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Vegetable supply to Tokyo disrupted by 2023 and 2024 summer heatwaves

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Abstract

Understanding the impacts on urban food supply from extreme climate events is a first step towards building climate-resilient agri-food systems. Here, we report on vegetable supply disruptions in the Tokyo metropolitan area due to the summer heatwaves of 2023 and 2024, using the governmental survey on wholesale market arrival volumes and prices. Fifteen vegetables (broccoli, cabbage, carrot, Chinese cabbage, cucumber, eggplant, Japanese radish, lettuce, onions, potatoes, spinach, sweet pepper, taro, tomato and Welsh onion) were considered. Compared to the 2010–2022 average, the arrival volume in the September-October period was on the bottom third level or severer for carrot (−27.1%) and Japanese radish (−22.3%) in 2023, and for tomato in both 2023 (−19.9%) and 2024 (−22.9%), with their price increases of 46.0–81.9%. The negative impact of high temperatures in August or September on arrival volumes in the following month was detected for these vegetables in at least one main producing prefecture. However, in 2024, the price increases were more widespread, affecting 14 vegetables. As there were no appreciable decreases in arrival volumes, it is unlikely that climatic factors were the primary cause of the price increases in 2024. These results highlight the need for domestic vegetable production to be more heat tolerant, given its influence on downstream of agri-food systems, such as urban consumers.

Key words: Cities, Extreme climate event, Food supply, Price increase, Vegetable

1. Introduction

As agri-food systems continue to change with many factors, including the globalization of economy, climate change and urbanization, their robustness and resilience to shocks remains a public concern (Seto and Ramankutty, 2016; Gaupp, 2020; Gomez *et al*., 2021; Long *et al*., 2024). With 68% of the world population expected to live in urban areas by 2050 (United Nations Department of Economic and Social Affairs, 2018), agri-food systems, as a key infrastructure and service for societies, have become an important piece for the climate-resilient development of cities (Dodman *et al*., 2022; Tchonkouang *et al*., 2024). To achieve this goal, understanding the impacts of extreme climate events on urban food supply is an important first step.

Although socio-economic factors, such as the demand-supply balance, share of domestic production (or imports) and stock-to-use ratio, are fundamental determinants of food prices, including those of vegetables, extreme climate events have increasingly been recognized as the cause of day-to-seasonal price fluctuations (Yang *et al*., 2022; Duncan, 2024). Extreme climate events, such as heatwaves, excessive rainfalls and droughts, often result in a decline in the quality of harvests, meaning that harvested crops do not meet the market standards and are not shipped from producing areas to cities. This leads to a decline in the volume of harvests arriving in cities and supply disruptions.

In line with the record high temperatures globally (Wong, 2023), the summer of 2023 saw record high temperatures in Japan over the past 126 years, with the June-August average being +1.76°C warmer than the 1991–2020 average (Takemura *et al*., 2024; Sato *et al*., 2024). In particular, northern and eastern Japan experienced unprecedented high temperatures of +3.0°C and +1.7°C above normal, respectively. Moreover, the summer average temperature in Japan hit the record high of +1.76°C again in 2024 (Tokyo Climate Center, 2024).

These extreme hot summer events provided an opportunity to observe how high temperatures throughout the season (heatwave) can disrupt the supply of vegetables to cities. Among others, the Tokyo metropolitan area is the one of populous cities in Japan and worldwide, with about 13.5 million people (Tokyo Metropolitan Government, 2024). We aimed to use this opportunity to report on the consequences of the 2023 and 2024 summer heatwaves on the volumes arriving at the main wholesale markets in Tokyo, as well as on the prices of 15 major vegetables.

2. Vegetable production in Japan

Although the share of vegetables to the human caloric and protein intake is small, they are important sources of micronutrients that contribute to a healthy diet (e.g., vitamins A, C, E, and K, folic acid, potassium, iron, and dietary fiber) (Xia *et al*., 2022). According to the Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF, 2024), vegetable production

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accounts for 2.23 trillion yen in 2022, or a quarter of Japan's total agricultural output, making the vegetable production the second largest agricultural subsector after livestock. Imported vegetables account for 20% of national demand and are increasing for industrial use (frozen, canned and other processed forms). However, 97% and 68% of fresh vegetables consumed by households and food industry, respectively, are domestically produced. This fact highlights the importance of domestic vegetable supply to urban consumers in Japan, such as those in Tokyo.

3. Materials and methods

3.1. Weather

Daily data on air temperature and precipitation over the land area in Japan at the 1-km resolution were obtained from the National Agriculture and Food Research Organization's Agro-Meteorological Grid Square Data System (Ohno *et al*., 2016). Solar radiation was not used in this study because it is generally strongly correlated with precipitation on a monthly scale. This grid data product was derived by spatially interpolating site observations.

The monthly average temperature and total precipitation were calculated for each 1-km grid cell. The monthly 1-km data were then spatially averaged to represent the climatic conditions over the vegetable-producing areas in the prefecture of interest. To that end, the major producing municipalities were first identified per vegetable and prefecture based on the Crop Statistics (Vegetables) (https://www.maff.go.jp/j/tokei/kouhyou/sakumotu/sakkyou_yasai/index.html; accessed 21 July 21 2024). Second, the fraction of non-paddy cropland areas within a 1-km grid cell were calculated using the 100-m resolution land-use/land-cover data in the National Land Numerical Information (as of 2009) (https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-L03-b.html; accessed 5 August 2024). Last, the 1-km monthly temperature and precipitation data were averaged over the 1-km grid cells that distributed within the major producing municipalities for the vegetable of interest, using the non-paddy cropland area fractions as weights. The same procedure was repeated for major prefectures in terms of arrival volume in Tokyo.

3.2. Wholesale markets' arrival volumes and prices

We used the statistical data from 2010 to 2024, as reported in the Fruit and Vegetable Wholesale Market Survey (Daily Survey) published by MAFF (https://www.seisen.maff.go.jp/seisen/bs04b040md001/BS04B040UC020SC998-Evt001.do; accessed 19 June 2025). Included items were the volumes arriving at the wholesale markets from main producing prefectures (in tons) and the wholesale prices (in Japanese yen per kilogram) collected from all wholesalers operating in the wholesale markets. In the survey, daily volumes and prices were recorded for the five largest supplying prefectures or, if there were less than five, for the prefectures accounting for >80% of the total arrival volume.

The 15 vegetables examined in this study were broccoli, cabbage, carrot, Chinese cabbage, cucumber, eggplant, Japanese radish, lettuce, onions, potatoes, spinach, sweet pepper, taro, tomato and Welsh onion. All of them except broccoli are "designated" in the Vegetable Production and Marketing Stabilization Act that enacted in 1966 with the aim of stabilizing domestic production and supply of major vegetables (Ito and Dyck, 2002). Although broccoli is currently one of the 35 "specified" vegetables, it will be "designated" in 2026 due to the recent increase in consumption and production. Indeed, nine of the "designated" vegetables (cabbage, cucumber, eggplant, Japanese radish, lettuce, onion, spinach, tomato and Welsh onion) account for 46.5% of the output of Japan's vegetable production in 2022 (MAFF, 2024).

Among 11 wholesale markets in the Tokyo metropolitan area, the data we examined covered four major wholesale markets dealing vegetables and fruits, i.e., Toyosu, Ota, Toshima and Yodobashi (Tokyo Metropolitan Central Wholesale Market Network, 2024). These wholesale markets are designated by MAFF to collect data to represent the Tokyo metropolitan area. The daily data in September and October were aggregated for volume and averaged for price, respectively, for each month.

3.3. Imports

To examine possible changes in the vegetable supply in 2023 and 2024 due to imports, we also used the statistical data on the annual import volume of fresh, refrigerated and dried vegetables from 2010 to 2024. The data were obtained from the Agricultural, Forestry and Fishery Products Import and Export Information published by MAFF (https://www.maff.go.jp/j/tokei/kouhyou/kokusai/index.html#m1; accessed 19 June 2025). As monthly data were only partially available during the study period, we used the annual data for this study.

3.4. Visualization

The data visualization was performed using the statistical package R (R Core Team, 2024). The monthly total arrival volume and average price were respectively averaged over the 2-month period (September and October), and then were standardized so that the 2010−2022 average equaled 100. This standardization made it easier to visualize the results for multiple vegetables at once when drawing a radar chart. The radar charts were drawn using R with *fmsb* library (Nakazawa, 2024). For monthly prefectural temperature and precipitation, we calculated averages for the June-August period, and then their anomalies, relative to the 2010−2022 average. The anomalies were further averaged over the major prefectures in terms of arrival volume in Tokyo (the number of the prefectures varied by vegetable). Although a three-month period (June-August) are relatively long compared to the growth period of the vegetables, we selected to capture an overview of climatic conditions in the summer of 2023 and 2024.

3.5. Regression analysis

Regression analysis was performed for the vegetables that exhibit a notable decline in arrival volumes in the September−October period of 2023 or 2024. We hypothesized that climatic conditions in the prefectures where the vegetable of interest was grown in August and September affected the arrival volumes in Tokyo the following month (September and October) due to the lag between cultivation and shipment, and prices were

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affected by arrival volumes in the same month. We assumed that prices were not affected by temperature or precipitation. Multiple regression was used to associate monthly total arrival volume with monthly mean temperature and total precipitation. The regression analysis was done separately for September and October. We confirmed that most of the cultivation types adopted in the main producing prefectures were likely operated in August and September (National Institute of Vegetable and Tea Science, 2009) (Fig. S1, Fig. S2, Fig. S3). In addition, simple regression was also conducted to give readers a visual representation of the relationships between arrival volume and temperature, and between arrival volume and precipitation.

Furthermore, the relationship between arrival volume and price was examined using simple regression. Simple regression was also applied to analyze the relationship between changes in the annual total imports and average prices in September and October for 2023 and 2024. All regression analyses described above were done using the ordinary least squared method in R (Chambers and Hastie, 1992). Considering the inherent errors in the nationwide climate-crop analysis, we set the significance level to as 10% ($p<0.1$).

4. Results

4.1. Temperature and precipitation

The summer of 2023 was characterized by high temperatures. Unprecedented high temperature anomalies, ranging from +0.86℃ for tomato to +2.36℃ for Japanese radish, were experienced in the prefectures that produced and shipped the vegetables to Tokyo (Fig. 1). The average precipitation anomalies in the producing prefectures during the summer of 2023 ranged from 79.8% for Japanese radish to 104.2% for sweet pepper, and were similar to those experienced in previous years. The summer of 2024 was also characterized by high temperatures, though it was slightly cooler and wetter than in 2023. Exceptions were only temperature for tomato and precipitation for carrot, onions and potatoes (Fig. 1).

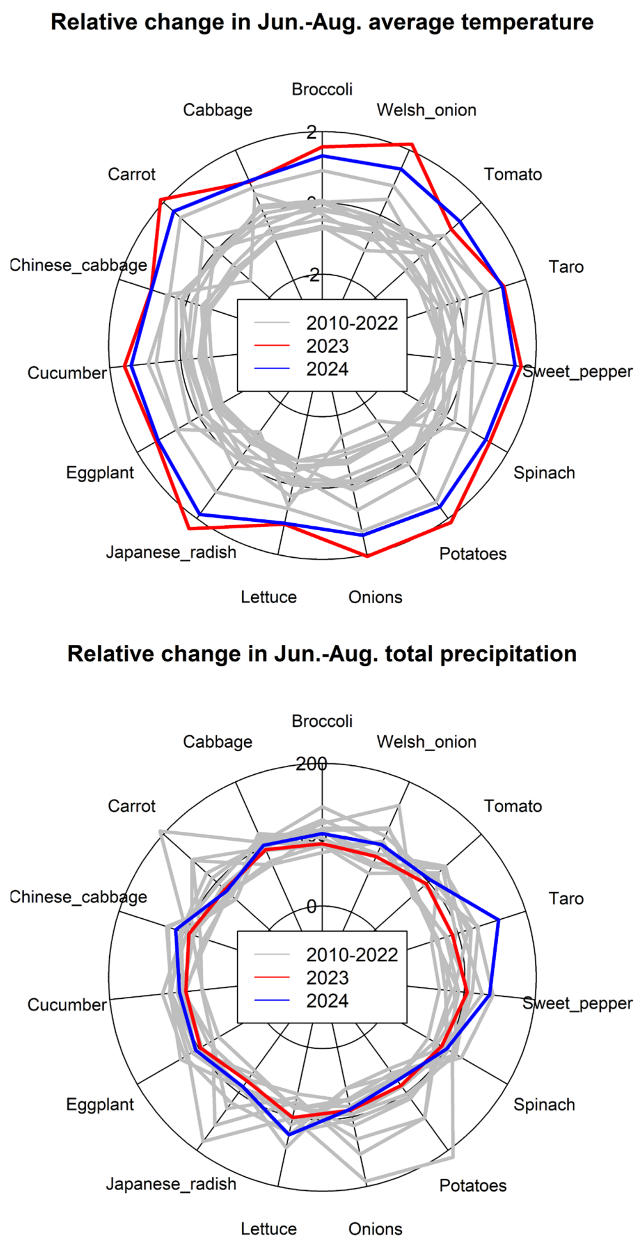

Fig. 1. Rader charts showing the seasonal climate averaged over the major vegetable-producing prefectures shipped to the Tokyo metropolitan area in the September-October period. Data indicate the anomalies in June-August average air temperature and total precipitation, relative to their 2010−2022 averages.

4.2. Prices and volumes

Of the 15 vegetables examined, 10 had high prices in the September-October period of 2023, in the top third of the 15-year period studied (Fig. 2, Table 1). Broccoli, Japanese radish, tomato and Welsh onion in particular reached record levels of high prices, with respective price increases of 35.8%, 46.0%, 81.9% and 62.5% compared to their 2010−2022 averages. However, only three−carrot, Japanese radish and tomato−were notable for their low arrival volumes (−19.9%, −22.3% and −27.1%, respectively).

In 2024, the prices of all the vegetables considered here, except carrot were high in September and October. Three of them (cucumber, sweet pepper and taro) reached record high prices, with respective price increases of 44.6%, 65.3% and 18.1%, (Fig. 2, Table 1). However, despite the overall price increases, a notable decline in arrival volumes was found only for tomato (−22.9%). Reductions in arrival volumes were also found for Japanese radish and taro, but these were relatively minor in terms of the amplitude (−7.3% and −7.7%).

4.3. Regressions

In the regression analysis, we focused on carrot, Japanese radish and tomato, which exhibited a notable decline in arrival volume in 2023 or 2024. As summarized in Table 2, the multiple regression results showed that August temperature had a significant negative effect on the arrival volumes of carrot from Hokkaido in September (the simple regression results are also displayed for visualization purposes; Fig. 3). Hokkaido is the main producer shipping carrot to Tokyo in the period. Similarly, a significant negative temperature effect was also found for the arrival volumes of Japanese radish and tomato

Table 1. Mean total arrival volumes, average wholesale prices for the September-October period from 2010 to 2022, and their coefficient of variations (CVs) and percentage anomalies in 2023 and 2024, relative to the corresponding average value, for the 15 vegetables.

Vegetable	Volume				Price			
	Ave. (t)	CV (%)	Anomaly in 2023 (%)	Anomaly in 2024 (%)	Ave. (yen/kg)	CV (%)	Anomaly in 2023 (%)	Anomaly in 2024 (%)
Broccoli	1923	29.9	19.7	67.3	531	10.9	35.8 **	19.0 *
Cabbage	17738	9.2	8.8	19.8	92	24.5	11.3	24.4 *
Carrot	12682	14.5	−27.1 *	13.6	142	36.6	60.5 *	−11.3
Chinese cabbage	17344	12.3	19.6	6.9	95	18.8	6.7	18.4 *
Cucumber	3829	9.3	6.9	2.9	347	14.4	17.4 *	44.6 **
Eggplant	2397	11.2	4.2	5.8	339	13.8	8.4	17.5 *
Japanese radish	15113	10.0	−22.3 **	−7.3	105	16.1	46.0 **	31.7 *
Lettuce	12113	7.8	7.2	3.6	205	29.8	12.1	35.9 *
Onions	17787	15.2	6.0	12.1	99	15.7	21.0 *	15.0 *
Potatoes	13337	9.3	−2.5	10.3	126	21.9	3.1	5.5 *
Spinach	714	14.2	−0.2	23.9	703	11.8	20.0 *	19.2 *
Sweet pepper	2784	13.0	15.4	46.1	364	21.0	56.2 *	65.3 **
Taro	707	21.9	−9.4	−7.7	310	10.3	10.6 *	18.1 **
Tomato	2137	13.7	−19.9 *	−22.9 *	436	9.0	81.9 **	52.3 *
Welsh onion	4446	10.5	4.9	47.6	343	15.0	62.5 **	33.1 *

* Volume (price) in the bottom (top) third of the study period.
** Lowest (highest) volume (price) in the study period.

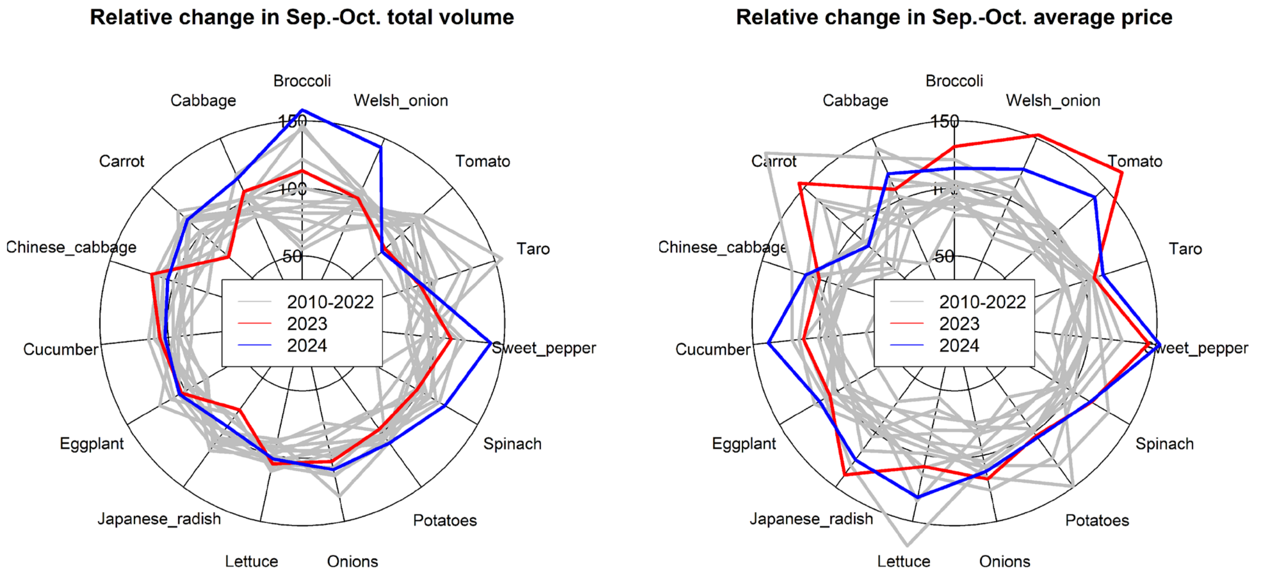

Fig. 2. Rader charts showing the impact on vegetable supply to the Tokyo metropolitan area from the extreme summer heat event of 2023 and 2024. Data indicate the relative changes in total arrival volume and average wholesale price in the September-October period for the 15 major vegetables (the average of 2010−2024 equals 100).

from Aomori in September, and tomato from Chiba in October (Fig. 3, Fig. 4). Aomori and Hokkaido are the main producers for Japanese radish in the period, while Aomori, Chiba, Fukushima, Hokkaido and Kumamoto are the main producers for tomato. Exceptionally, a significant positive effect of temperature was detected for the arrival volume of tomato from Kumamoto. The effect of precipitation was detected to be significantly negative for the arrival volumes of carrot from Hokkaido in September, and tomato from Aomori in September (Table 2).

It is worth noting that, as expected, the lower the total arrival volume, the higher the average price. This relationship was estimated to be highly significant for carrot in both September and October ($p \leq 0.001$) Fig. 5). However, it was marginally non-significant for Japanese radish and tomato in September

Table 2. A summary of the multiple regression analysis for the three vegetables that showed a notable reduction in arrival volume in the September-October period of 2023. The asterisks indicate that the regression coefficient value is significant at the 1% (***), 5% (**), and 10% (*) level, respectively.

Prefecture	Arrival month	Adj-R^2	Temperature	Precipitation	Intercept
Carrot					
Hokkaido	September	0.507	−346.67 **	−5.097 *	13812
Hokkaido	October	0.284	−365.01	−5.678	13482
Japanese radish					
Aomori	September	0.545	−204.17 ***	−0.115	7418
Aomori	October	0.051	−3.19	−0.887	3444
Hokkaido	September	0.197	−668.75	−2.820	26080
Hokkaido	October	0.133	−358.51	0.743	13426
Tomato					
Aomori	September	0.485	−825.20 **	−2.263 **	24897
Aomori	October	0.187	−78.96	0.617	2090
Chiba	September	0.054	−76.24	−0.296	3781
Chiba	October	0.539	−321.29 ***	−0.558	9419
Fukushima	September	0.034	84.71	0.286	−443
Fukushima	October	0.061	−71.33	−0.076	2663
Hokkaido	September	0.027	−78.09	0.715	6933
Hokkaido	October	0.149	86.46	−2.533	2893
Kumamoto	October	0.367	41.47 **	0.088	−635

(p=0.150 and p=0.142, respectively) and non-significant in October.

No significant relationship was found between the annual imports and prices in September and October for either 2023 or 2024. However, the result for 2024 showed that higher imports led to higher prices, although this tendency was marginally non-significant (P=0.164) (Table 3, Fig. 6).

5. Discussion

The results indicate that the summer heatwaves of 2023 affected the supply of certain vegetables (carrot, Japanese radish and tomato in particular) from domestic production areas to Tokyo. This led to a decline in the volume of the vegetables arriving in the city and a rise in their price for urban consumers. For these vegetables, the negative impact of high temperatures in August or September on arrival volumes the following month was evident in at least one producing prefecture. However, although price increases were more prevalent in 2024 than in 2023, affecting 14 out of 15 vegetables, there were no markable changes in arrival volumes from domestic production areas. Only tomato was accompanied by a decline in arrival volumes. The slightly lower temperatures in August and September of 2024 compared to 2023 can partly explain the smaller impact on arrival volumes for many vegetables and prefectures in 2024. The changes in imports may be linked to the price increases that occurred in 2024. The findings of this study provide valuable information for the growing body of literature on the threat that extreme climate events pose to agri-food systems worldwide (Kotz *et al*., 2025).

The decrease in arrival volumes occurred in 2023 or 2024 is probably due to a decline in the quality of the harvests (meaning that the vegetables harvested do not meet the market standards and are not shipped to cities, including Tokyo). Although not in 2023 or 2024, the cloudy and rainy weather in Ibaraki and Nagano in 2016 caused damage and reduced the size of the harvests, resulting in lower-than-normal arrival volumes in Tokyo (Agriculture & Livestock Industries Corporation, 2025).

Extreme climate events had a direct impact on harvests and producers in agricultural areas, which then had an indirect effect on cities by reducing urban consumers' economic access to perishable food, as shown in this study. It is also worth noting that the extreme climate events cooccurred alongside unpreferable economic conditions. Although the share of household expenditure on vegetables is small, the rise in vegetables' price occurred during the event that the share of household expenditure on food (or the Engel coefficient) in Japan reaching its highest level since 2000 at 27.8% in 2023 (Statistics Bureau of the Ministry of Internal Affairs and Communications, 2024).

Research to increase the tolerance of individual vegetable species to extreme climate events, particularly high temperatures, is encouraged, as literature are currently limited (e.g., Shimoda *et al.*, 2018; Suzuki, 2019; Ohara and Okada, 2020a; 2020b; Zhao *et al.*, 2025). Research also needs to consider ways of reducing heat stress for agricultural workers (de Lima *et al.*, 2021). Collaborative research between private and public sectors is especially important since breeding and seed production of vegetables are mainly conducted by private sector

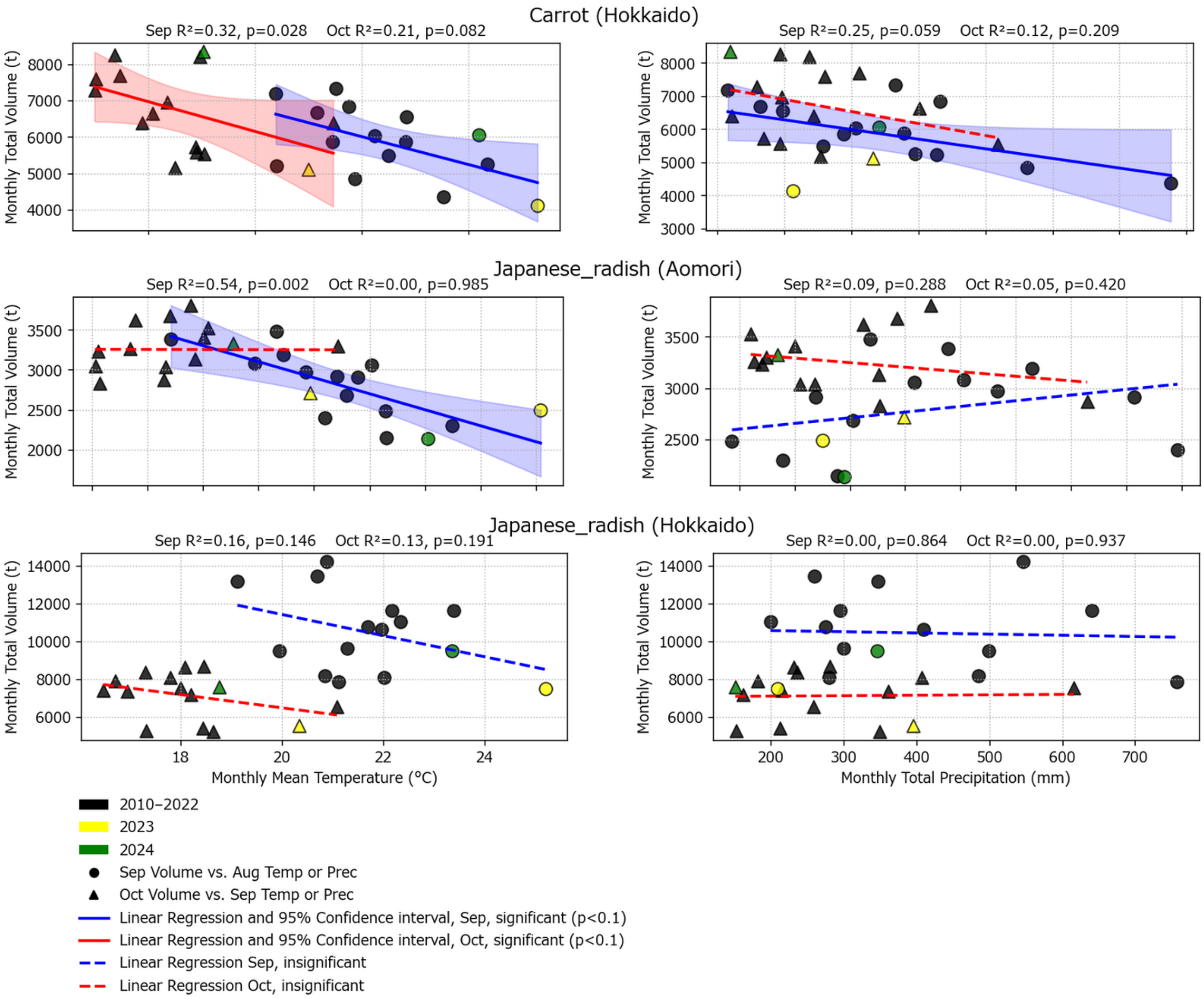

Fig. 3. Response of the monthly total arrival volume of carrot (upper panels) and Japanese radish (middle and lower panels) to the monthly mean temperature (left panels) and the monthly total precipitation (right panels). The total arrival volumes in September and October are plotted against the weather conditions in August and September, respectively.

(Schreinemachers *et al.*, 2017; Nishikawa and Pimbert, 2022).

6. Conclusions

We reported the vegetable supply disruptions in Tokyo occurred in September and October of 2023 and 2024. In both years, the June-August temperatures in Japan were on an unprecedented level, while the precipitation conditions showed relatively less markable deviations from the long-term averages. The high temperatures in August and September decreased arrival volumes the following month at the wholesale markets in Tokyo for some vegetables. Carrot, Japanese radish and tomato were such vegetables. The impact of high temperatures on arrival volumes was prominent in 2023 but not in 2024. However, price increases were more widespread in 2024 than in 2023, suggesting that non-climatic factors would play a greater role in 2024. The findings of this study point to the need for improvements in domestic vegetable production systems to be more heat tolerant for producers, food manufacturers and urban consumers.

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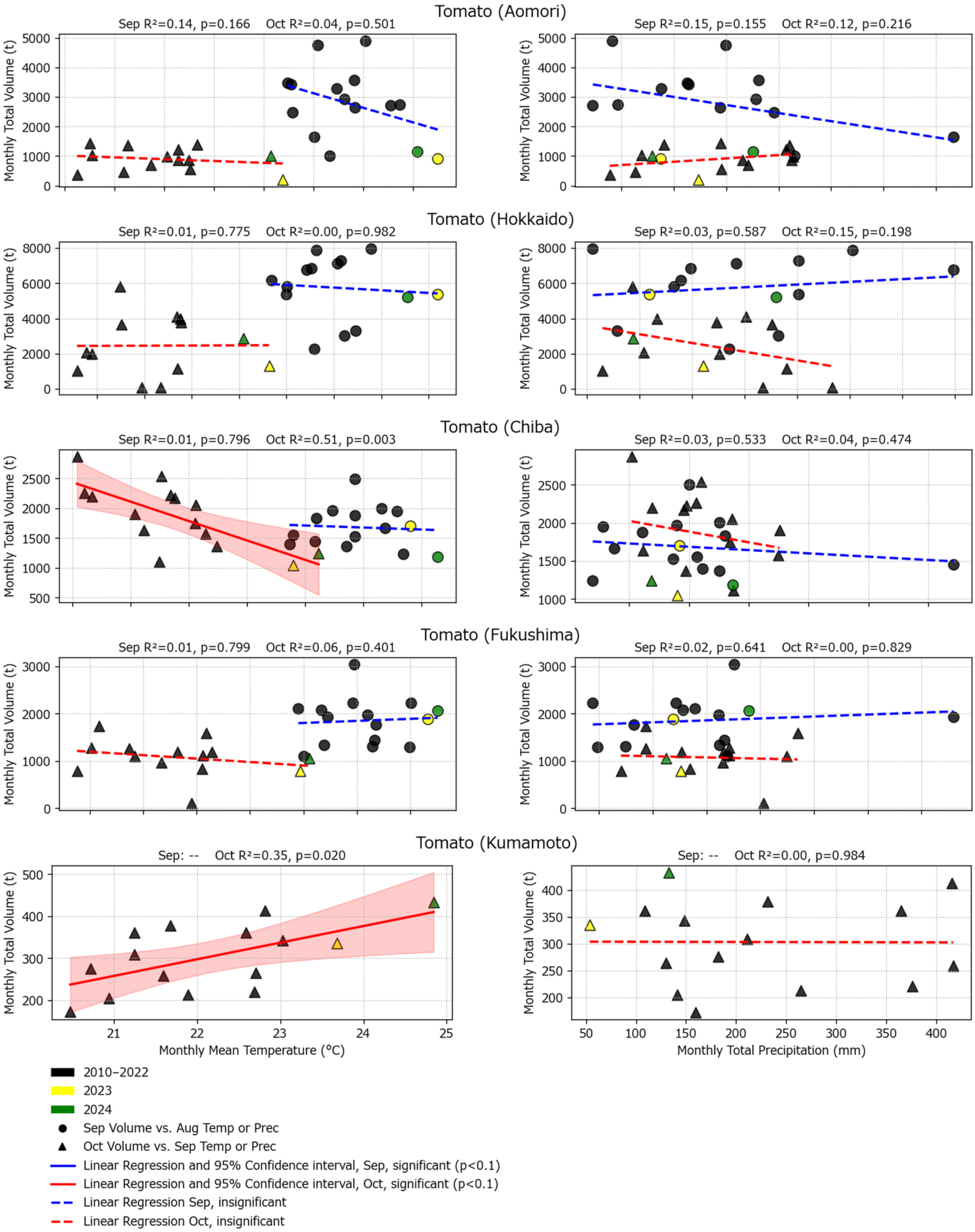

Fig. 4. Same as Fig. 3 but for tomato.

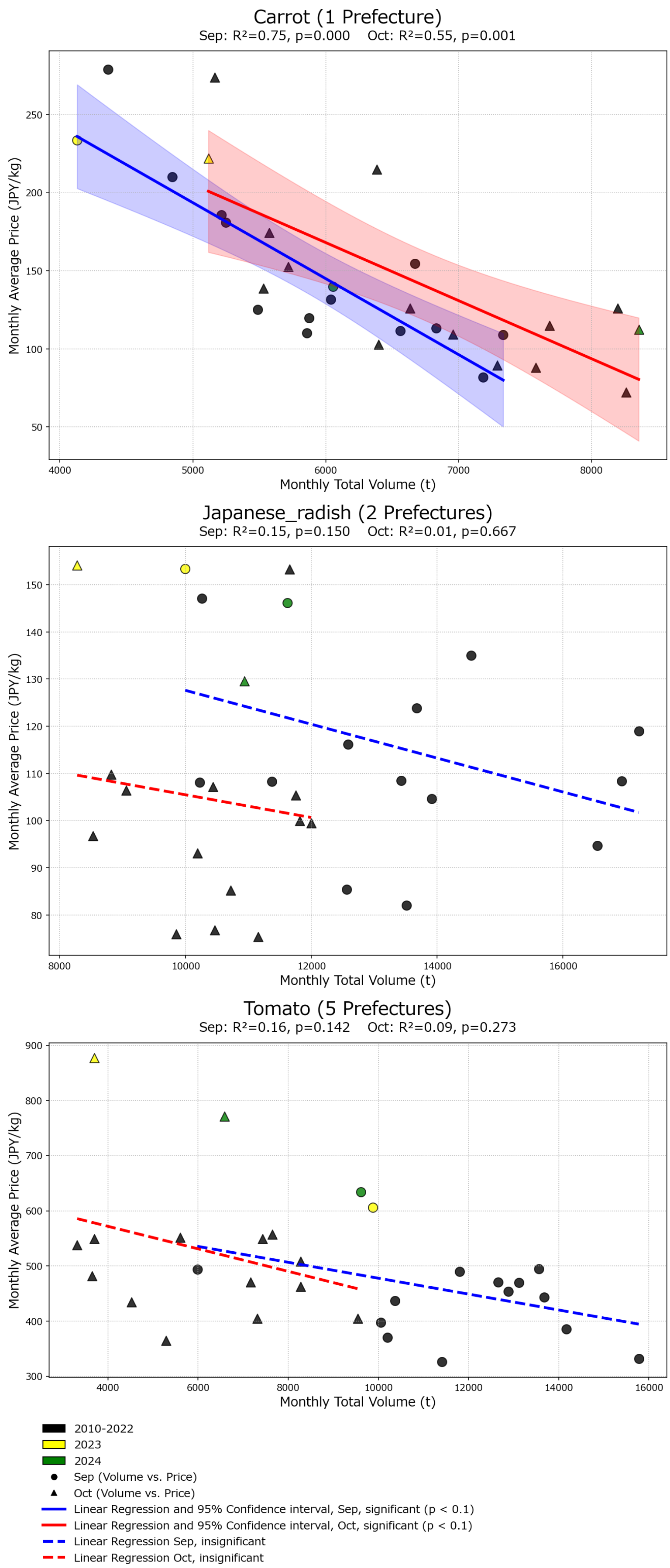

Fig. 5. Response of the monthly mean price of carrot, Japanese radish, and tomato to the monthly total arrival volume. The prices in September and October are plotted against the total arrival volumes in the same month.

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Table 3. Average volume of imports for the 2010–2022 period and changes in imports (fresh, refrigerated, dried) in 2023 and 2024. No data are available for eggplant, lettuce, and spinach. The data for Japanese radish and sweet pepper are represented by those of the aggregated category "salsify, radish, and other edible roots" and "jumbo bell pepper", respectively.

Vegetable	Average of 2010–2022 (t)	Change in 2023 (%)	Change in 2024 (%)
Broccoli	22,162	−90.1	−92.0
Cabbage	32,964	−64.4	−31.5
Carrot	81,414	9.5	13.4
Chinese Cabbage	2,499	−77.3	−49.2
Cucumber	19	−10.5	−76.7
Japanese Radish	49,138	−12.1	−8.2
Onions	299,225	−19.4	−10.2
Potatoes	24,565	59.5	45.2
Sweet pepper	35,212	−28.9	−44.1
Taro	5,384	−72.1	−59.2
Tomato	7,139	−23.0	−42.5
Welsh onion	54,568	4.9	9.0

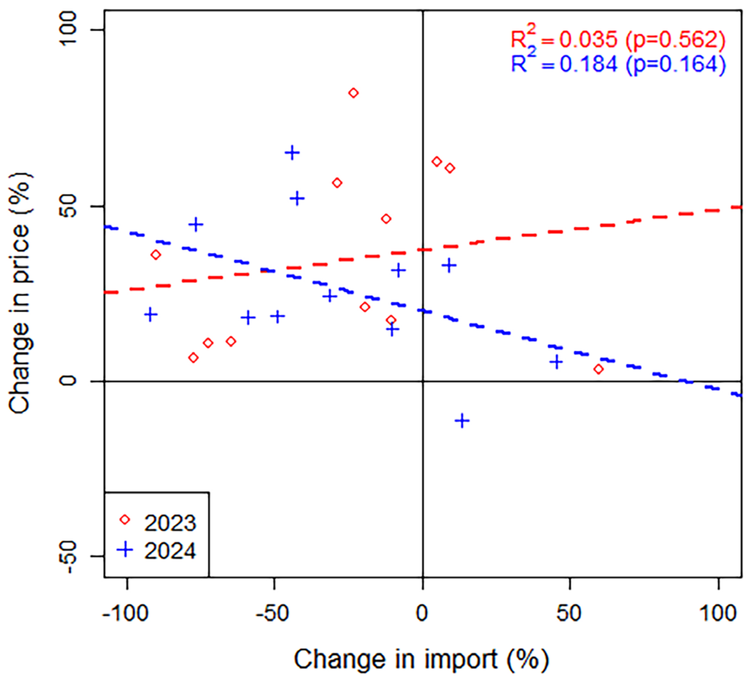

Fig. 6. Relationship between changes in annual imports and changes in average prices in September and October for 2023 (red) and 2024 (blue). The dashed lines show the regression lines.

References

Agriculture & Livestock Industries Corporation, 2025: *Monthly supply and demand trends*. https://vegetable.alic.go.jp/yasaijoho/index.html (accessed 1 April 2025)

Chambers JM, Hastie TJ, 1992: *Statistical Models in S*. Wadsworth & Brooks, New York, pp. 608.

de Lima CZ, Buzan JR, Moore FC, *et al.*, 2021: Heat stress on agricultural workers exacerbates crop impacts of climate change. *Environmental Research Letters* **16**, 044020. https://doi.org/10.1088/1748-9326/abeb9f

Dodman D, Hayward B, Pelling M, *et al.*, 2022: Cities, settlements and key infrastructure. In *Climate Change 2022: Impacts, Adaptation and Vulnerability* (ed. by Pörtner H-O, Roberts DC, Tignor M, *et al.*), Cambridge Univ. Press, Cambridge, pp. 907–1040. https://doi.org/10.1017/9781009325844.008

Duncan G, 2024: *Wet weather pushes wholesale veg prices by up to 66%* https://www.thegrocer.co.uk/news/wet-weather-pushes-wholesale-veg-prices-by-up-to-66/691872.article (accessed 1 April 2025)

Gaupp F, 2020: Extreme events in a globalized food system. *One Earth* **2**, 518–521. https://doi.org/10.1016/j.oneear.2020.06.001

Gomez M, Mejia A, Ruddell BL, *et al*., 2021: Supply chain diversity buffers cities against food shocks. *Nature* **595**, 250–254. https://doi.org/10.1038/s41586-021-03621-0

Ito K, Dyck J, 2002: *Vegetable Policies in Japan*. Economic Research Service, United States Department of Agriculture. https://www.ers.usda.gov/publications/pub-details?pubid=39486 (accessed 3 August 2024)

Kotz, M, Donat MG, Lancaster T, *et al*., 2025: Climate extremes, food price spikes, and their wider societal risks. *Environmental Research Letters* **20**, 081001. https://doi.org/10.1088/1748-9326/ade45f

Long Y, Yoshida Y, Kajikawa Y, 2024: Extreme heat disproportionately exacerbates health issues by threatening fresh food supply. *Nature Climate Chang* **14**, 1109–1111. https://doi.org/10.1038/s41558-024-02172-2

MAFF, 2024: *The situation regrading vegetables*. https://www.maff.go.jp/j/seisan/ryutu/yasai/attach/pdf/index-93.pdf (accessed 21 July 2024)

Nakazawa M, 2024: *fmsb: Functions for Medical Statistics Book with some Demographic Data*. https://minato.sip21c.org/msb/ (accessed 5 August 5, 2024)

National Institute of Vegetable and Tea Science, 2009: *Cropping type catalog for each type of vegetable*. https://www.naro.go.jp/publicity_report/publication/archive/files/yacya_shiryou_5.pdf (accessed 20 June 2025)

Nishikawa Y, Pimbert M, 2022: *Seeds for Diversity and Inclusion*. Palgrave Macmillan Cham, Cham, pp. 199. https://link.springer.com/book/10.1007/978-3-030-89405-4

Ohara G, Okada K, 2020a: An attempt to identify the production situations for major open-field vegetables. *Climate in Biosphere* **20**, 67–75. https://doi.org/10.2480/cib.J-20-047

Ohara G, Okada K, 2020b: An impact evaluation of global warming on market arrival based on the identification of production situations for major open-field vegetables in Japan. *Climate in Biosphere* **20**, 107–116. https://doi.org/10.2480/cib.J-20-046

Ohno H, Sasaki K, Ohara G, *et al*., 2016: Development of grid square air temperature and precipitation data compiled from observed, forecasted, and climatic normal data *Climate in Biosphere* **16**, 71–79. https://doi.org/10.2480/cib.J-16-028

R Core Team 2024: *R: A Language and Environment for Statistical Computing*. https://www.r-project.org/ (accessed 5 August 5, 2024)

Sato H, Takemura K, Ito A, *et al*., 2024: Impact of an unprecedented marine heatwave on extremely hot summer over Northern Japan in 2023. *Scientific Reports* **14**, 16100. https://doi.org/10.1038/s41598-024-65291-y

Schreinemachers P, Rao KPC, Easdown W, *et al*., 2017: The contribution of international vegetable breeding to private seed companies in India. *Genetic Resources and Crop Evolution* **64**, 1037–1049. https://doi.org/10.1007/s10722-016-0423-y

Seto KC, Ramankutty N, 2016: Hidden linkages between urbanization and food systems *Science* **352**, 943–945. https://doi.org/10.1126/science.aaf7439

Shimoda S, Kanno H, Hirota T, 2018: Time series analysis of temperature and rainfall-based weather aggregation reveals significant correlations between climate turning points and potato (*Solanum tuberosum L*) yield trends in Japan. *Agricultural and Forest Meteorology* **263**, 147–155. https://doi.org/10.1016/j.agrformet.2018.08.005

Statistics Bureau of the Ministry of Internal Affairs and Communications, 2024: A Summary of Average Result 2023 of Household Survey Report (Household Income and Expenditure). https://www.stat.go.jp/data/kakei/sokuhou/tsuki/pdf/fies_gaikyo2023.pdf (accessed 22 July 2024)

Suzuki K, 2019: Physiological disorders and their management in greenhouse tomato cultivation at high temperatures. In *Adaptation to Climate Change in Agriculture* (ed. by Iizumi T, Hirata R, Matsuda R). Springer, Singapore, pp. 81–96. https://doi.org/10.1007/978-981-13-9235-1_6

Takemura K, Sato H, Ito A, *et al*., 2024: Preliminary diagnosis of primary factors for an unprecedented heatwave over Japan in 2023 summer. *SOLA* **20**, 69–78. https://doi.org/10.2151/sola.2024-010

Tchonkouang RD, Onyeaka H, Nkoutchou H, 2024: Assessing the vulnerability of food supply chains to climate change-induced disruptions. *Science of The Total Environment* **920**, 171047. https://doi.org/10.1016/j.scitotenv.2024.171047

Tokyo Climate Center, 2024: *Climate characteristics and factors behind extremely high temperatures from July onward and heavy rainfall in late July 2024*. https://www.data.jma.go.jp/tcc/data/news/press_20241018.pdf (accessed 31 March 2025)

Tokyo Metropolitan Central Wholesale Market Network, 2024: *Wholesale Market Guide*. https://www.english.metro.tokyo.lg.jp/w/016-101-003986 (accessed 29 July 2024)

Tokyo Metropolitan Government, 2024: Tokyo's History, Geography, and Population. https://www.english.metro.tokyo.lg.jp/documents/d/english/tokyo-city-profile-and-government_2023-pdf-1 (accessed 29 July 2024)

United Nations Department of Economic and Social Affairs, 2018: *Revision of World Urbanization Prospects*. https://population.un.org/wup/ (accessed 3 August 2024)

Wong C, 2023: Earth just had its hottest year on record – climate change is to blame *Nature* **623**, 674–675. https://doi.org/10.1038/d41586-023-03523-3

Xia L, Robock A, Scherrer K, *et al*., 2022: Global food insecurity and famine from reduced crop, marine fishery and livestock production due to climate disruption from nuclear war soot injection. *Nature Food* **3**, 586–596. https://doi.org/10.1038/s43016-022-00573-0

Yang H, Cao Y, Shi Y, *et al*., 2022: The dynamic impacts of weather changes on vegetable price fluctuations in Shandong province, China: An analysis based on VAR and TVP-VAR models. *Agronomy* **12**, 2680. https://doi.org/10.3390/agronomy12112680

Zhao R, Zhao C, Xiao Y, *et al*., 2025: Real-time emulation of leafy vegetables yield and quality response to 2°C warming in northeast China. *Journal of the Science of Food and Agriculture*. https://doi.org/10.1002/jsfa.14427