Whole cow milk dry	Rem.
Pelagic fish fresh	12.6		Skim milk of cows	3.4
Pelagic fish fillet	20.2		Skim milk evaporated	7.6
Pelagic fish cured	26.4		Skim milk condensed	10
Pelagic fish canned	20.8		Skim milk dry	Rem.
Pelagic fish prepared nes	44.2		Buttermilk curdled	3
Marine fish nes fresh	10.3		Buttermilk dry	Rem.
Marine fish nes fillet	19.0		Yoghurt	3.5
Marine fish nes cured	32.1		Yoghurt concentrated	4.7
Marine fish nes canned	22.9		Reconstituted milk	1.8
Marine fish prepared nes	17.5		Whey fresh	0.8
Crustaceans fresh	9.3		Whey condensed	0.9
Crustaceans frozen	18.4		Whey dry	Rem.
Crustaceans cured	25.4		Casein	Rem.
Crustaceans canned	19.8		Buffalo milk	3.8
Crustaceans prepared nes	19.5		Skim milk of buffalo	4.3
Molluscs fresh	2.3		Sheep milk	5.9
Molluscs frozen	10.5		Skim milk of sheep	6.1
Molluscs cured	49.4		Goat milk	3.6

Molluscs canned	14.9	Skim milk of goat	3.4
Cephalopods fresh	13.5	Camel milk	3.8
Cephalopods frozen	15.1	**Average:**	**4.3**
Cephalopods cured	61.6	**Cheese**	
Cephalopods canned	20.8	Cheese goat milk	16
Cephalopods prepared nes	20.8	Cheese whole cow milk	25
Aquatic mammals meat	Rem.	Cheese skim cow milk	46
Aquatic mammals prepared nes	Rem.	Whey cheese	12.4
Aquatic animals nes fresh	4.0	Processed cheese	Rem.
Aquatic animals nes cured	5.5	Cheese buffalo milk	Rem.
Aquatic animals prepared nes	11.5	Cheese sheep milk	23.2
Aquatic plants	Rem.	**Average:**	**25**
Aquatic plants dried	Rem.		
Aquatic plants prepared nes	Rem.		
Average:	**20.9**		

This work uses the FAO protein content of food (groups) for diet shift assessment. Listed items are considered to be consumed on a regular basis in developed economies globally. The raw data had to be recomposed to align with the taxonomy of this study and a number of product are left out of the assessment. The breakdown below forms the basis of aggregated indicators listed in Tables 2 and A3. Excluded items are noted by *rem.*, i.e., removed. Excluded food items/products/groups are:

- Processed items (with exception of the cheese category)
- Concentrates
- Starches/Malts/Flour/Gluten/Germs/Brans/Cakes
- Fruit/vegetable juices (=processed & drink)
- Non-staple foods categories

NES = Not Elsewhere Specified. Note: Retail product assumed for meat replacer: Tofu, uncooked (33% of water), 13 g protein/100 g product. Note: Retail product assumed for dairy replacer: Soy Drink, natural, 3.0 g/100 mL of product.

Original dataset is retrieved from [45].

Appendix C

Table A4. Overview of data sources for Global Warming Potential (GWP) and protein content of food groups. Data sources addressed for this study are accessible to the general public. Please note: this study uses the protein content dataset by the FAO for further assessment. An extensive break-down and references of case study food consumption can be found in [12].

	GWP	Protein Content
unit>	*kg CO₂eq/kg_food*	*g/100 g_food*
AMS	[49] *Published by the National Institute for Public Health and the Environment. GWP based on LCI studies, conducted by Blonk Consultants. Full dataset can be downloaded from website.*	[54] *Online interactive platform called NEVO. Developed by the RIVM, a service department from the Ministry of Health, Welfare and Sports*
BEL	[19] *Open-access article published by Springer (Appendix, Table 4 in source article)*	[55] *Aggregated dataset. Overview can be downloaded from website. Data is based on the work McCance and Widdowson's — The Composition of Foods (2015) [this work is not freely accessible]*
DET	[51] *Open-access article Published by IOP Publishing Ltd. Data is integrated to 'dataFIELD' (database of Food Impacts on the Environment for Linking to Diets). Download and more information can be found here [62].*	[56] Data provided by the US Department of Agriculture — National Agricultural Library. Dataset can be downloaded online.
World	[10] *Open-access research article published in Science. LCA-based GWP data based on a worldwide study.*	[45] *Extensive list of food items + nutritional content (protein, calories & fat), provided by the UN Food & Agriculture Organisation. Dataset can be retrieved online.*

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