Developing Design Baseline to Reduce Urban Environmental Load in Food-Energy-Water Demand

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1 ABSTRACT

Cities reflect diverse spatial patterns as a result of their composition in population density, building forms, and household types. These differences, to a large extent, reflect the quality of life of an area's inhabitants and the correspondent environmental load their lifestyles impose. Environmental load is related to the supply and demand for food, energy and water. As a result, identifying gaps between supply and demand is a common starting point for urban planning and design aimed at zero-carbon emissions and other forms of sustainable urbanism. In this regard there is substantial research and tools that can be applied to these issues. One typical example is the Ecological Footprint which uses an equivalent land area to express the demand for the production of goods and CO2 absorption. This indicator is powerful at the macro level with regards to the conceptualization of the problem, but difficult to use at the small scale when considering the benefits of particular design options. Against this background, this study aims to develops an indicator to express a design baseline that enables the quantitative evaluation and comparison of the demand and supply of FEW as well as their contribution to environmental load with regards to food, energy, and water at the city block level.

Many environmental indicators were developed in recent years to clarify the interaction of the so-called FEW Nexus, or the confluence between the otherwise separate realms of food, energy, and water. However, these indicators are also difficult to apply at a small scale. This study develops an index that enables the quantitative evaluation and comparison of the relationship between food, energy and water at the city block level. The demand and consumption for food, energy, and water associated with residences are strongly influenced by the type of households under consideration. Meanwhile, the potential production and supply of food, energy, and water for a given household is mostly determined by the capacity to install solar panels and home gardens, which are themselves strongly determined by building forms and land use. Therefore, the baseline of a city block for FEW demand and supply can be assessed by identifying the type of households and the form of buildings within it. With this in mind, we categorized "household types" in terms of the number of family members, the age group and gender; "building form" is defined either as a detached house or an apartment. The demand for food, energy, and water associated with a given "household type" (per household or per capita) is defined as social intensity. The unit associated with "building form" is defined as physical intensity. The social and physical intensity were carefully identified through statistical data and previous studies. Based on these preparations, the demand for FEW, as well as the amount of production, can be estimated at a household level and aggregated to the city block level. Physical estimation of the demand and supply are then converted to an environmental footprint by applying the concept of the Ecological Footprint to FEW.

This indicator was applied to the Tokyo-Yokohama metropolitan area as a case study. In order to improve the comparability at the regional level, the metropolitan area was categorized by three forms, namely the inner city, near urban and suburban. Typical areas were selected to represent the social and spatial characteristics of each. Finally, the method was applied at the metropolitan scale using GIS data in sample areas.

The result clearly shows the spatial differences in demand and supply of food-water-energy as well as the correspondent environmental print. While the environmental print per unit area is greater in the inner city, the per capita number is greater in suburban areas. This indicates that suburban areas have a larger responsibility to reduce their environmental footprint through food-water-energy consumption. This knowledge is helpful to move environmental issues from being a matter of concern for the government to being a problem for communities and individuals.

Keywords: Ecological footprint, GIS, Building form, Environmental load, Food-Water-Energy Nexus

2 BACKGROUND

While food, energy, and water (FEW) play a central role in the system that supports the demands of human life, the CO2 emitted in the process reaches nearly 70% of the global CO2 emissions (Ramaswami et al., 2016). In addition, the majority of the world's population was officially urban from 2007, and the number is only increasing. By 2050 two-thirds of the world's population is expected to live in urban areas, and FEW consumption is subsequently concentrating in urban area(Kammen & Sunter, 2016). As a result, urban areas face increased sustainability challenges and are faced with the need to pursue ever higher resource efficiencies. However, the demand and supply of FEW have traditionally been managed separately in each sector, and efforts to reduce carbon outputs are reaching their limits. Therefore, in recent years, attention has been focused on the complex demand and supply networks that exist between FEW sectors, and resource efficiency is expected to be improved using these interactions.

It is known that there are large local differences in FEW consumption in cities, and that the potential of the FEW nexus is regionally dependent(Jones & Kammen, 2011). This is connected to the fact that 50% of a city's CO2 emissions are attributed to its urban structure, including population density, land use, and building types(Christen et al., 2011). Given the extraordinary diversity of urban systems (climate, geography, morphology, demographics, culture, and economy), effective CO2 emission reductions are necessarily context dependent(Kellett et al., 2013). Without that simple understanding, cities cannot make decisions on how and where to direct the application of policies and regulatory measures. However, with regard to the FEW nexus at the city level, previous efforts by researchers have concentrated on quantifying the flow of the FEW nexus, with little assessment of qualitative factors such as the geographic, historical, and political context of the cities that house them(Newell et al., 2019). Cities are beginning to implement the FEW nexus, and accumulating qualitative knowledge in implementing the nexus approach is an urgent (Artioli et al., 2017; Simpson & Jewitt, 2019).

Against this backdrop, the design-led implementation of the FEW Nexus is gaining attention as an interdisciplinary design-led approach.(Yan & Roggema, 2019). Such a design-led approach is characterized by its ability to comprehensively handle complex systems, such as supply chains or those involving multiple stakeholders(Fleischmann, 2019). This shows how a design-led approach is suitable for dealing with the complex supply and demand that exists between the various sectors of the FEW, but the tools to support this approach are not yet well developed. For example, there is no FEW Nexus indicator designed to accommodate the multi-scale approach often seen in urban design.

In order to develop an indicator tool to support a design-led approach, this study visualized the relationship between FEWs at the urban, neighborhood, and city scales, and developed an environmental load indicator that can be used as a design baseline for the FEW Nexus. This environmental load is limited to that associated with FEW demand, and in this study, it is limited to carbon dioxide (CO2) emissions, the largest GHG. We applied this indicator to a case study of the Tokyo metropolitan area to verify the validity and operability of the indicator.

3 CONCEPT OF FEWPRINT

Although many indicators have been developed to assess the environmental impacts of people's daily activities, there is still little consensus on how to apply them(Ramaswami et al., 2021), and the same is true for FEW-related indicators(Newell et al., 2019). However, in the context of linking urban design and environmental impact indicators, the Ecological footprint has gained some recognition(Moos et al., 2006). The Ecological footprint can be converted into a unified unit of area even for different sectors, is convenient for visualization, and is easy to set as a Key Performance Indicator(Moos et al., 2006). The greatest advantage is that there is a common language of "area" between Ecological Footprint and urban design. In general, the space that can be reserved for local production or management of FEW in a dense urban environment is very limited, and clarifying this area is an important first step in urban design. The Ecological Footprint, on the other hand, is calculated as the sum of the land area required to produce and manage various services and the forest area required to absorb the CO2 emissions generated through the production, transportation, and consumption of these services. In other words, it makes it possible to integrate land use and environmental impact into one study.

On the other hand, there are some challenges in calculating the Ecological Footprint, such as the need to collect data from various sources and the difficulty in applying the method at relatively micro scales due to the problem of data sources(Moos et al., 2006). The main reason for this issue is that most previous ecological footprint studies have focused on entire cities and used a top-down approach of spatially disaggregating energy consumption(Kellett et al., 2013). This top-down approach not only poses the challenge that it is not suitable for application at micro scales, but also that it does not require an understanding of the processes that lead to CO2 emissions and is therefore not suitable for design-driven approaches or scenario-based predictions(Kellett et al., 2013). To address this challenge, recent research has presented an extension of bottom-up models based on consumption processes to enable environmental impact assessment at the micro-scale(Christen et al., 2011; Kellett et al., 2013). This approach not only facilitates the calculation of design baselines at the neighborhood or city block scale, but also facilitates the assessment of the environmental impact reduction potential of new urban forms as indicated by design scenarios. However, this concept has not yet been introduced into the Ecological Footprint.

In this study, the FEWprint will be developed as a subset of the Ecological Footprint, a general indicator that evaluates the impact of human life on nature in terms of equivalent land area, and will be maintained as a support tool for urban design in order to develop the FEW Nexus. As with the Ecological Footprint, the FEWprint is calculated as the sum of the land area required to produce and manage FEW services and the forest area required to absorb the corresponding CO2 emissions through the production, transport, and consumption of FEW services. To estimate the corresponding CO2 emissions through production, transport and consumption of FEW services, a bottom-up approach using social and physical intensities is adopted. Social intensities consist of any group of individuals, households, or age groups, while physical intensities are defined as single-family homes, apartment units, buildings, neighborhoods, or cities. Thus, FEW demand can be assessed at the household or building scale, and further extended to the neighborhood, city, or regional scale. The current FEW demand is used as a baseline from which to begin the FEWprint analysis.

4 METHOD

4.1 Typological analysis

Cities develop diverse spatial patterns as a result of their composition in population density, building forms, and household types. In order to closely represent the impact of these spatial differences on the demand and supply of food, energy, and water, two typologies need to be considered. Firstly, the demand and consumption for food, energy, and water associated with residential life is strongly influenced by the type of households. Secondly, the potential of production and supply of food, energy, and water for a household to alleviate the demand is mostly determined by the capability to install solar panels and home gardens, which is in turn strongly determined by building forms. Therefore, the baseline of a city block for FEW demand and supply can be assessed by identifying the type of households and the form of buildings. We categorized the "household type" in terms of the number of family members, and the groupings of age and gender, and the "building form" in terms of detached houses and apartments. The basis for this classification depends on the available FEW consumption intensity data.

4.2 Baseline calculation

4.2.1 Amount of demand and supply

Food Demand

Regarding food, its demand is largely dependent on age and sex. In other words, the demand for foodstuff (k) in the target area (FD_k) can be calculated by multiplying the food demand intensity by age and sex ($FD_{k,\ age,\ sex}$) by the population by age and sex ($P_{age,\ sex}$), as shown in Equation 1.

$$FD_k = FD_{k,age,sex} \times P_{k,age,sex}$$

In urban areas, the decline in labor force due to the aging of agricultural workers has led to the conversion of ordinary farmlands into allotment gardens. Home vegetable gardens are also gaining popularity because they can be easily managed at home. While it is important to understand the actual situation of such small-scale vegetable production, it is difficult to identify the products in home and allotment gardens without careful fieldwork. However, when estimating for a large area, the work becomes an unmanageable amount.

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Therefore, by using the cultivated area of home vegetable gardens by building type (SKGbldg) and the rate of home vegetable garden implementation by building type (RKGbldg), we can simply obtain the production area.

$$L_{FP,farm} = \sum_{bldg} SKG_{bldg} \cdot RKG_{bldg}$$

Energy Demand

In terms of energy, the demand depends largely on the household size. In other words, the energy demand (ED) of the target area can be calculated by multiplying the energy demand intensity ($ED_{household}$) by the number of households per household size ($H_{household}$), as shown in Equation 3.

$$ED = ED_{household} \times H_{household}$$

On the other hand, it is necessary to consider the existence of existing autonomous decentralized energy supply systems. Solar panels are a decentralized power generation system possible at the household level. The amount of electricity generated by solar panels can be estimated from the size and number of panels. The annual electricity production (EP) from solar panels in the target area can be expressed as Equation 4 using the system capacity intensity of solar panels by building type (P_{bldg}) and the solar panel installation rate by building type (RPV_{bldg}). (H), (P), and (K) refer to the average solar radiation, the system capacity of the solar panels, and the loss factor, respectively.

$$EP = H \cdot K \cdot 365 \cdot \sum_{bldg} P_{bldg} \cdot RPV_{bldg}$$

Therefore, the exact energy demand (ED) needs to be expressed as in Equation 5, taking into account the amount of electricity generated by solar panels (EP).

$$ED = ED_{household} \times H_{household} - EP$$

Water Demand

In the water sector, the demand depends largely on the number of household members. In other words, the water demand (WD) in the target area can be calculated by multiplying the water demand intensity ($WD_{household}$) by the number of households per household size ($H_{household}$), as shown in Equation 6.

$$WD = WD_{household} \times H_{household}$$

On the other hand, the construction of a water supply environment in residential areas is being promoted with the installation of water tanks. This is a system in which the rain that falls on the roof is channeled into a water tank to store rainwater. In other words, if we can determine the area of the roof of a house where a water tank is installed, we can calculate the annual water supply by multiplying it by the annual rainfall. The amount of water available for self-sufficiency (WP) of the target area can be expressed as Equation 7, using the positive radiant area of the roof of each building (RA_x), the water storage tank installation rate by building type (RWS_{bldg}), and the annual precipitation (RW).

$$WP = RW \cdot \sum_{bldg} \sum_{x} RWS_{bldg} \cdot RA_x$$

Therefore, the exact water demand (WD) needs to be expressed as in Equation 8, taking into account the amount of water available for self-sufficiency (WP).

$$WD = WD_{household} \times H_{household} - WP$$

Conversion to footprint

Food Demand

Food is linked to energy, water, and land in the process of its supply. For example, land is indispensable during food production. Therefore, the land ($L_{k,farm}$) needed to meet the demand (FD_k) for foodstuff (k) in the target area can be expressed as in Equation 9 using the land ($L_{k,base}$) needed to produce 1 kg of foodstuff (k).

$$L_{k,farm} = L_{k,base} \times FD_k$$

In other words, the total land for the production of food demand (FD) in the target area ($L_{FD,farm}$) is shown in Equation 10.

$$L_{FD,farm} = \sum_k L_{k,farm}$$

Next, we evaluate the energy associated with the supply of foodstuff (k). The CO_2 emissions (CE_k) associated with meeting the demand (FD_k) for foodstuff (k) in the target area can be expressed as in Equation 11 using the CO_2 emission factor ($CE_{k,base}$) of foodstuff (k).

$$CE_k = CE_{k,base} \times FD_k$$

Furthermore, this CO_2 emission amount (CE_k) can be converted into land by replacing it with the forest area required to absorb that CO_2 emission amount. In other words, the forest area ($L_{k,CO2}$) for absorption of CO2 emissions associated with the demand (FD_k) for foodstuff (k) in the target area can be expressed as shown in Equation 12 using the forest area ($L_{CO2,base}$) required to absorb 1 kg of CO_2.

$$L_{k,CO2} = \frac{CE_k}{L_{CO2,base}}$$

In other words, the total land area ($L_{FD,CO2}$) required to absorb CO_2 emissions associated with food demand (FD) in the target area can be expressed as in Equation 13.

$$L_{FD,CO2} = \sum_k L_{k,CO2}$$

And the water associated with the supply of food (k) is usually referred to as virtual water. This virtual water (VW_k) associated with food demand (FD) in the target area can be converted into land area by replacing it with the area required to absorb equivalent water as rainwater. Introducing this idea, the area ($L_{k,VW}$) required to acquire the virtual water (VW_k) associated with the demand (FD_k) for foodstuff (k)in the target area from rainwater can be expressed as in Equation 14 using the annual rainfall (RW) in the target area.

$$L_{k,VW} = \frac{VW_k}{RW}$$

In other words, the area ($L_{FD,rain}$) required to obtain the virtual water associated with the food demand (FD) of the target area from rainwater can be expressed as in Equation 15.

$$L_{FD,rain} = \sum_k L_{k,VW}$$

Energy Demand

Energy is supplied from a variety of energy sources, and each energy source generates different CO_2 emissions. In other words, the CO_2 emissions (CE_{ED}) associated with the energy demand (ED) in the target area can be expressed as in Equation 16 using the sharing ratio (ERR_l) of a certain energy source and its CO_2 emission coefficient ($CE_{l,base}$).

$$CE_{ED} = ED \sum_l (ERR_l \cdot CE_{l,base})$$

This CO2 emission (CE_{ED}) can be converted to land by replacing it with the forest area required to absorb the CO2 emission. In other words, the forest area ($L_{ED,CO2}$) required to absorb CO2 emissions associated with energy demand (ED) in the target area can be expressed as in Equation 17 using the forest area ($L_{CO2,base}$) required to absorb 1 kg of CO_2.

$$L_{ED,CO2} = \frac{CE_{ED}}{L_{CO2,base}}$$

By the way, hydroelectric power generation is one of the energy sources. The area ($L_{ED,rain}$) required to obtain the amount of water ($W_{ED,hydro}$) used in hydropower generation from rainwater can be expressed as in Equation 18 using the annual precipitation (RW) of the target area.

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$$L_{ED,rain} = \frac{W_{ED,Hydro}}{RW}$$

Water Demand

A lot of energy is required for water supply. This energy is supplied from various energy sources, and each energy source has different CO_2 emissions. In other words, the amount of CO_2 emissions (CE_{WD}) associated with the water demand (WD) in the target area can be expressed as Equation 19 using the amount (ER_m) shared by a certain energy source (m) in water supply and its CO_2 emission coefficient ($CE_{m,base}$).

$$CE_{WD} = \sum_m (ER_m \cdot CE_{m,base})$$

This CO_2 emission (CE_{WD}) can be converted to land by replacing it with the forest area required to absorb the CO_2 emission. In other words, the forest area ($L_{WD,CO2}$) required to absorb CO_2 emissions associated with water demand (WD) in the target area can be expressed as in Equation 20 using the forest area ($L_{CO2,base}$) required to absorb 1 kg of CO_2.

$$L_{WD,CO2} = \frac{CE_{WD}}{L_{CO2,base}}$$

The area required to obtain the water demand (WD) from rainwater ($L_{WD,rain}$) in the target area can be expressed as Equation 16 using the annual rainfall (RW) in the target area.

$$L_{WD,rain} = \frac{WD}{RW}$$

Environmental loads of FEW demands

The total environmental impact in terms of land, is calculated in 4.2.2. However, it should be noted that the water used for hydropower generation is subsequently used for domestic and agricultural purposes. To reflect this, the environmental impact (EI) can be expressed by the following equations.

When $L_{ED,rain} \geq L_{FD,rain} + L_{WD,rain}$

$$EI = L_{FD,farm} + \sum_n L_{n,CO2} + L_{ED,rain}$$

When $L_{ED,rain} < L_{FD,rain} + L_{WD,rain}$

$$EI = L_{FD,farm} + \sum_n L_{n,CO2} + L_{FD,rain} + L_{WD,rain}$$

$$(n = FD, ED, WD)$$

5 CASE STUDY

5.1 Features of study area

The target areas are Tokyo prefecture and Kanagawa Prefecture, the latter being located in the southwest part of the Tokyo metropolitan area, which has the world's largest population. In these two prefectures, more than 23 million people live in an area of about 4,600 square kilometers. Many of the urbanized, built-up areas were developed during the high economic growth period after WW II and widely spread in suburban and extra-urban along radially distributed railways. Similar with all of Japanese cities, this region is facing declining birthrates and an aging population. Therefore, the governmens are trying to remake the cities in a more compact form by attracting services and residents to the walkable area near railway stations. In addition to, the built-up areas are approaching a time when infrastructure and other upgrades will be needed, as the vulnerability witnessed by the devastating disasters like the Great East Japan Earthquake in 2011, the heat wave in 2018, and the super typhoon Hagibis in 2019. Adding to that existential fear is a political and moral issue. In consideration of its size, the metropolis has a responsibility to act urgently to reduce CO2 production. It is similarly useful to recognize that the production and consumption of food-energy-water is responsible for more than 60 percent of total CO2 emissions. In responce the Japanese government initiated an action plan on climate change adaptation in 2015. It also lunched the SDGs Future City Program in 2018 to accelerate the transition and transformation towards a carbon neutral and sustainable society.

5.2 Data management

The respective data on age and number of households by household size required to determine the social typology was obtained from the 2015 census. Other data required in the process of analysis were maintained as shown in Table 1.

Variable	Description	Data Source
$CE_{k,base}$	CO2 emission coefficient of food (k)	Ministerial Order Concerning Calculation of Greenhouse Gas Emissions from Business Activities of Specific Emitters (2016)
$CE_{l,base}$	CO2 emission coefficient of energy source (l)	
$CE_{m,base}$	CO2 emission coefficient of energy source (m) required for water supply	
$ED_{household}$	Energy demand intensity by household size	(Inoue et al., 2006)
ER_{m}	Share of energy sources (m) in water supply	Energy Consumption Statistics by Prefecture (2017)
ERR_{l}	Share of energy source (l)	
$FD_{k, age, sex}$	Food demand intensity by gender by age	National Health and Nutrition Survey (2019)
$H_{household}$	Number of households by household size	National Censes (2015)
$L_{CO2,base}$	Forest area required to absorb 1 kg of CO2	Forestry Agency
$L_{k,base}$	Land required to produce 1 kg of food (k)	(Yan & Nakayama, 2021)
$P_{age, sex}$	Population by age and sex	National Censes (2015)
RW	Annual precipitation	Japan Meteorological Agency
VW_{k}	Virtual water for food (k)	(Oki & Kanae, 2004)
$WD_{household}$	Water demand intensity by household size	Bureau of Waterworks Tokyo Metropolitan Government

Table 1: “List of sources of data needed for calculating FEWprint”

5.3 Result

Using the methods in Chapter 4 and the data collected in 5.2, we visualized the FEWprint in GIS in Figure 1 and Figure 2. Figure 1 shows how many times the FEWprint is the area of the city by the census truck. In Figure 2, we visualize the value of FEWprint per capita. The result clearly shows the spatial differences in demand and supply of food-water-energy as well as the correspondent environmental footprint. While the environmental footprint per unit area is greater in the inner city, the amount per capita is greater in suburban areas. This indicates that suburban areas bear a larger responsibility to reduce their environmental load through food-water-energy consumption.

6 DISCUSSION

A study that analyzed CO2 emissions in Chicago showed similar results to our analysis, with per capita CO2 emissions being higher in the suburbs(Farr, 2007). However, compared to Figure 1, the difference between urban centers and suburban areas in Figure 2 is not as clear. This is a feature that was not seen in the previous report(Farr, 2007). This suggests the characteristics and issues of the FEWprint presented here. In this calculation of the FEWprint, we considered differences in demand due to household size and age, and supply capacity due to building structure, but there were no variables that directly represented differences between urban centers and suburbs, such as building size. Furthermore, we did not take into account the mobility associated with food procurement, which is expected to be very different between urban centers and suburbs. However, it has been pointed out that the environmental burden associated with food access is significant(Coveney & O’Dwyer, 2009). In order to bring environmental issues down to the level of the general public and to make concrete designs, the urban structure needs to be reflected in more detail in the FEWprint.

The key point of the design-led approach for FEW Nexus is the use of area. How much productive area already exists, how much is potentially available, and how much can be created through design. The potential of an area can be calculated with the use of the FEWprint tool in an iterative manner, a familiar

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process for those who work professionally in any design field. This means that each time a design is considered and re-evaluated in the normal design process, it can also be modified and evolved depending on how much productive area can be developed. In this way, the FEWprint serves as a baseline for design.

The FEWprint is useful not only for evaluating the baseline of FEW demand, but also for evaluating efforts to reduce CO2 emissions in the process. Implementing the FEW Nexus as a policy or policy vision also requires assessments and approaches at different spatial levels, such as buildings, city blocks, neighborhoods,

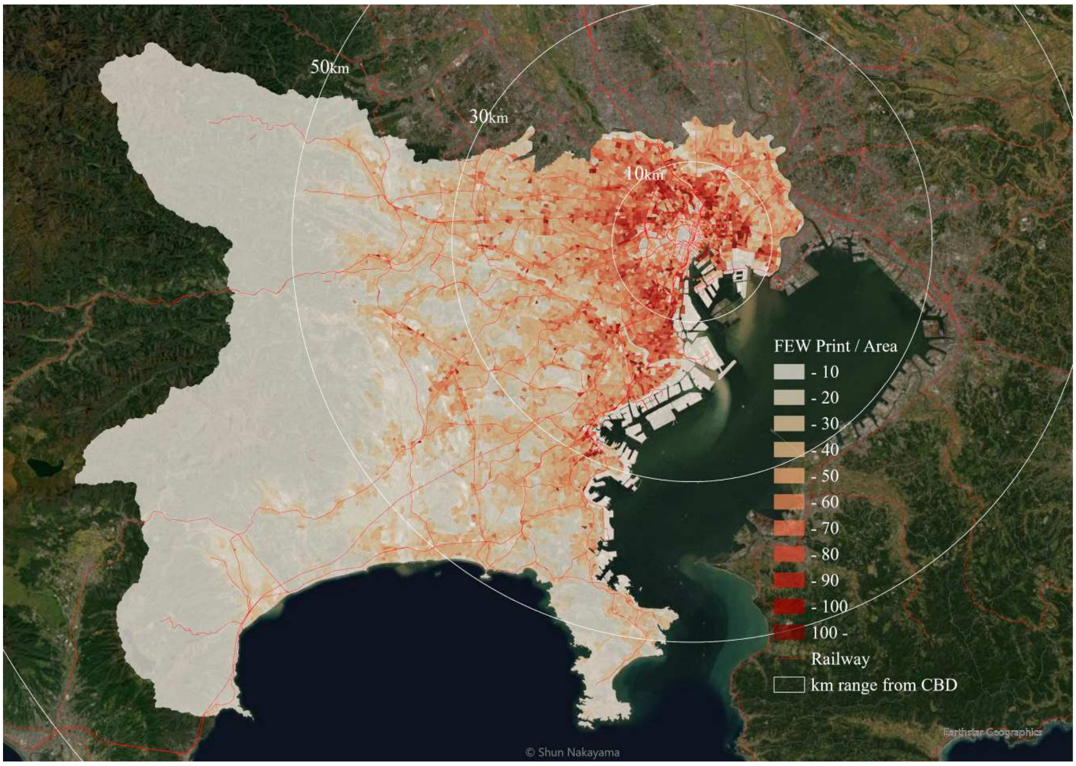

Fig. 1: How many times the FEWprint is the area of the city by the census truck.

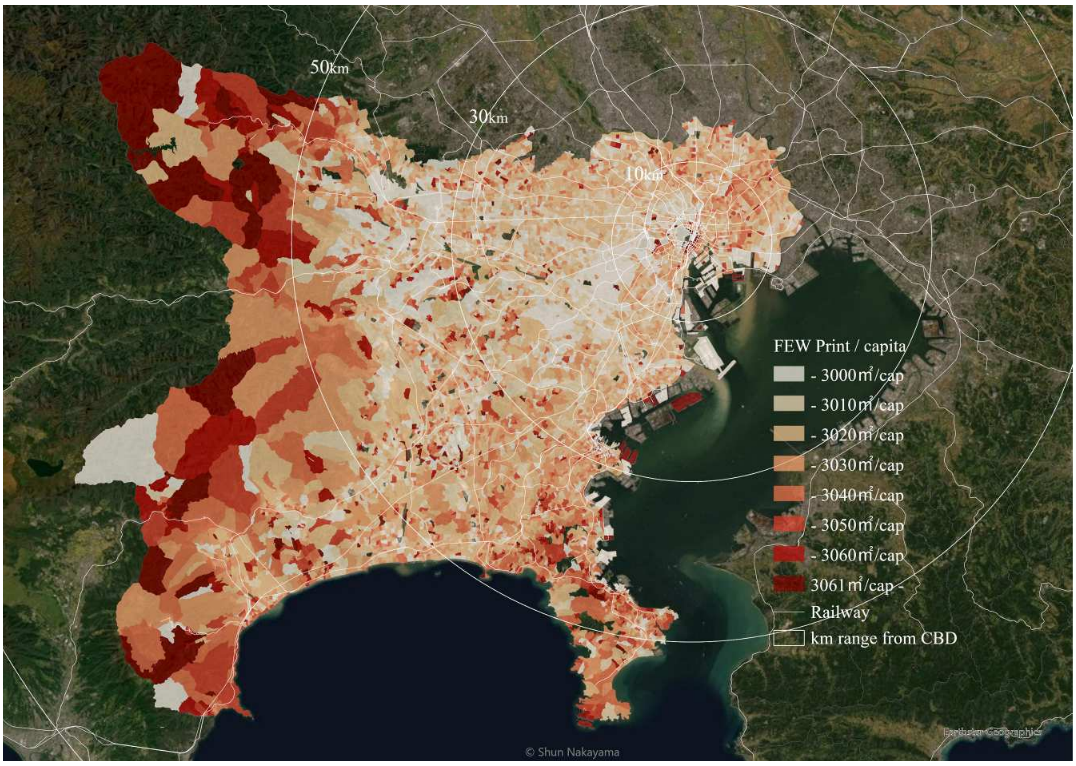

Fig. 2: The value of FEWprint per capita

and cities. This can be done by applying the FEWprint to future scenarios. If this results in a reduction of FEWprint, it means a more efficient use of FEW resources. GIS is a suitable way to represent FEWprints at multiple scales.

7 CONCLUSION

In this study, we noted that the essence of the design-led approach for FEW Nexus is the area available to meet the demand-supply for FEW physically and the area required to absorb the environmental costs both in the present and the future. These two apects are evaluated quantitatively by introducing the FEWprint as a key performance indicator.

Armed with this instrument, we could quickly evaluate the FEW baseline in any specific conditions by identifying a set of dietary tables, household and building types. This baseline can be used as reference to examine the performance of new designs, the nexus effects that will be achieved by specific solutions, the performance of a stakeholder, or the effect of relevant urban policy. By giving the available area in a house, a building, a block or a neighborhood as well as the social and physical intensity for food, energy, water, the M-NEX method is applicable to any scale with the support of GIS.

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9 REFERENCES

Artioli, F., Acuto, M., & McArthur, J. (2017). The water-energy-food nexus: An integration agenda and implications for urban governance. Political Geography, 61, 215–223. https://doi.org/10.1016/j.polgeo.2017.08.009

Christen, A., Coops, N. C., Crawford, B. R., Kellett, R., Liss, K. N., Olchovski, I., Tooke, T. R., van der Laan, M., & Voogt, J. A. (2011). Validation of modeled carbon-dioxide emissions from an urban neighborhood with direct eddy-covariance measurements. Atmospheric Environment, 45(33), 6057–6069. https://doi.org/10.1016/j.atmosenv.2011.07.040

Coveney, J., & O'Dwyer, L. A. (2009). Effects of mobility and location on food access. Health and Place, 15(1), 45–55. https://doi.org/10.1016/j.healthplace.2008.01.010

Farr, D. (2007). Sustainable Urbanism: Urban Design With Nature. Wiley. https://www.wiley.com/en-us/Sustainable+Urbanism%3A+Urban+Design+With+Nature-p-9780471777519

Fleischmann, K. (2019). Design-led innovation and Circular Economy practices in regional Queensland. Local Economy, 34(4), 382–402. https://doi.org/10.1177/0269094219854679

Inoue, T., Mizutani, S., & Tanaka, T. (2006). Energy consumption in housing on the basis of national scale questionnaire : Analysis of influence of various factors on annual energy consumption Part 2. Journal of Environmental Engineering (Transactions of AIJ), 71(606), 75–80. https://doi.org/10.3130/aije.71.75_2

Jones, C. M., & Kammen, D. M. (2011). Quantifying carbon footprint reduction opportunities for U.S. households and communities. Environmental Science and Technology, 45(9), 4088–4095. https://doi.org/10.1021/es102221h

Kammen, D. M., & Sunter, D. A. (2016). City-integrated renewable energy for urban sustainability. In Science (Vol. 352, Issue 6288, pp. 922–928). American Association for the Advancement of Science. https://doi.org/10.1126/science.aad9302

Kellett, R., Christen, A., Coops, N. C., van der Laan, M., Crawford, B., Tooke, T. R., & Olchovski, I. (2013). A systems approach to carbon cycling and emissions modeling at an urban neighborhood scale. Landscape and Urban Planning, 110(1), 48–58. https://doi.org/10.1016/j.landurbplan.2012.10.002

Moos, M., Whitfield, J., Johnson, L. C., & Andrey, J. (2006). Does design matter? The ecological footprint as a planning tool at the local level. Journal of Urban Design, 11(2), 195–224. https://doi.org/10.1080/13574800600644381

Newell, J. P., Goldstein, B., & Foster, A. (2019). A 40-year review of food-energy-water nexus literature and its application to the urban scale. In Environmental Research Letters (Vol. 14, Issue 7, p. 073003). Institute of Physics Publishing. https://doi.org/10.1088/1748-9326/ab0767

Oki, T., & Kanae, S. (2004). Virtual water trade and world water resources. Water Science and Technology, 49(7), 203–209. https://doi.org/10.2166/wst.2004.0456

Ramaswami, A., Russell, A. G., Culligan, P. J., Rahul Sharma, K., & Kumar, E. (2016). Meta-principles for developing smart, sustainable, and healthy cities. In Science (Vol. 352, Issue 6288, pp. 940–943). American Association for the Advancement of Science. https://doi.org/10.1126/science.aaf7160

Ramaswami, A., Tong, K., Canadell, J. G., Jackson, R. B., Stokes, E. (Kellie), Dhakal, S., Finch, M., Jittrapirom, P., Singh, N., Yamagata, Y., Yewdall, E., Yona, L., & Seto, K. C. (2021). Carbon analytics for net-zero emissions sustainable cities. Nature Sustainability, 1–4. https://doi.org/10.1038/s41893-021-00715-5

Simpson, G. B., & Jewitt, G. P. (2019). The water-energy-food nexus in the anthropocene: moving from ‘nexus thinking’ to ‘nexus action.’ In Current Opinion in Environmental Sustainability (Vol. 40, pp. 117–123). Elsevier B.V. https://doi.org/10.1016/j.cosust.2019.10.007

Yan, W., & Nakayama, S. (2021). Redesigning the Urban Food Life Through the Participatory Living Lab Platform: Practices in Suburban Areas of the Tokyo Metropolitan Region BT - TransFEWmation: Towards Design-led Food-Energy-Water Systems for Future Urbanization (R. Roggema (ed.); pp. 209–234). Springer International Publishing. https://doi.org/10.1007/978-3-030-61977-0_10

Yan, W., & Roggema, R. (2019). Developing a design-led approach for the food-energy-water nexus in cities. Urban Planning, 4(1), 123–138. https://doi.org/10.17645/up.v4i1.1739