reviewed paper

# Performance of Urban Agriculture in Tokyo: a Geospatial Perspective of the Food-Water-Energy Nexus

*Keidai Kishimoto, Wanglin Yan*

(Keidai Kishimoto, Keio University, 5322 Endo, Fujisawa, Kanagawa, Japan, keidai@keio.jp)
(Prof. Wanglin Yan, Keio University, 5322 Endo, Fujisawa, Kanagawa, Japan, yan@sfc.keio.ac.jp)

## 1 ABSTRACT

Urban agriculture plays a role in modern food systems to reduce transportation energy, improve local production for local consumption, and so on. However, the demand for local food, the supply of farmland, and even the attitudes of farmers may vary with the process of urbanization as well as the urban structure of cities. This is significant particularly in Asian megacities such as Tokyo, where the built-up areas have mostly spread to suburbs along rail lines and expanded outward from train stations on topographic and historical fundamentals. Furthermore, urban agriculture in Tokyo is facing strong pressure from urban development, the aging of farmers, and depopulation. Few previous studies have discussed the performance of urban agriculture in a megalopolis like Tokyo based on detailed evidence.

The aim of this study was to clarify the relationship of food, water and energy in Tokyo through input-output analysis ofresource use and vegetable production. We created a database of water and energy resource inputsfor greenhouses, fertilizers, and pesticides, etc., for farming and vegetable production. We quantitatively calculated the input-output efficiency of energy and water resources per unit of food production in the Tokyo metropolitan area and visualized regional characteristics by hierarchical cluster analysis.

We found that Tokyo produced 75,566t of vegetables per year, or an average of about 5.5kg per capita for its 13.8 million population, with 426.1TJ of energy consumed,especially in greenhouses and manufacturing compost, and 8.7 ML of water, especially in manufacturing phosphorus fertilizer. With cluster analysis identified four types of urban agriculture in terms of environmental load: “lowenvironmental load,”“medium environmentalload,”“highwaterload,” and “highenergyload.” In summary, the closer to the CBD, the more intensive the agriculture type in the sense of environmentally burden, due to the impacts of urbanization; the central part of the Tama area, with more open space for agriculture, shows moderate consumption of energy and water; and the farmlands in western Tama far from the CBD are less intensive and often cultivated with low environmental load.

These findings suggest that the conservation and promotion of urban agriculture in Tokyo should consider geospatial characteristics. As land prices rise, could become more intensive, meanwhile, with a possible transition from “low environmentalload” to “mediumenvironmental load” and from “mediumenvironmental load” to “high water load” or “high energy load” to environment. This is a challenge for urban policymakers to manage the synergistic effects and conflicts in agriculture-inclusive urban development.

Keywords: Urban structure, environmental load,input-output efficiency,hierarchical cluster analysis

## 2 INTRODUCTION

Many cities expect that urban agriculture plays an important role in improving the sustainability of the modern food system (Morgan, 2015; Mohareb et al., 2017; Howe & Wheeler, 1999).Cities typically depend on the outside for resources such as food and consume them in large quantities, and have an enormous environmental load.Moreover, the environmental impact of the food system is in many cases the leading one (Goldstein et al., 2017). Large amounts of food consumption are required to support huge urban populations, but their production and distribution processes need to be rethought to reduce the environmental impacts. Urban agriculture, on the other hand, has diverse ecological, economic, and social-environmental benefits (Lovell, 2010; Lovell & Johnston, 2009; Peng et al., 2015), andcan serve five major functions: energy generation, urban symbiosis, supply chain efficiency, and in situ and ex situ environmental improvement (Goldstein et al., 2016b). From a food system perspective, shorter transportation distances reduce food miles and the environmental impact of production and distribution, while also providing a fresh and diverse supply of vegetables. With growing awareness of the high environmental load and the verified environmental benefits of urban agricultural food systems over the past two decades, cities try to reconnect with urban agriculture.


ISBN 978-3-9504945-0-1. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER, G. STÖGLEHNER

Nevertheless, urban agriculture is not free from environmental loads. In many cases, agriculture consumes resources such as fertilizers and pesticides to increase vegetable production (Foley et al., 2011) and emits large amounts of greenhouse gases (Weber & Matthews, 2008). It has been pointed out that despite the environmental benefits of urban agriculture, it also hasenvironmental impacts, such as high water consumption, inability to respond to local conditions, and soil management problems (Sanyé-Mengual et al., 2018, 2019). Meanwhile, inefficient siting, production practices, and transportation methods can lead to greater environmental impacts; one study found that urban agriculture did not necessarily lead to carbon reduction, using tomato and lettuce cultivation in Boston as a case study (Goldstein et al., 2016a). Although there arecurrently only a few studies that show urban agriculture is rather environmentally burdensome, the environmental impacts in urban agriculture may be contrary to the intentions of cities to reduce environmental impacts. Therefore, it is necessary to evaluate the relationship between the input resources for production and the vegetables produced, i.e., the input-output efficiency, when developing urban plans aimed at the environmental performance of urban agriculture.

Some studies have been conducted to clarify the input-output efficiency of urban agriculture. In a study of urban and surrounding areas, researchers compared environmental indicators, including life-cycle carbon emissions and water use in lettuce production for five farms near and far from Sydney (Rothwell et al., 2016). Another study assessed the possibility that life-cycle carbon emissions could be reduced by using urban agriculture in Lisbon, with the challenge of assessing the entire food system rather than a single commodity(Benis & Ferrão, 2017). Even within cities, the input-output efficiency of urban agriculture under different conditions has been compared and characterized.Researchers comparedtwo conventional and organic farming systems in urban Seville, Spain, and characterized their life-cycle energy demand and CO2 emissions (Pérez-Neira & Grollmus-Venegas, 2018).Another study compared life-cycle greenhouse gas emissions based on economic value for conventional and home delivery agriculture in Beijing (Hu et al., 2019). Thus, it is important not only to clarify the input-output efficiency of urban agriculture from comparisons between areas inside and outside the city, but also to reveal the diverse input-output efficiencies of urban agriculture based on several different characteristics in recent years.

This study asked how the urban structure of a region affects the input-output efficiency of urban agriculture production. Tokyo and other Asian megacities have developed in complex ways from the CBD to the suburbs and from train stationsoutwards through rail lines development. As a result, urban land use sprawls in a wedge shape along the rail lines, and agricultural land is relegated to areas stretching away from train stations and more distant suburbs (Yamamoto et al., 1977). We can assume that urban structure factors such as topography, distance from CBD, and population,affect input-output efficiency. However, few studies have quantified such differences. To reconnect urban agriculture to urban planning, it is important to understand the underlying urban structures, and such an understanding would be a great advantage in formulating new strategies.

Therefore in this study, we aim to clarify the relationships between urban structure, resource use and the production of vegetables, in order to assessinput-output efficiency for municipalities. To achieve this, we constructed a framework that combines the food-water-energy (FEW) nexus approach with input and output analysis.Using this analysis, we quantitatively calculated the efficiency of energy and water resources per unit of food production for cities in the Tokyo metropolitan area and visualized regional characteristics by hierarchical cluster analysis.

## 3 METHODOLOGY

### 3.1 Food-water-energy nexus approach

In this study, we use the nexus approach of FEW to quantify the input-output efficiency of urban agriculture in different municipalities. The nexus approach is based on the idea that integrated management across sectors and scales can produce synergistic effects as a system (Hoff, 2011). In particular, food, energy and water are core factors at the heart of sustainable development, and the visualization and management of their nexus is an important issue (Liu et al., 2018). A literature review showed that the study of the FEW nexus is rapidly expanding, with nearly 1,000 papers published up to 2017 (Newell et al., 2019).

One of the features of the FEW nexus approach is that it can quantitatively show the relationships among water and energy used for food production, food and energy used for water production, and food and water used for energy production, and thereby the interrelationships can be clarified. Looking at agriculture, vegetables are obtained by using water and energy.Examples of applying FEW to urban agriculture are sprouting up(Caputo et al., 2021).

One study focused on wastewater-based irrigation to evaluate its impact on energy use, food production, and health (Miller-Robbie et al., 2017). It found that the use of treated wastewater can lead to reduced energy use and increased food productivity while clearing pathogens. Other researchers reviewed individual farming methods, materials, and resource uses, and summarized the indirect and direct energy uses and their impacts in urban agriculture from the perspective of the FEW nexus (Mohareb et al., 2017). They discussed the possibility of efficiency variations and trade-offs between energy and water. The results of the review suggested that there was a need to study urban agriculture in individual regions, paying close attention to the context of operations, crops, and climates.

### 3.2 Research framework

In this study, to quantitatively examine the input-output efficiency from resource utilization to vegetable production, it is first necessary to define the system boundary. In the life-cycle assessment study of vegetable production and distribution in Japan, the energy used for cultivation, fertilizer, pesticide, heating, cooling, and drying was defined as production energy (Nishizono & Moteki, 2007). Of these, our study usedfertilizer, pesticides, and heating in the production sector. In the case of fertilizer, potassium (K2O, hereinafter referred to as K), phosphorus (P2O5, hereinafter referred to as P), nitrogen (N), and compost are mainly required (Nishizono & Moteki, 2007; Tokyo Metropolitan Government, 2003). Irrigation is not considered for open field cultivation because rainfed agriculture is the main form of agriculture in the suburbs of Tokyo, and water use is considered only in greenhouse production. Thus, rainwater use was not considered as a load.

Within the system boundary, the amounts of energy and water used as inputs were converted into joules and liters, respectively, and added up. The intensity of use of each resource was quantified and visualized in a Sankey diagram. The vegetables produced were shown by weight for each item. This ability to visualize the relationship among FEW is a unique feature of the FEW nexus approach.

### 3.3 Analysis and dataset

Within the system boundary of this study, energy and water consumption and vegetable production were calculated from the following formulae. Growing vegetables usedsome resources:fertilizer (energy: $IE_{fertilizer}$,water:$IW_{fertilizer}$), pesticide ($IE_{pesticide}$and $IW_{pesticide}$), and greenhouse ($IE_{greenhouse}$ and $IW_{greenhouse}$). Vegetable production ($OF_{vegetables}$) is defined as fruit vegetables ($OF_{fruit}$), root vegetables ($OF_{root}$), leafy vegetables ($OF_{leaf}$), and tubers ($OF_{tubers}$).

$$IE_{vegetables} = IE_{fertilizer} + IE_{pesticide} + IE_{greenhouse} \#(1)$$

$$IW_{vegetables} = IW_{fertilizer} + IW_{pesticide} + IW_{greenhouse} \#(2)$$

$$OF_{vegetables} = OF_{fruit} + OF_{root} + OF_{leaf} + OF_{tubers} \#(3)$$

To compare the food production of different regions, a cluster analysis was conducted to classify the municipalities using the amount of energy input per unit weight of vegetable production($ie_{vegetables}$) and the amount of water input($iw_{vegetables}$). We normalized these to mean 0 and variance 1. The datasets were subjected to hierarchical cluster analysis using the “scipy.clujster.hierarchy” library in a Python 3 runtime environment.

$$ie_{vegetables} = \frac{IE_{vegetables}}{OF_{vegetables}} \#(4)$$

$$iw_{vegetables} = \frac{IW_{vegetables}}{OF_{vegetables}} \#(5)$$

#### 3.3.1 Vegetables

We used the Tokyo Metropolitan Crop Production Survey, published annually by the Tokyo Metropolitan Government (2015).The survey providesdata on production items, volumes, and cropping area. We


ISBN 978-3-9504945-0-1. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER, G. STÖGLEHNER

obtained $OF_{fruit}$, $OF_{root}$, $OF_{leaf}$, and $OF_{tubers}$ for 2013. We also obtain the cropped area ($A_v$) for each vegetable. In general, it is not easy to grasp the actual situation of urban agriculture, but the Tokyo Metropolitan Government has started to conserve and promote urban agriculture earlier than the national government (Tokyo Metropolitan Government, 2019), and this survey can be a valuable dataset to grasp the actual situation of urban agriculture.

### 3.3.2 Fertilizer

It is difficult to understand the actual situation of fertilizers used in agricultural production because of the wide variety of fertilizers used and the lack of statistical data available. Therefore, in this study, based on some studies(Chen et al., 2018; Kobayashi & Sago, 2001; Nishizono & Moteki, 2007; Tokyo Metropolitan Government, 2003), we used the amount of fertilizer used per cropped area($K_v$, $P_v$, $N_v$, and $COM_v$), energy used per unit of vegetable production($ie_K$, $ie_P$, $ie_N$, and $ie_{compost}$) and water ($iw_K$, $iw_P$, $iw_N$, and $iw_{compost}$).

$$IE_{fertilizer} = ie_K * \sum(K_v * A_v) + ie_P * \sum(P_v * A_v) + ie_N * \sum(N_v * A_v) + ie_{compost} * \sum(COM_v * A_v) \#(6)$$

$$IW_{fertilizer} = iw_K * \sum(K_v * A_v) + iw_P * \sum(P_v * A_v) + iw_N * \sum(N_v * A_v) + iw_{compost} * \sum(COM_v * A_v) \#(7)$$

### 3.3.3 Pesticides

It is difficult to obtain statistical data on pesticide use, and the wide variety of pesticides makes it difficult to understand life-cycle costs. In existing data(Ministry of Economy Trade and Industry, 2016), average cost and unit price were used to calculate pesticide use per unit of area for each crop($PES_v$). The amount of input energy per unit of pesticide use($ie_{pesticide}$=250MJ/kg) and the amount of water($iw_{pesticide}$=4.0909kg/kg) were obtained from previous studies(Natalia & Robert, 2016; Nishizono & Moteki, 2007).

$$IE_{pesticide} = ie_{pesticide} * \sum(PES_v * A_v) \#(8)$$

$$IW_{pesticide} = iw_{pesticide} * \sum(PES_v * A_v) \#(9)$$

### 3.3.4 Greenhouse production

As data on greenhouse production, we used the 2015 Census of Agriculture and Forestry published by the Tokyo Metropolitan Government. We obtained the area of greenhouse production($A_{greenhouse}$). However, it is not possible to know the use of each greenhouse. The amount of energy required to operate greenhouses($IE_{greenhouse}$)was obtained by multiplying by $A_{greenhouse}$, the amount of heavy oil A used per area of greenhouse production, anda coefficient to convert heavy oil A into energy. In the study on greenhouses (tomatoes), the facility area was 5,848m$^2$ and the fuel power cost was 3,326,000 yen in 266 greenhouses (Japan Finance Corporation Agriculture Forestry Fisheries and Food Business Unit, 2017). Based on the average monthly price of fuel oil A in 2017 from the Agency for Natural Resources and Energy, the price was assumed to be 67.7 yen per liter. The conversion factor between A fuel oil and energy was assumed to be 38.9MJ/L. The amount of water used ($IW_{greenhouse}$) was obtained by multiplying the area of greenhouseproduction $A_{greenhouse}$ by the water consumption and cultivated area ratio obtained from previous studies. The water consumption was set at 816mm per year and the cultivated area ratio was set at 90% (Nishide, 1990).

## 3.4 Study area

This study area covers 49 cities, excluding islands and rural areas under the Tokyometropolitan area(Fig.1). However, some cities donot have farmland, so this study effectively covers 36 municipalities. The central business district (CBD) is located in the eastern part of the study area, and major sub-districts such as

Otemachi, Shibuya, Shinjuku, and Ikebukuro are located along and inside the Japan Railway Yamanote Line. Currently,in terms of population density, most cities in the Tokyo region have a population of more than 4,000persons per km2. The central part of the study area is on the Musashino plateau, which includes suburban communities. Meanwwhile, in the western part of the study area, the population density is lower due to topographical conditions such as hills and mountains and reduced accessibility to the CBD.

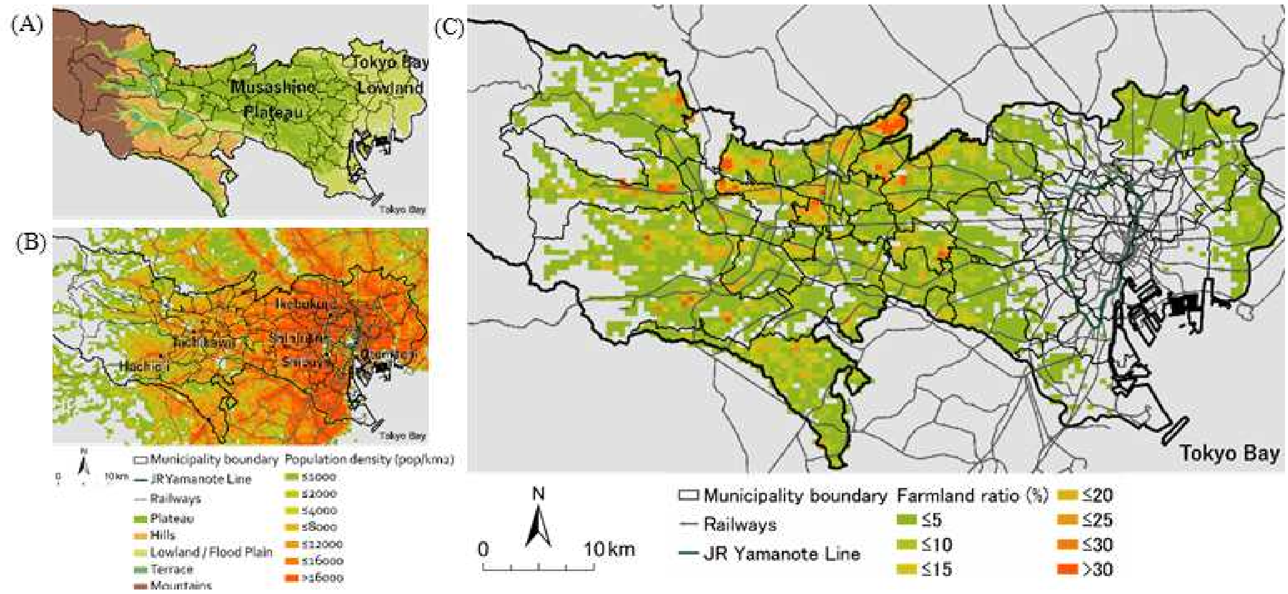


Fig.1:Three maps of the study area showing the urban structure.Processed from National Land Information (Railway, Municipal Data) (Ministry of Land, Infrastructure, Transport and Tourism).(A) shows the topography of the area.Processed from "National Land Survey" (Ministry of Land, Infrastructure, Transport and Tourism). (B) shows the population density. Processed from 2015 Census. (C) shows the farmland ratio.

## 4 RESULTS

### 4.1 Descriptive statistics

Fig.2 shows the input-output indices for vegetable production. Energy consumption in greenhouseswas the greatest.Greenhouses in the study area include 1,674 facilities with a total of 13,168 m2 in area, but a large amount of input energy per unit area (32,679.5MJ/m2). To produce one ton of vegetables, they consume energy at 5,714MJ/t on average, or 426.1TJ for the study area. However, there is a large difference among municipalities. Manufacturing compost(from mulch, manure, organic waste, etc.) consumed an average of 3,234.3MJ/t of energy, or 241.2TJ for the study area. Compost accounted for 85.6% of the total energy of fertilizer. Manufacturing pesticides consumed an average of 1,704.5MJ/t of energy, or 127.1TJ for the study area. In contrast to the above, the values of various fertilizers other than compost were very small. Manufacturing nitrogen consumed an average of 326.6MJ/t and 24.4TJ for the study area, phosphorus consumed an average of 208.3MJ/t of energy and 15.5TJ for the study area, and potassium consumed an average of 11.3MJ/t of energy and 0.84TJ for the study area. In total, the energy input of Tokyo as a whole amounted to 835.1TJ. The energy consumption per farm unit of area was 19.1MJ/m².

Comparing water inputs, phosphorus had the largest value, while facilities hada very small value. On average, manufacturing phosphorus used 116.2L/t per vegetable and consumed 8.7ML in total. The results were similar except for phosphorus and facilities. Manufacturing potassium consumed at an average rate of 44.5 L/t, and 3.3ML for the study area. Manufacturing nitrogen consumed at an average rate of 33.2L/t, or 2.5ML for the study area. Manufacturing compost consumed at an average rate of 32.3L/t, or 2.4ML for the studyarea. Manufacturing pesticides consumed 27.9L/t on average, and 2.1ML for the study area. In contrast, greenhouse production consumed an average of 0.013L/t of water per vegetable production or 957.5L for the entire area. With these water inputs, 18.9ML was used for the entire Tokyo metropolitan area.Water consumption per unit of farmland area was 0.434L/m².

As for the output of food production, leafy vegetables were the largest category, followed by fruit vegetables, root vegetables, and tubers (including potatoes, sweet potatoes, taro, konjac, etc.). The output of leafy vegetables, fruit vegetables, root vegetables, and tubers was 32,566t, 19,964t, 13,192t, and 7,825t,


ISBN 978-3-9504945-0-1. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER, G. STÖGLEHNER

respectively, for a total of 75,566t. Among leafy vegetables, cabbage was the most abundant at 8,033t, followed by komatsuna (Japanese mustard spinach) at 7,525t. Tomatoes and eggplants accounted for 5,904t and 5,872t, respectively, of the fruit crops. As for root crops, 8,097t of radish and 3,669t of carrot were produced, and 4,310t of potato were produced for tubers. The production per unit of farm area was 1.71kg/m².

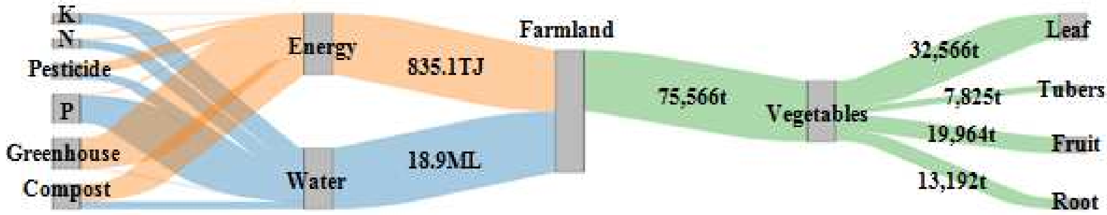


Fig.2:Sankey diagram showing the inputs of water and energy and outputs of vegetables in urban agriculture in the study area. Orange indicates energy, blue indicates water, and green indicates food. The line widths were normalized so that the maximum values for food, water, and energy are equal. The thicker the line, the larger the volume.

| | Per unit of weight (tons) of products | | Per unit of area (m²) of farmland | | |
|---|---|---|---|---|---|
| | E (MJ/t)* | W (L/t)* | E (MJ/m²)* | W (L/m²)** | F (kg/m²)*** |
| Low environmental load | 7.6 (1.7) | 200 (17) | 12.7 (4.8) | 0.333 (0.087) | 1.67 (0.44) |
| Medium environmental load | 11.6 (2.0) | 264 (28) | 20.0 (5.6) | 0.451 (0.101) | 1.71 (0.32) |
| High water load | 18.6 (7.0) | 404 (27) | 25.7 (19.4) | 0.513 (0.262) | 1.28 (0.67) |
| High energy load | 26.5 (8.6) | 270 (33) | 63.9 (51.9) | 0.753 (0.673) | 2.60 (2.10) |

Table 1:Amount of energy and water per unit of production in each cluster and per area of farmland. Mean (standard deviation). *<0.01, **<0.05, ***>0.1 with Kruskal-Wallis test with SPSS.

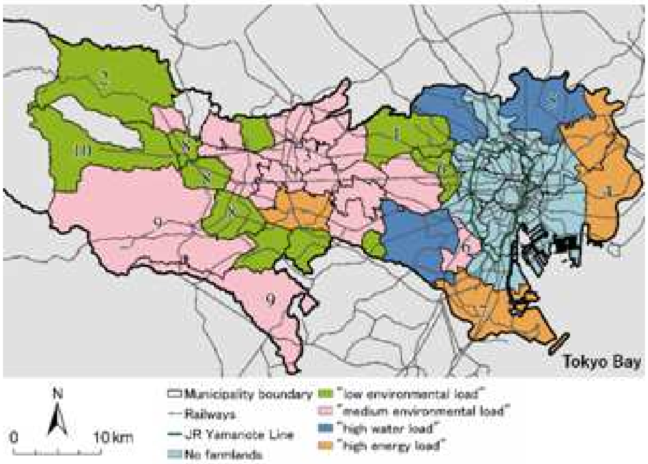


Fig.3:Results of cluster analysis based on production efficiency. The numbers in the map arethe areas mentioned in the Fig.4, results, and discussion.Processed from National Land Information (Railway, Municipal Data) (Ministry of Land, Infrastructure, Transport and Tourism).

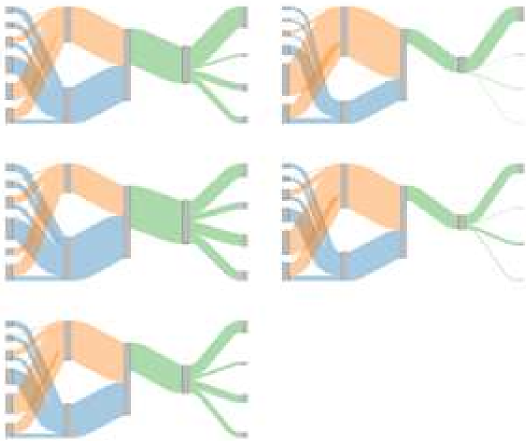

Fig.4:Sankey diagram in five cities as an example. The order of the items is the same as in Fig.2.The thickness of the lines is standardized based on Nerima.

## 4.2 Cluster analysis

Hierarchical cluster analysis produced four clusters. The clusters were named "low environmental load,""medium environmental load,""high water load," and "high energy load" based on their characteristics (Table 1).Fig.3 shows a map of the distribution of each cluster, and Fig.4 shows the Sankey diagram for the five citiesas an example.

The "low environmental load" type was a cluster that uses less energy and water. Totalsfor energy and water consumption of fertilizer were 2,621.9MJ/t and 177.8L/t, respectively, much lower than other clusters. Water and energy per unit of area was also minimal.The most significant feature of the cluster was the polarization of the location distribution. The cluster was mostly located in the central and western parts of the study area.

The "medium environmental load" type was a cluster in which the energy and water consumption was higher than that of the "low environmental load" type. A total of 18 municipalities fell into this category, making it the largest cluster. Many of the regions located on the Musashino Plateau (Fig.1), which are suburban communities, belonged to the "medium environmental load" type.

The "high water load" type was a cluster in which water consumption was larger than energy use. This cluster was characterized by the high consumption of fertilizers and pesticides. The water consumption per unit of vegetable production was 404.2L/t, or twice that of the "low environmental load" type. In contrast, the weight of food production per farmland unit of area was the smallest. Only three municipalities are highly urbanized areas close to the CBD fell into this category.

The "high energy load" type was a cluster that used more energy than water. Itwas characterized by the large amount of energy used in greenhouses. For example, Ota City(Area 7 in map) consumed 33,700.8MJ/t of energy per unit of vegetable production. This cluster included only four municipalities, and the energy and water consumption per unit of area varied greatly, but it tended to be larger than that of other municipalities.

## 5 DISCUSSION

This study clarified input-output efficiency of Tokyo urban agriculture by quantifying energy and water inputs and vegetable production outputs, then classified and mapped municipality characteristics by cluster analysis.

### 5.1 Influence of urban structure on input-output efficiency in Tokyo

The urban structure affected the distribution of each cluster in several ways. First, the "high water load" and "high energy load" clusters were concentrated in the CBD. In both clusters, the proximity to the CBDis reflected in the agricultural production of leafy vegetables, as well as the cultivation of a wide variety of plants, leading to high energy and water consumption. In addition, different topography distinguished these clusters. The "high water load" cluster was located on the Musashino plateau in the western and northern parts of the CBD, while the three "high energy load" municipalities in the CBDwere located in the Tokyo Bay lowlands in the eastern and southern partsof theCBD. It is important to note that greenhouses are used not only for vegetable production but may also be used for flower cultivation.However, "high water load" cluster has less food production per unit of area because it produces more low-weight leafy vegetables, while the "high energy load"cluster produces more intensively. Although some municipalities can be interpreted as outliers because of their small agricultural scale (Area6 in the map), it is worth considering that Nerima City was classified as a "low environmental load" type (Area 1). Although Nerimawas not outstanding in terms of population structure and topography, it hasmany farmlands and boasts one of the highest agricultural yields in Tokyo. Nerima has the potential to become an advanced case study of urban agriculture in that it can abundantly produce agricultural products with low impacts despite being in a highly urbanized area (Fig.4).

The plateau area located in the center of the study area isdominated by the "mediumenvironmental load" type. The plateau isa suburban area for workers commuting to the CBD, with a high density of railway lines and urbanization around train stations. Fields are present on a small scale further away from train stations."Medium environmental load" agriculture in these areasispositioned between intensive agriculture and less intensive agriculture in the more suburban areas.

In the western and southern regions, there were "lowenvironmental load" and "medium environmental load"areas. The "low environmental load"areas included two cities with a low degree of urbanization (Area 2 and 10) and small municipalities located along rail lines (Area 8). The "medium environmental load"areasincluded two cities where urbanization was well advanced (Area9). The former is likely to haveless-intensive agriculture and a high proportion of fruit crops and tubers. In the latter case, the reason is not clear, but it is reasonable to interpret it as being relatively less intensive compared to the CBD.

The spatial distribution of the clusters shown above is similar to the distribution of agriculture with the degree of urbanization traditionally revealed by geography (Kikuchi et al., 2002). However, urban agriculture is more sensitive to urbanization, and small changes in railway lines, topography, and population distribution are immediately reflected in clusters. The visualization of urban structure at a detailed level reveals differences in the input-output efficiencies of urban agriculture. We also found some good examples of low environmental load even near the CBD, such as Nerima City. Small geographic differences in urban agriculture appear to make a big difference, but are often not noticed in traditional analysis on a large scale.

Further studies could provide important data for the conservation and promotion of small-scale and fragile urban agriculture.

### 5.2 Impacts of input-output efficiency on urban environmental performance

In the input-output efficiency of urban agriculture in Tokyo, the use of greenhouses, in particular, loaded energy inputs, while the use of fertilizers and pesticides, including phosphorus, loaded water inputs. In this study, the total inputs of 426.1TJ of energy and 8.7ML of water resulted in an output of 75,566t of vegetable production. This efficiencyis similar to that of a study that investigated the input energy for vegetable production in Gunma Prefecture in Japan (Nishizono & Moteki, 2007). However, the study by Nishizono &Motekiwas more extensive than the system boundary of this study, and if this study is adapted to their system boundary, the environmental performance of urban agriculture may produceworse results. This confirms that urban agriculture has the same or even greater environmental impacts than regular agriculture. This is contrary to the objectivesof cities that want to use urban agriculture to improvetheir environmental performance.

However, in urban agriculture in the study area, a wide variety of vegetables are beingcultivated, mainly leafyvegetablesfor whichfreshness is important. This freshness and availability of local vegetables is a service that contributes more to the enrichment of choices, nutrition, preservation of local culture, and education, rather than production or food self-sufficiency. The 75,566t of vegetablesproduced in Tokyo is equivalent to 5.5kg per capita, or only 15 days of consumption if we assume that each person consumes 350g per day aspromotedby national health programs.

In light of the above, the main benefit in terms ofenvironmental performance of cities provided by the input-output efficiency of urban agriculture is not the reduction of environmental load, but rather the non-material services and added values arising simultaneously with the supply of food. To increase non-material services and added value, we can shift from greenhouses to open field cultivation, reduce pesticide use, and shift to organic farming. Those actions may reduce the food supply, but actually improveinput-output efficiency.

### 5.3 Hints for policy decisionsaffecting urban agriculture

Based on the impacts of urban structure on urban agriculture and impacts of urban agriculture on environmental performance of cities, we can find several hints on how cities can be reconnected with urban agriculture.

In reconnecting cities with urban agriculture, it is important to design, plan, and implement areas based on evidence. There is a growing movement to explore the policies and possibilities of converting vacant urban land, rooftops, and brownfields to agriculture(Hara et al., 2018; Saha & Eckelman, 2017). This study calculated amounts of water and energy per unit of vegetable production and agricultural land area (Table1). These values can be included in such measures for preliminary assessments of the environmental performance of urban agriculture. Alternatively, it is possible to reflect on the current environmental performance of urban agriculture and explore ways to reduce the environmental impacts of farming. The approaches used here can also provide an opportunity for farmers and citizens to review the methods of urban agriculture.

The population of Tokyo is expected to continue growing until around 2030, and then remain high (National Institute of Population and Social Security Research, 2018). Conversion of farmland to urban uses is expected to continue due to the pressures of urban development and the aging of farmers. In other words, the urban structure and the performance of urban agriculture will continue to change, and the input-output efficiency of urban agriculture may be affected by these changes. Given that urbanization will continue, there is a great possibility that urban agriculturetypologies will move from "lowenvironmental load" to "medium environmental load," and from "medium environmental load" to a "highwater load" or "highenergy load."Such shifts would not be favorable changes for urban planning in terms of environmental performance.

Finally, urban planning has important roles to play in predicting how the urban structure of a region will change in the future, examining things from a wide range of perspectives, including population, nature, and industry, and in adapting predictions of changes in urban structure to urban agricultural management, or in adjusting the urban structure to control impacts on urban agriculture.Meanwhile, farmland in urbanized areas is no longer regarded only as private property but also as public space.If local governments wish to promote good environmental performance, they must continue to intervene actively in the transformation of urban agriculture toward organic farming, in the conservation of farmland, and in providing an environment that makes it easier for farmers and businesses to continue farming. These efforts can prevent deterioration of input-output efficiency of urban agriculture and in fact improve it further.These measures are described in the Basic Plan for Urban Agriculture Promotion, howeverlocal governments should incorporate these measures more concretely into urban planning. In Japan,Productive Green LandAct helps prevent the conversion of agricultural land, because owners of Land designated as Productive Green Landcannot convert it to other land use for 30 years in general (Yagi & Garrod, 2018).Furtehr, it may be desirable to develop new urban planning strategy such as Location Normalization Plan.

## 6 CONCLUSION

By visualizing the relationship between vegetable production and the use of water and energy resources in the case of urban agriculture in Tokyo, we found that small differences in urban structure affected the input-output efficiency of urban agriculture, and conversely, the input-output efficiency of urban agriculture can have negative impacts on environmental performancecompared with non-urban agriculture. Based on the above, the role of urban planning is to use the prediction of urban structure for urban agriculture management and to adjust urban structure so that it does not affect urban agriculture.Since it is the farmers who ultimately sustain urban agriculture, a key point for future discussion will be how urban planning can intervene in the relationship between the agricultural sector of a municipality and the farmers.

## 7 ACKNOWLEDGEMENTS

The authors would like to thank Tokyo Metropolitan Government for providing GIS datasets. This work was supported by the Tokyu Foundation in 2020-2021 (Grant no. 2020-219),the Keio University Doctorate Student Grant-in-Aid Program from Ushioda Memorial Fund in 2021, and the Belmont ForumSUGI NEXUS/M-NEX project (Grant no. 11314551).

## 8 REFERENCES

BENIS, Khadija, FERRÃO, Paulo: Potential mitigation of the environmental impacts of food systems through urban and peri-urban agriculture (UPA): a life cycle assessment approach. In: Journal of Cleaner Production, Vol. 140, 784–795. 2017. https://doi.org/10.1016/j.jclepro.2016.05.176

CAPUTO, Silvio, SCHOEN, Victoria, SPECHT, Kathrin, GRARD, Baptiste, BLYTHE, Chris, COHEN, Nevin, FOX-KÄMPER, Runrid, HAWES, Jason, NEWELL, Joshua, PONIŻY, Lidia: Applying the food-energy-water nexus approach to urban agriculture: From FEW to FEWP (Food-Energy-Water-People). In: Urban Forestry and Urban Greening, Vol. 58, 126934. 2021. https://doi.org/10.1016/j.ufug.2020.126934

CHEN, Wei, GENG, Yong, HONG, Jinglan, YANG, Donglu, MA, Xiaotian: Life cycle assessment of potash fertilizer production in China. In: Resources, Conservation and Recycling, Vol. 138, 238–245. 2018. https://doi.org/10.1016/j.resconrec.2018.07.028

FOLEY, Jonathan A., RAMANKUTTY, Navin, BRAUMAN, Kate A., CASSIDY, Emily S., GERBER, James S., JOHNSTON, Matt, MUELLER, Nathaniel D., O'CONNELL, Christine, RAY, Deepak K., WEST, Paul C., BALZER, Christian, BENNETT, Elena M., CARPENTER, Stephen R., HILL, Jason, MONFREDA, Chad, POLASKY, Stephen, ROCKSTRÖM, Johan, SHEEHAN, John, SIEBERT, Stefan, … ZAKS, David P. M.: Solutions for a cultivated planet. In: Nature, Vol. 478, Issue 7369, 337–342. 2011. https://doi.org/10.1038/nature10452

GOLDSTEIN, Benjamin, BIRKVED, Morten, FERNÁNDEZ, John, HAUSCHILD, Michael: Surveying the environmental footprint of urban food consumption. In: Journal of Industrial Ecology, Vol. 21, Issue 1, 151–165. 2017. https://doi.org/10.1111/jiec.12384

GOLDSTEIN, Benjamin, HAUSCHILD, Michael, FERNÁNDEZ, John, BIRKVED, Morten: Testing the environmental performance of urban agriculture as a food supply in northern climates. In: Journal of Cleaner Production, Vol. 135, 984–994. 2016a. https://doi.org/10.1016/j.jclepro.2016.07.004

GOLDSTEIN, Benjamin, HAUSCHILD, Michael, FERNÁNDEZ, John, BIRKVED, Morten: Urban versus conventional agriculture, taxonomy of resource profiles: a review. In: Agronomy for Sustainable Development, Vol. 36, Issue 1, 9. 2016b. https://doi.org/10.1007/s13593-015-0348-4

HARA, Yuji, MCPHEARSON, Timon, SAMPEI, Yuki, MCGRATH, Brian: Assessing urban agriculture potential: a comparative study of Osaka, Japan and New York city, United States. In: Sustainability Science, Vol. 13, Issue 4, 937–952. 2018. https://doi.org/10.1007/s11625-018-0535-8

HOFF: Understanding the Nexus. In: Background Paper for the Bonn2011 Nexus Conference: The Water, Energy and Food Security Nexus., Stockholm Environment Institute, Stockholm.2011.

HOWE, Joe, WHEELER, Paul: Urban food growing: the experience of two UK cities. In: Sustainable Development, Vol. 7, 13–24. 1999. https://doi.org/10.1002/(SICI)1099-1719(199902)7:1<13::AID-SD100>3.0.CO;2-B

HU, Yingjie, ZHENG, Ji, KONG, Xiangbin, SUN, Jin, LI, Yu: Carbon footprint and economic efficiency of urban agriculture in Beijing – a comparative case study of conventional and home-delivery agriculture. In: Journal of Cleaner Production, Vol. 234, 615–625. 2019. https://doi.org/10.1016/J.JCLEPRO.2019.06.122

JAPAN FINANCE CORPORATION AGRICULTURE FORESTRY FISHERIES AND FOOD BUSINESS UNIT: Survey on the scale and profitability of greenhouse horticulture (tomatoes) (freely translated from Japanese).2017. (in Japanese) https://www.jfc.go.jp/n/findings/pdf/topics_170407a.pdf

KIKUCHI, Toshio, OISHI, Taro, SAITOH, Ryuta: Recreating of the rurality in the urban fringe of Tokyo metropolitan area : a case study of Kodaira city. In: Geographical Reports of Tokyo Metropolitan University, Vol. 37, 93–102. 2002. http://ci.nii.ac.jp/naid/110008607060/en/

KOBAYASHI, Hisashi, SAGO, Ryuichi: A study on life cycle assessment of energy consumption and CO2 emissions in the manufacturing and transportation processes of nitrogen and phosphate fertilizers. In: Japanese Journal of Farm Work Research, Vol. 36, Issue 3, 141-151 (in Japanese with English abstract). 2001.

LIU, Jianguo, HULL, Vanessa, GODFRAY, H. Charles J., TILMAN, David, GLEICK, Peter, HOFF, Holger, PAHL-WOSTL, Claudia, XU, Zhenci, CHUNG, Min Gon, SUN, Jing, LI, Shuxin: Nexus approaches to global sustainable development. In: Nature Sustainability, Vol. 1, 466–476. 2018. https://doi.org/https://doi.org/10.1038/s41893-018-0135-8

LOVELL, Sarah Taylor: Multifunctional Urban Agriculture for Sustainable Land Use Planning in the United States. In: Sustainability, Vol. 2, 2499–2522. 2010. https://doi.org/10.3390/su2082499

LOVELL, Sarah Taylor, JOHNSTON, Douglas M.: Designing Landscapes for Performance Based on Emerging Principles in Landscape Ecology. In: Ecology and Society, Vol. 14, Issue 1, 44. 2009. https://www.ecologyandsociety.org/vol14/iss1/art44/

MILLER-ROBBIE, Leslie, RAMASWAMI, Anu, AMERASINGHE, Priyanie: Wastewater treatment and reuse in urban agriculture: Exploring the food, energy, water, and health nexus in Hyderabad, India. In: Environmental Research Letters, Vol. 12, 075005. 2017. https://doi.org/10.1088/1748-9326/aa6bfe

MINISTRY OF ECONOMY TRADE AND INDUSTRY: Emissions related to pesticides (freely translated from Japanese). 2016.

MOHAREB, Eugene, HELLER, Martin, NOVAK, Paige, GOLDSTEIN, Benjamin, FONOLL, Xavier, RASKIN, Lutgarde: Considerations for reducing food system energy demand while scaling up urban agriculture. In: Environmental Research Letters, Vol. 12, 125004. 2017. https://doi.org/10.1088/1748-9326/aa889b

MORGAN, Kevin: Nourishing the city: the rise of the urban food question in the Global North. In: Urban Studies, Vol. 52, Issue 8, 1379–1394. 2015. https://doi.org/10.1177/0042098014534902

NATALIA, TG, ROBERT, MH: Life-Cycle Assessment of Neonicotinoid Pesticides. In: Journal of Fertilizers & Pesticides, Vol. 7, Issue 1, 1000165. 2016. https://doi.org/10.4172/2471-2728.1000165

NATIONAL INSTITUTE OF POPULATION AND SOCIAL SECURITY RESEARCH: Regional population projects for Japan: 2015-2045. In: Population Research Series, Vol. 3402018.

NEWELL, Joshua P., GOLDSTEIN, Benjamin, FOSTER, Alec: A 40-year review of food-energy-water nexus literature and its application to the urban scale. In: Environmental Research Letters, Vol. 14, 073003. 2019. https://doi.org/10.1088/1748-9326/ab0767

NISHIDE, Tsutomu: The actural conditions of water demand and irrigation plan on the house plant zone. In: Journal of the Agricultural Engineering Society, Japan, Vol. 58, Issue 11, 1109-1114. 1990. (in Japanese) https://doi.org/10.11408/JJSIDRE1965.58.11_1109

NISHIZONO, Hiromi, MOTEKI, Hiromi: Study of environment evaluation by LCA method on production and distribution of vegetables. In: Annual Reports of the Faculty of Education, Gunma University. Art, Technology, Health and Physical Education, and Science of Human Living Series, Vol. 42, 145-157. 2007. (in Japanese) http://ci.nii.ac.jp/naid/120000912826/

PENG, Jian, LIU, Zhicong, LIU, Yanxu, HU, Xiaoxu, WANG, An: Multifunctionality assessment of urban agriculture in Beijing City, China. In: Science of The Total Environment, Vol. 537, 343–351. 2015. https://doi.org/10.1016/J.SCITOTENV.2015.07.136

PÉREZ-NEIRA, David, GROLLMUS-VENEGAS, Anibal: Life-cycle energy assessment and carbon footprint of peri-urban horticulture. A comparative case study of local food systems in Spain. In: Landscape and Urban Planning, Vol. 1722018. https://doi.org/10.1016/j.landurbplan.2018.01.001

ROTHWELL, Alison, RIDOUTT, Brad, PAGE, Girija, BELLOTTI, William: Environmental performance of local food: Trade-offs and implications for climate resilience in a developed city. In: Journal of Cleaner Production, Vol. 114, 420–430. 2016. https://doi.org/10.1016/j.jclepro.2015.04.096

SAHA, Mithun, ECKELMAN, Matthew J.: Growing fresh fruits and vegetables in an urban landscape: A geospatial assessment of ground level and rooftop urban agriculture potential in Boston, USA. In: Landscape and Urban Planning, Vol. 165, 130–141. 2017. https://doi.org/10.1016/j.landurbplan.2017.04.015

SANYÉ-MENGUAL, Esther, ORSINI, Francesco, GIANQUINTO, Giorgio: Revisiting the sustainability concept of urban food production from a stakeholders' perspective. In: Sustainability, Vol. 10, 2175. 2018. https://doi.org/10.3390/su10072175

SANYÉ-MENGUAL, Esther, SPECHT, Kathrin, GRAPSA, Erofili, ORSINI, Francesco, GIANQUINTO, Giorgio: How Can Innovation in Urban Agriculture Contribute to Sustainability? A Characterization and Evaluation Study from Five Western European Cities. In: Sustainability, Vol. 11, 4221. 2019. https://doi.org/10.3390/su11154221

TOKYO METROPOLITAN GOVERNMENT: Recommended rate of fertilizer application (freely translated from Japanese). 2003. (in Japanese)

TOKYO METROPOLITAN GOVERNMENT: Report for agricultural production in Tokyo (2013) (freely translated from Japanese). 2015. (in Japanese)

TOKYO METROPOLITAN GOVERNMENT: Tokyo agriculture promotion plan (English ed.): new steps for the next stage. 2019.

WEBER, Christopher L., MATTHEWS, H. Scott: Food-miles and the relative climate impacts of food choices in the United States. In: Environmental Science and Technology, Vol. 42, Issue 10, 3508–3513. 2008. https://doi.org/10.1021/es702969f

YAGI, Hironori, GARROD, Guy: The future of agriculture in the shrinking suburbs: The impact of real estate income and housing costs. In: Land Use Policy, Vol. 76, 812–822. 2018. https://doi.org/10.1016/j.landusepol.2018.03.013

YAMAMOTO, Syozo, KOBAYASHI, Kouji, TABAYASHI, Akira, SAKURAI, Akihisa: Landuse pattern in western Tokyo: Analysis from mesh (freely translated from Japanese). In: Tsukuba Studies in Human Geography, Vol. 1, 155–171. 1977. (in Japanese)