Spatiotemporal heterogeneities in water and land appropriations related to food losses and waste in China

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Abstract

Fast-growing food losses and waste (FLW) have caused major environmental issues, yet little is known about the role of trade in the inefficient resource consumption related to FLW. In this study, we estimated the inter-annual water footprints (WFs) and land footprints (LFs) related to FLW in consideration of associated inter-provincial virtual water (VW) and virtual land (VL) flows within China from 2000 to 2017. Additionally, differences between eating at home and out in rural and urban regions were distinguished. The FLW-related WF and LF showed 1.5- and 1.2-fold increasing trends, respectively, over the study period. Eating at home in rural regions caused the most FLW and associated water and land appropriations. Both FLW-related gross inter-provincial VW and VL flows increased by 99% and 22% during the study period, respectively, and inter-provincial VW and VL flows in corresponding FLW-related WF and LF differed significantly. In addition, food losses were found to cause more inefficient resource consumption than food waste. This analysis shows that the substantial role of FLW in shaping the intra-national food-related VW and VL networks, and that the policies for FLW diminution at the food supply chain stage are as important as those at the consumption stage.

1. Introduction

Global food security has been dramatically affected by climate change and COVID-19, with approximately 12% of the global population suffering severe food insecurity in 2020 (FAO et al 2021). Globally, approximately one-third of food has been lost or wasted each year (Gustavsson et al 2011). Food losses before reaching the retail level account for approximately 14% of food production (FAO 2019). Food waste in households, restaurants, and other food services accounts for up to 17% of the total available food (UNEP 2021). Reducing food losses and waste (FLW) is an explicit requirement for sustainable development goal (SDG) 12 (responsible consumption and production) (UN 2015). Additionally, reducing FLW is also of great significance for ensuring food and nutrition security, improving environmental sustainability, and conserving natural resources, all of which are closely related to SDG two (zero hunger), three (good health and well-being), and six (clean water and sanitation) (Marston et al 2021, Xue et al 2021).

FLW causes inefficient natural resource consumption alongside serious conflicts between agriculture and other sectors on water and land (Chen et al 2020, Ortiz-Gonzalo et al 2021). Global annual food waste accounts for 24% and 28% of global crop water use and arable land, respectively (FAO 2013). There is enormous potential in mitigating environmental impacts by reducing FLW (Foley et al 2011, Springmann et al 2018, Marston et al 2021). Mekonnen and Fulton (2018) found that reducing FLW resulted in the largest potential reduction in the water footprint (WF) compared to a dietary shift in the United States.
(U.S.) food system. Read et al (2020) proposed that halving FLW could reduce the environmental impact of the U.S. food system by 8%–10%.

Both intensified inter- and intra-national virtual water (VW) and virtual land (VL) flows embedded in food trade have been driven by the growing food demand and increasingly diverse diets across the world (Dalin et al 2012, Wein泽t et al 2013, D’Odorico et al 2019, Liu et al 2019a, 2021a). Currently, 24% of the global WF and LF in food production have formed the corresponding international food-related VW (Carr et al 2013) and VL trade (Wein泽t et al 2013), respectively. However, most existing studies did not consider the VW and VL flows related to FLW. Little is known regarding the contribution of FLW to interregional water and land resource consumption and redistribution by trade. Therefore, this study aims to explain and clarify the VW and VL flows related to FLW from a macroscopic perspective, which provide an important basis for optimising the trade and planting structure under finite water and land resources.

As the most populous country, China faces increasing food demand and environmental pressures. Although northern China currently only has 20.4% of nature water resources, it includes 54.1% of crop harvested land, accounting for 64.6% of national total crop production (NBSC 2022). This spatial mismatch between water and land for crops has further increased in past decades (Dalí et al 2014, Zhao et al 2015, D’Amour et al 2017, Ji et al 2022). Despite increasing food demands, the Chinese government has set strict redlines, with the upper limits of national total agricultural water use at 670 billion m$^3$ yr$^{-1}$ and arable lands at 120 million hectares by the middle of the 21st century (SCPRC 2010). Simultaneously, a national self-sufficiency target of staple food crops has also been set (SCIOPRC 2019). Recent studies also warned of the increasingly visible FLW and associated environmental consequences (Cattaneo et al 2020, Xue et al 2021). Apparently, research into the environmental issues associated with FLW is urgently needed. Compared to those conducted in developed countries, such as the U.S. and European countries, relevant studies in China have primarily focused on individual provinces, and data sources include field surveys (Lang et al 2020, Luo et al 2020, Xu et al 2020, Li et al 2021), the China Health and Nutrition Survey database (Song et al 2015, Min et al 2020, Qi et al 2020), and other literature (Liu et al 2013, Liu 2014, Zhang et al 2018). Research objects include college canteens (Wu et al 2019), eating at restaurants in urban regions (Filimonau et al 2020, Lang et al 2020), and eating at home in rural regions (Li et al 2021). For example, Xu et al (2020) investigated food waste in 170 restaurants in the cities of Beijing and Lhasa and showed that greater food variety caused less food waste and larger food portions caused more food waste. Li et al (2021) used a direct weighing method to survey the rural household food waste in Shandong province and analysed its characteristics and driving factors. It was found that the average rural household food waste generation was 8.74 g cap$^{-1}$ meal$^{-1}$ and up to 90% of plant-based food was wasted, of which nearly half was vegetable waste. Liu et al (2013) reported that the total WF and LF related to FLW in 2010 were 135 ± 60 billion m$^3$ yr$^{-1}$ and 26 ± 11 million ha yr$^{-1}$, respectively. Song et al (2015) showed that the average person wasting food at home (16 kg) caused 18 m$^3$ and 173 gm$^2$ of water and ecological footprints, respectively. Based on surveys and literature reviews, Xue et al (2021) calculated the relevant resource and environmental footprints associated with FLW from farm to fork. However, the widely shown spatial and temporal differences in the WF and LF within the country (Zhuo et al 2016a, Mao et al 2021, Liu et al 2021b) were not considered, which may have caused serious over- or under-estimations that misled the relative policy implementations.

To address the knowledge gaps mentioned above, this study focused on the case for China, with quantification of the FLW-related WFs, LFs, inter-provincial VW and VL flows. The analysis covers 22 agricultural products (including 18 crops and 4 animal products; table 1) in 31 provincial-level administrative regions in mainland China (figure 1) over the study period 2000–2017. The considered crops and animal products contributed to 90.0% and 98.7% of total corresponding production, respectively, in China by the year 2017 (NBSC, National Bureau of Statistics of China 2022). The proportion of considered food consumption in the national total was 81.2% in 2017 (FAOSTAT 2022). The differences between urban and rural regions and eating at home and out were also distinguished. This study applies the definition of FLW according to Gustavsson et al (2011). Food loss refers to the loss of food (or raw materials) caused by technology, equipment, and other non-subjective behavioural factors that occur during postharvest handling and storage, processing and packaging, and distribution stages. Food waste could have been avoided under the current conditions due to unreasonable consumption and behaviour as well as the lack of subjective consciousness, such as enthusiasm for saving food.

2. Methods and data

2.1. FLW estimation

FLW is equal to the sum of food loss and food waste. This study estimated FLW in urban and rural regions and distinguished between eating at home and eating out. Taking FLW in eating out in the urban region as an example, the calculation formulae were as follows:

\[
FL_i = (P_i + I_i - E_i) \times (h_i + l_i \times f_{\text{proc}} + b_i \times f_{\text{consum}}),
\]

(1)
Figure 1. Population and structure at the provincial level in China (2017).

\[ FW_i = (P_i + I_i - E_i - FL_i) \times up_i \times uw \times w, \]  
\[ LFL_i = ULF_i \times FL_i [local] + ULF_j \times FL_j [import], \]  
\[ LFW_i = ULF_i \times FW_i [local] + ULF_j \times FW_j [import]. \]

where FL\(_i\) and FW\(_i\) (t yr\(^{-1}\)) are the food losses and food waste of eating out, respectively, in the urban region in province \(i\); \(P_i\), \(I_i\), and \(E_i\) (t yr\(^{-1}\)) are the production, import, and export volumes in province \(i\), respectively; \(l_1\), \(l_2\), and \(l_3\) are the loss rates during postharvest handling and storage, processing, and the distribution stage, respectively; \(f_{i, proc}\) and \(f_{i, consum}\) are the proportions of food processing and food consumption to the food supply, respectively; \(up_i\) represents the proportion of the urban population in province \(i\); \(uo\) is the ratio of people eating out in urban regions; \(w\) is the waste rate of eating out.

2.2. WF and LF accounting related to FLW
The WF and LF related to FLW (WFL\(_i\) and LFL\(_i\), m\(^3\) yr\(^{-1}\) and ha yr\(^{-1}\), respectively) are the sum of the WF and LF related to food loss and food waste, which is quantified by multiplying the corresponding unit WF and LF of product and the amount of food losses (WFL\(_i\) and LFL\(_i\), m\(^3\) yr\(^{-1}\) and ha yr\(^{-1}\), respectively) and food waste (WF\(_W\) and LFW\(_i\), m\(^3\) yr\(^{-1}\) and ha yr\(^{-1}\), respectively)

\[ WFL_i = UWF_i \times FL_i [local] + UWF_j \times FL_j [import], \]  
\[ WFW_i = UWF_i \times FW_i [local] + UWF_j \times FW_j [import]. \]

Here, UWF, and ULF (m\(^3\) t\(^{-1}\) and ha t\(^{-1}\)) are the unit WF and LF of the product in import province \(i\); UWF\(_j\) and ULF\(_j\) (m\(^3\) t\(^{-1}\) and ha t\(^{-1}\)) are the unit WF and LF of the product in export province \(j\); FL\(_i\) [local] (t yr\(^{-1}\)) and FW\(_i\) [local] refer to local FL and FW, respectively (local production minus export volume); and FL\(_j\) [import] (t yr\(^{-1}\)) and FW\(_j\) [import] refer to the FL and FW embedded in the import volume, respectively.

The unit WF of crops is calculated using the fast track method (Tuninetti et al 2017), which has been extensively used (Dalin et al 2012, Gao et al 2020, Tuninetti et al 2020, Ma et al 2021, Liu et al 2021b). The method has been demonstrated to be acceptable at a global scale (with a standard deviation of the error of approximately 0.1) (Tuninetti et al 2017) and a national scale (with a difference between the FastTrack and WF assessment manual method within 20% in China) (Gao et al 2020). The weighted average unit WF of the crop was obtained from Mekonnen and Hoekstra (2011):

\[ UWF_{c,i,t} = \frac{UWF_{c,i,96-05} \times Y_{c,i,96-05}}{Y_{c,i,t}}, \]
where \( \text{UWF}_{a,i,t} \) (m\(^3\) t\(^{-1}\)) is the unit WF of crop \( c \) in year \( t \) of province \( i \); \( \text{UWF}_{c,i,96-05} \) (m\(^3\) t\(^{-1}\)) is the weighted average unit WF of crop \( c \) from 1996 to 2005 in province \( i \); \( Y_{c,i,t} \) (t ha\(^{-1}\)) is the yield of crop \( c \) in year \( t \) of province \( i \); and \( Y_{c,i,96-05} \) (t ha\(^{-1}\)) is the weighted average yield of crop \( c \) from 1996 to 2005 in province \( i \).

The total WF of animal products is composed of feed crop WF, which accounts for 98% of the total WF, service water, and drinking water consumed (Mekonnen and Hoekstra 2010). The feed conversion efficiency of the animal, feed composition, and feed origin are predominant in the WF of the animal, and the production system influences these three factors (Mekonnen and Hoekstra 2010). In this context, this study considered the animal productivity and feed conversion ratio (Bouwman et al. 2005, Zhuo et al. 2016b, Liu et al. 2021b):

\[
\text{UWF}_{a,i,t} = \frac{\text{UWF}_{a,i,96-05} + \Delta \text{UWF}_{a,i,t}}{1 + \Delta \text{AP}_{a,i,t}} \times \left(1 + \Delta \text{FCR}_{a,i,t}\right) \tag{8}
\]

\[
\Delta \text{UWF}_{a,i,t} = \sum_f \left[ \left( \text{UWF}_{a,i,96-05} \times m_f \%ight) - \left(Y_{f,i,96-05} - Y_{f,i,t}\right) \right], \tag{9}
\]

where \( \text{UWF}_{a,i,t} \) (m\(^3\) t\(^{-1}\)) is the unit WF of animal product \( a \) in year \( t \) of province \( i \); \( \text{UWF}_{a,i,96-05} \) (m\(^3\) t\(^{-1}\)) is the weighted average unit WF of animal product \( a \) from 1996 to 2005, which is obtained from Mekonnen and Hoekstra (2010); \( \Delta \text{UWF}_{a,i,t} \) represents the change in the main feed crop consumed for animal product \( a \) in year \( t \) of province \( i \) compared to the period 1996–2005; \( \Delta \text{AP}_{a,i,t} \) and \( \Delta \text{FCR}_{a,i,t} \) are the rates of change in animal productivity and feed consumption ratio of animal product \( a \), respectively, in year \( t \) of province \( i \) compared with the weighted average value over the period 1996–2005 (Mekonnen and Hoekstra 2012); and \( Y_{f,i,96-05} \) and \( Y_{f,i,t} \) (t ha\(^{-1}\)) are the weighted average yields from 1996 to 2005 and year \( t \) of feed crop \( f \) in province \( i \), respectively.

The LF is the land required to produce a product (Borucke et al. 2013). The unit LF of a crop product (ULF\(_{c,i,t}\)) (ha t\(^{-1}\)) is equal to the reciprocal of the yield (\( Y_{c,i,t} \), t ha\(^{-1}\)):

\[
\text{ULF}_{c,i,t} = \frac{1}{Y_{c,i,t}}. \tag{10}
\]

The LF of animal products includes grazing land and cropland for animal feed (Bosire et al. 2015):

\[
\text{ULF}_{a,i,t} = \frac{\text{TLF}_{a,i,t}}{W_a \times R_{a,i,t}}, \tag{11}
\]

\[
\text{TLF}_{a,i,t} = \frac{S_{a,t}}{L_{D,a,i,t}} + \sum_f A_{f,i,t} \times \omega_{f,a,i,t}. \tag{12}
\]

Here, \( \text{ULF}_{a,i,t} \) and \( \text{TLF}_{a,i,t} \) (ha t\(^{-1}\) and ha yr\(^{-1}\)) represent the unit LF and total LF of animal \( a \) in year \( t \) of province \( i \), respectively; \( W_a \) (t head\(^{-1}\)) is the mean live weight of animal \( a \) (FAO 2003); \( R_{a,i,t} \) and \( S_{a,t} \) are the stock of animals in the units of head yr\(^{-1}\) and LSU yr\(^{-1}\), respectively (Chilonda and Otte 2006, FAOSTAT 2022); \( L_{D,a,i,t} \) (LSU ha\(^{-1}\)) is the density of animal products in the agricultural area, which is derived from the Statistics Division of Food and Agriculture Organization of the United Nations (FAOSTAT 2022); \( A_{f,i,t} \) (ha yr\(^{-1}\)) is the planting area of forage crop required to raise animal products; and \( \omega_{f,a,i,t} \) is the proportion of feed consumption for animal \( a \) of feed crop \( f \) in total feed crop consumption, which is influenced by the number of animals and the structure of their diet.

\[
A_{f,i,t} = A'_{f,i,t} \times f_{f,i,t}, \tag{13}
\]

\[
f_{f,i,t} = \frac{\text{FCR}_{f,i,t}}{P_{f,i,t} + f_{f,i,t} - E_{f,i,t}}, \tag{14}
\]

\[
\omega_{f,a,i,t} = \frac{S_{a,t} \times \alpha_{fa}}{\sum_a (S_{a,t} \times \alpha_{fa})}. \tag{15}
\]

Here, \( A'_{f,i,t} \) (ha yr\(^{-1}\)) is the total sowing area of the feed crop \( f \); \( f_{f,i,t} \) is the proportion of the consumption of crop \( f \) as animal feed (FCR\(_{f,i,t}\)) in total consumption of crop \( f \); \( \alpha_{fa} \) is the proportion of feed crop \( f \) in total feed crops (Mekonnen and Hoekstra 2010); and other parameters are the same as above.

### 2.3. Estimating inter-provincial VW and VL flow related to FLW

The VW flows related to FLW (VWL\(_{i,p}\)) are equal to the sum of the VW flows related to food losses (VWL\(_{i,p}\)) and waste (VWW\(_{i,p}\)), which refers to the product of the unit WF in producing regions and the corresponding VWL volume embedded in trade. The VL flows related to FLW were estimated in the same way:

\[
\text{VWL}_{i,p} = \text{VWI}_{i,p} \times \text{FL}_{i,p} |\text{trade}| + \text{UWF}_{i,p} \times \text{FW}_{i,p} |\text{trade}|, \tag{16}
\]

\[
\text{VLL}_{i,p} = \text{VLI}_{i,p} + \text{VWI}_{i,p} = \text{ULF}_{i,p} \times \text{FL}_{i,p} |\text{trade}| + \text{ULF}_{i,p} \times \text{FW}_{i,p} |\text{trade}|. \tag{17}
\]

Here, \( \text{UWF}_{i,p} \) (m\(^3\) t\(^{-1}\)) and \( \text{ULF}_{i,p} \) (ha t\(^{-1}\)) refer to the unit WF and LF of product \( p \) in province \( i \), respectively; and \( \text{FL}_{i,p} |\text{trade}| \) (t yr\(^{-1}\)) and \( \text{FW}_{i,p} |\text{trade}| \) (t yr\(^{-1}\)) denote the FL and FW in product trade, respectively.

The inter-provincial product trade volume is estimated with the optimal objective of minimizing transportation cost, and the constraint condition is the annual relationship between supply and demand.
for each crop (Dalín et al 2014, Wang et al 2019, Zhuo et al 2019). The detailed calculation can be seen in Zhuo et al (2019).

2.4. Data sources

Food loss rates in each food supply chain were obtained from Gustavsson et al (2011) (table S1 available online at stacks.iop.org/ERL/17/054020/mmedia), the ratios of people eating out were from Wang et al (2020) (table S4). The available data in Wang et al (2020) are for the years 2000, 2004, 2006, 2009, and 2011. For the other years, the ratios were obtained using linear interpolation. The waste ratios of eating out were derived from Wang et al (2017) and were identical in urban and rural regions. The waste ratios of eating at home in the rural region were reported by Li et al (2017), and the ratio in urban region was assumed to be 20% higher than that in the rural area (Li et al 2020). The detailed data is presented in the Supplementary Information. Food consumption, food processing, and feed were obtained from FAOSTAT (2022). Populations in urban and rural regions, agricultural production, and the amount of animal product raised data were obtained from the National Bureau of Statistics of China (NBSC 2022).

3. Results

3.1. Volume of FLW

The FLW volume in China increased from 165.5 to 277.8 million t yr$^{-1}$ in the period 2000--2017, accounting for a mean 14.9% increase in food consumption, of which FL and FW accounted for 80.8% and 19.2%, respectively (figure 2(a)). The largest proportion of the FLW volume of eating at home in rural regions (49.0% at national weighted average) declined, in contrast to the proportion of the FLW volume of eating at home in urban regions (42.5%). The FLW volume proportion of the eating out in rural (2.4%) and urban regions (6.2%) showed the same trend. Vegetables accounted for the most FLW (118 million t yr$^{-1}$ in 2017), followed by maize (33.7 million t yr$^{-1}$ in 2017) and rice (31.7 million t yr$^{-1}$ in 2017).

Among the provinces, Sichuan province accounted for the highest FLW from 2000 to 2017 (8.7%--8.2% of the total FLW) (figure 2(b)). Focusing on FL and FW separately, Henan and Sichuan caused the highest FL and FW, respectively, which were closely related to the food consumption and waste ratio. Henan, Shandong, Sichuan, and Guangdong provinces had the highest consumptions and large amounts of FL. Sichuan province had the highest FW, accounting for 16% of the total FW in China on average, which was caused by the high waste ratio and consumption. Other provinces such as Fujian, Gansu, and Jiangxi, had a high waste ratio but less FLW because of their low consumption. Comparing the amount of FLW between urban and rural regions in various provinces, the results showed that the urban FLW in economically developed provinces, such as Beijing, Tianjin, and Shanghai, were much higher than those in rural regions. In 2017, the urban FLW in Shanghai was 7.2 times higher than that in rural regions.

The national weighted average FLW per capita increased from 131.4 to 200.1 kg cap$^{-1}$ from 2000 to 2017. By the year 2017, the FLW per capita eating at home in rural regions was the highest (188.7 kg cap$^{-1}$ at national weighted average), followed by eating at home in urban regions (174.0 kg cap$^{-1}$), eating out in urban regions (24.6 kg cap$^{-1}$), and eating out in rural regions (13.6 kg cap$^{-1}$). The difference resulted from the increasing amount of FLW per capita. The volume of FLW per capita in rural regions was slightly larger than that in urban regions (figure S1). By food types, the volume of urban FLW per capita for meat, vegetables, and fruits was higher than the rural by 2017. The differences among crops were in alignment with the total FLW.

The FLW per capita increased in all provinces from 2000 to 2017 (figure 3). Among provinces, Inner Mongolia experienced the largest increase of 85.3% (figure 3(f)), with visible increases in both the urban population (by 54.9% over the study period) and its weight in total provincial population (from 43% to 62%) (NBSC 2022). In general, northwest China had a relatively higher FLW per capita, mainly due to the higher waste ratios of cereals (table S3). Tibet had both the highest FL (figures 3(a) and (b)) and the highest FW per capita (figures 3(c) and (d)), and thus the highest level of FLW per capita (figures 3(e) and (f)) among provinces. The higher per capita FL in Tibet was due to the higher crop production per capita with the smaller population size. The Tibetan higher per capita FW, which was the weighted average considering differences between the urban and rural regions, was a result of the much larger weight of urban population (~69% by 2017) and relative higher waste rates of cereals in its rural regions (table S3). In most provinces, the percentage of FLW per capita for vegetables and fruits was the most significant proportion.

3.2. WF and LF related to FLW

The WF related to FLW increased from 107.3 to 159.2 billion m$^3$ yr$^{-1}$ during the period 2000--2017, of which the blue WF accounted for 14.3%--13.5%. The WF (blue WF) related to food loss and food waste accounted for 9.3% (10.8%) and 2.2% (2.6%) of the total WF, respectively, in 2017 (figure 4(a)). Considering the location of food consumption, 50.2% of the WF related to FLW was sourced from at-home urban regions, followed by at-home rural regions (48.8%), out-of-home urban regions (8.8%), and out-of-home regions (8.2%) (figure 4(b)). The highest WF and LF from 2000 to 2017 (8.7%--8.2% of the total FLW) (figure 2(b)).
rural regions (4.9%) in 2017. Although the ratio of food waste of eating at home in urban areas is 20% higher than that in rural areas, the average larger population from 2000 to 2011 (NBSC 2022) defined more WF-related FLW in rural areas than in urban areas. With the growth of the affluent urban population, the WF related to FLW consumed at home in urban regions surpassed that at home in rural regions in 2012. In contrast to the amount of FLW, pork (26.6 billion m³ yr⁻¹) had the largest WF related to FLW of each product owing to the high unit WF of pork, followed by wheat (20.9 billion m³ yr⁻¹) in 2017 (table 1). The crop with the largest weighted average blue WF related to FLW was rice (6.4 billion m³ yr⁻¹) as rice had the highest proportion of the unit blue WF, and the highest proportion was observed in Xinjiang province (83%).

The LF related to FLW increased from 37.8 to 47.2 million ha yr⁻¹ from 2000 to 2017, accounting for 10.4%–10.8% of the total LF. The LFs related to food loss and food waste accounted for 80.6% and 19.4%, respectively, in 2017 (figure 5(b)). The distributions of the LF and WF related to FLW in different dining locations in urban and rural regions were the same. Among the agricultural products, chicken had the largest LF related to FLW (9.3 million ha yr⁻¹), followed by pork (5.9 million ha yr⁻¹), which was also caused by the difference in the unit LF.

As shown in figure 5(d), the WF related to FLW between each province showed a considerable difference and was very similar to the FLW. The highest WF related to FLW in 2017 occurred in Shandong province (12.5 billion m³ yr⁻¹), which differed from that in Sichuan province, which had the highest FLW. The highest levels of FLW in Shandong and Sichuan provinces were due to vegetable waste, accounting for 44% and 43.4% in 2017, respectively. However, the unit WF of vegetables in Shandong province (233.2 m³ t⁻¹) was nearly 1.9 times higher than that in Sichuan province (124.4 m³ t⁻¹) in 2017, causing a difference in the WF related to FLW. Shandong province had the highest total blue WF related to FLW from 2000 to 2017, followed by Xinjiang province. The share of agricultural water in China in Xinjiang province was 13.7% in 2017 (NBSC 2022), resulting in a high unit blue WF in Xinjiang province. The unit blue WF of vegetables in Xinjiang province was 10.5 times higher than in Shandong province in 2017.

Henan (7.3 million ha) and Guangdong (9.7 million ha) provinces had the highest LFs related to FLW in 2000 and 2017, which were caused by chicken (82.3%) and pork (59.3%), respectively. In 2017, the change in the LF related to FLW was the same as that related to FLW, except in Guangdong and Shanghai provinces. The consumption of pork and chicken in Guangdong and Shanghai provinces relied on international imports, accounting for 96.9% and 66.1% of China's total imports in 2017, respectively. Meanwhile, the LF per unit of pork and chicken at the global level was high, causing a high LF related to FLW.

The WF per capita related to FLW increased from 170.4 to 229.5 m³ cap⁻¹ from 2000 to 2017. In the different consumption locations, the WF per capita showed an upward trend. The WF per capita related to FLW in at-home rural regions was always at the highest level (86.6 m³ cap⁻¹) in the study period, followed by at-home urban regions (78.1 m³ cap⁻¹), out urban regions (14.8 m³ cap⁻¹), and out rural regions (7.5 m³ cap⁻¹). The highest WF per capita of pork increased from 25.8 to 38.1 m³ cap⁻¹. The LF per capita increased by 13.3% to 34 ha cap⁻¹. The LF per capita at home in urban regions outpaced that in at-home rural regions (from 25.0 to 31.2 ha cap⁻¹ and 27.9–26.9 ha cap⁻¹, respectively). In the eating out regions, the LF per capita in urban and rural regions were 4.9 and 4.1 ha cap⁻¹, with growth rates of 21.2% and 51.5%, respectively, in 2017. At 7.6, 5.3, and 4.0 ha cap⁻¹, pork, chicken, and wheat had the highest LFs per capita, respectively, in 2017.

In terms of the WF per capita related to FLW for each province, the spatial distribution was
similar to the FLW volume per capita, ranging from 29.8 m$^3$ cap$^{-1}$ (Hainan province in 2000) to 584.2 m$^3$ cap$^{-1}$ (Tibet province in 2015) (figure 5(a)). The blue WF per capita related to FLW in Xinjiang province (75.3 m$^3$ cap$^{-1}$) was the highest, followed by that in Inner Mongolia (40.0 m$^3$ cap$^{-1}$) (figure 5(c)). The largest LF per capita related to FLW in 2000 occurred in Shanxi province (127.8 ha 1000 cap$^{-1}$) (figure 5(b)). The LFs per unit of roots, soybean, and meat products in Shanxi province were relatively high, and the population was smaller than that of Henan province, resulting in the largest LF per capita related to FLW. The largest LF per capita related to FLW occurred in Shanghai province in 2017, caused by the LF of chicken. The LF per capita related to FLW in Shanghai province was high, with a high LF related to FLW and a small population.

Figure 3. Spatial distributions of food losses (FL), food waste (FW) and FLW per capita and structures by food types in 2000 and 2017.
Figure 4. Conversion between water footprint (WF; left) and land footprint (LF; right) of production and consumption in different dining locations, including eating at home and out in urban and rural regions (Uh, Uo, Rh, and Ro) in 2017.

3.3. Inter-provincial VW and VL flows related to FLW

The gross inter-provincial VW flows related to FLW increased from 34.0 to 67.8 billion m$^3$ yr$^{-1}$, accounting for 31.7%–42.6% of the WF related to FLW from 2000 to 2017. The proportion of gross blue VW flows in the gross VW flows related to FLW slightly decreased from 15.5% to 14.1%. The gross inter-provincial VL flows related to FLW increased from 22.7 to 27.7 million ha yr$^{-1}$, accounting for 60% to 58.7% of the LF related to FLW from 2000 to 2017. Over the study period, the VW and VL flows related to food losses accounted for 81.8% and 83.0%, respectively (figure S2). The same varying tendency under different consumption locations was found in VW and VL flows related to FLW. Among the crops, soybean and chicken contributed the most to VW and VL flows related to FLW (25.5% and 18.2%, respectively, in 2017).

The proportion of VW import in the WF related to FLW ranged from 13.8% (Jiangsu province in 2001) to 96.1% (Tibet province in 2015), which corresponded to the proportion of imports to total consumption related to FLW. The largest VW flow related to FLW occurred from Henan to Guangdong province in 2000 (1.36 billion m$^3$ yr$^{-1}$), caused by the transportation of wheat (70.7%) (figure 6(a)). The largest crop trade also occurred from Henan to Guangdong province; however, wheat and vegetables accounted for 50.3% and 37.4%, respectively. Because of the high unit WF of wheat, the VW flows related to the FLW of wheat were much higher than those of vegetables. The largest crop trade (from Guangxi to Guangdong province, that is, 10 million t yr$^{-1}$) was different from VW flows related to FLW (from Henan to Sichuan province, 1.42 billion m$^3$ yr$^{-1}$) in 2017 (figure 6(b)). This difference was also due to the difference in the unit WFs of vegetables and wheat.

In contrast to VW imports, the highest proportions of VL imports in the LF related to FLW occurred in Shanxi province in 2000 (91.5%) and Shanghai province in 2017 (98.7%) (figures 6(c) and (d)). As Shanxi province meets the consumption demand for international imports, this province was also the second-largest VL import province, whereas Henan was the province with the most VL import with 85.1% VL imports in the total LF related to FLW. The VL imports of Shanxi and Shanghai provinces were caused by the high unit LF of chicken at the global level. The largest VL flows related to FLW occurred in Henan to Hunan province and Henan to Guangxi province (0.44 and 0.40 million ha yr$^{-1}$), mainly caused by the VL flows of wheat in 2000 and 2017, accounting for 84.1% and 96.3%, respectively.

4. Discussion

This study quantified the WF, LF, inter-provincial VW and VL flows related to FLW with separation between different consumption locations in China. To the best of our knowledge, this is the first study to consider and elucidate the VW and VL flows related to FLW. The inter-provincial VW and VL flow related to FLW accounted for 42.6% and 58.7% of the WF and LF related to FLW in 2017 (67.8 billion m$^3$ yr$^{-1}$ and 27.7 million ha yr$^{-1}$). The results demonstrate that the environmental impacts caused by inefficient trade related to FLW are not negligible. In open economies and markets, trade plays a major role in the resource consumption related to FLW. The results showed that the weighted average WF and LF related to FLW were 123.9 billion m$^3$ yr$^{-1}$ and 38.0 million ha yr$^{-1}$, respectively. The result is of the same magnitude as that reported by Liu et al (2013), who showed that the total WF and LF related to FLW in China in 2010 were 135 ± 60 billion m$^3$ yr$^{-1}$ and 26 ± 11 million ha yr$^{-1}$, respectively. Xue et al (2021) showed that the FLW was 349 ± 4 million t yr$^{-1}$ in 2014–2018, and the WF and LF related to FLW were 580 ± 11 billion m$^3$ yr$^{-1}$ and 40 ± 0.4 million ha yr$^{-1}$, respectively.
### Table 1. Volumes of food losses and waste (FLW) associated water footprint (WF), and land footprint (LF) for each crop in 2017.

| Items                  | Representing crops | FLW (million t) | Food Consum. (million t) | Blue WFLW (billion m³) | WFLW (billion m³) | WF (billion m³) | LFLW (million ha) | LF (million ha) |
|------------------------|--------------------|-----------------|--------------------------|------------------------|-------------------|-----------------|-------------------|-----------------|
| Cerals                 | Wheat              | 18.6            | 137.4                    | 5.8                    | 20.9              | 133.0           | 5.5               | 25.5            |
|                        | Rice               | 31.7            | 213.4                    | 8.8                    | 24.3              | 153.6           | 4.5               | 31.3            |
|                        | Maize              | 33.7            | 264.1                    | 2.1                    | 23.9              | 187.4           | 6.1               | 43.2            |
|                        | Millet             | 0.2             | 1.7                      | 0.0                    | 0.2               | 1.8             | 0.1               | 0.6             |
| Roots                  | Potatoes           | 15.9            | 98.9                     | 0.1                    | 2.3               | 16.2            | 0.6               | 5.2             |
|                        | Sweet potatoes     | 9.7             | 71.8                     | 0.0                    | 2.1               | 14.8            | 0.4               | 3.2             |
| Sugar crops            | Sugar cane         | 10.8            | 113.9                    | 0.1                    | 1.2               | 16.8            | 0.1               | 1.5             |
|                        | Sugar beet         | 0.8             | 9.4                      | 0.0                    | 0.0               | 0.9             | 0.0               | 0.2             |
| Oil crops              | Soybeans           | 11.2            | 104.5                    | 0.7                    | 19.1              | 181.0           | 4.0               | 38.3            |
|                        | Groundnuts         | 1.3             | 16.5                     | 0.1                    | 1.5               | 18.7            | 0.4               | 4.6             |
|                        | Sunflower seed     | 0.2             | 2.3                      | 0.0                    | 0.3               | 4.5             | 0.1               | 0.9             |
|                        | Rapeseed           | 1.1             | 12.7                     | 0.1                    | 1.3               | 15.1            | 0.6               | 6.2             |
|                        | Sesame seed        | 0.1             | 1.0                      | 0.0                    | 0.6               | 6.1             | 0.2               | 1.6             |
| Vegetables & Fruits    | Vegetables         | 118.0           | 637.3                    | 0.7                    | 18.3              | 97.6            | 3.6               | 19.2            |
|                        | Citrus             | 6.8             | 38.8                     | 0.0                    | 1.3               | 10.0            | 0.4               | 2.5             |
|                        | Bananas            | 2.0             | 12.2                     | 0.0                    | 0.2               | 3.9             | 0.0               | 0.4             |
|                        | Apples             | 6.5             | 39.2                     | 0.1                    | 1.5               | 12.7            | 0.3               | 1.9             |
|                        | Grape              | 2.2             | 13.1                     | 0.0                    | 0.5               | 2.9             | 0.1               | 0.7             |
| Meat                   | Beef               | 0.6             | 8.2                      | 0.2                    | 6.0               | 79.1            | 0.7               | 9.6             |
|                        | Mutton             | 0.4             | 4.9                      | 0.1                    | 1.9               | 25.4            | 1.4               | 19.3            |
|                        | Pork               | 4.4             | 56.0                     | 2.0                    | 26.6              | 342.8           | 10.6              | 133.6           |
|                        | Chicken            | 1.6             | 18.2                     | 0.5                    | 5.4               | 62.4            | 7.4               | 86.7            |
| Total                  |                    | 277.8           | 1875.5                   | 21.5                   | 159.2             | 1386.9          | 47.2              | 436.2           |

FLW is the volume of food losses and waste. Consum is the food consumption. Blue WFLW and WFLW mean the blue and total water footprint of consumption related to FLW, respectively. WF and LF represent water and land footprint of consumption, respectively. LFLW is the land footprint of consumption related to FLW.
In contrast, the magnitude of results of this study is smaller than those of Xue et al (2021). The spatial heterogeneity of the WF and LF was not considered by Xue et al (2021), which is divergent from reality, and fish, seafood, and milk were also not considered. Owing to the limited availability of data, some inevitable assumptions were adopted in the present study. To identify the impact of different ratios used in the calculation process on the final result, the present study assumed that the FLW and eating out ratios increased by 20%, and the change in the final result was less than 10%, as shown in table 2. Hence, the results were considered reliable and acceptable.

The study showed that the largest volume of FLW occurred in rural households. However, FLW per capita of meat, vegetables and fruits in urban areas was greater than that in rural regions. Therefore, it is necessary to reduce FLW of both urban and rural residents. Although vegetables caused the most FLW, the related consumption of water and land resources was not serious. Conversely, animal products brought a high waste of resources, even if the FLW volume was low (Xue et al 2021). Therefore, measures to optimise the dietary structure by increasing intake of vegetables and fruits, which consume much less water for unit mass production (Hoekstra and Mekonnen 2012, Zhuo et al 2016a), and reducing meat or water- and land-intensive grain intake can be carried out to reduce the resource consumption caused by FLW. Furthermore, a reasonable diet structure is beneficial to human health, which is also beneficial for the environment (Tilman and Clark 2014).

Obviously, improving water and land use efficiency in agriculture has always been crucial to diminishing the environmental impact diminishes of FLW. The potential solutions to improve agricultural water use efficiency include promoting water-saving irrigation technologies, increasing investment in agricultural water-saving infrastructures, and reasonable agricultural water price compensation (Xue and Ren 2016, Berbel et al 2018, Yu et al 2021). In achieving higher agricultural land use efficiency, the potential measures include mechanisation in croplands and livestock feeding, and applications of advanced agricultural breeding techniques (Chen et al 2018, Ramankutty et al 2018, Fei et al 2021). Meanwhile, the circular economy represents a comprehensive framework for reducing FLW and associated natural resources occupation (Stahel 2016).

The FLW in the food supply chain accounted for a large proportion. The relevant departments should treat the development of infrastructure and the ‘Clear Your Plate’ campaign as equally important. This is also reflected in the Anti-Food Waste Law of the People’s Republic of China, which passed on 29 April 2021. In Tibet province, VW imports related to FLW
The proportion of inter-provincial virtual water (VWI) and land imports (VLI) in water footprint (WF) and land footprint (LF) related to food losses and waste (FLW), as well as the largest VW and VL flows in 2000 and 2017.

| Related ratios                              | FLW  | WFLW | LFLW |
|---------------------------------------------|------|------|------|
| Loss ratio at postharvest handling and storage stage | 9.68%| 9.14%| 7.37%|
| Loss ratio at processing and packaging stage | 0.91%| 1.10%| 0.87%|
| Loss ratio at distribution stage            | 5.01%| 5.50%| 7.74%|
| Waste ratio of eating at home               | 3.80%| 3.76%| 3.59%|
| Waste ratio of eating out                   | 0.04%| 0.06%| 0.06%|

Table 2. Changes as related ratios increased by 20%.

*FLW* means the volume of food losses and waste. *WFLW* and *LFLW* mean the water and land footprint of consumption related to FLW, respectively.

accounted for 96.1% of the total WF related to FLW. On the one hand, this was due to a higher dependence on external food; on the other hand, the early modes of food product transport (such as packet-based and bulk transport) are simple in structure, high in cost, low in efficiency, and easily cause food losses, especially in developing countries (Papargyropoulou et al 2014). Adopting specialised transportation facilities and centralised container transportation is of great significance for reducing food losses and inefficient resource consumption. Furthermore, temperature-controlled grain and nitrogen-filled grain storage technology can be used to improve grain storage losses during transportation and reduce insect pests and mildew problems during storage (Holsteijn and Kemna 2018, Luo et al 2020). Problems, such as the mixed loading of goods and waste caused by the human factor, can be avoided by strict supervision during transportation and storage (Wang et al 2017).

Eating out is inevitable; however, from the perspective of enterprises and restaurants, food waste can be reduced by introducing half-serving meals, incentives from the ‘Clear Your Plate’ campaign, rewards, and punishment measures regarding the amount
of food waste. In the food waste treatment stage, China’s food waste recycling system is fragile due to insufficient collection infrastructure and inadequate treatment facilities (Thi et al 2015), and the waste treatment capacity is only $20–3990 \text{ t day}^{-1}$ (Li et al 2019). The Chinese garbage classification policy has come into operation in several cities; however, it requires vigorous promotion (Yuan et al 2020). Waste treatment plants and related technologies should also be established and upgraded. The food processing software in China is relatively unpopular, such as Danish 'Too Good To Go' and Indian 'Feeding India' software, which avoids food waste and solves the problem of providing food for the poor by selling surplus food in shops at low prices or providing it at no cost.

In terms of reducing the WF and LF related to FLW, China also has several key leverage points (West et al 2014), especially accounting for the spatial differences in FLW ratios by food types, as well as the spatiotemporal heterogeneities in WF or LF of growing the same food product. For Sichuan, the province with the largest FLW caused by the high food waste ratio, measures to reduce its FLW is more urgent than others. The highest WF and LF related to FLW occurred in Shandong and Guangdong province in 2017, respectively. For these provinces, the priority is to improve the efficiency of agricultural water and land use. Similarly, the crop structure optimisation considering both water and land savings (e.g. Chouchane et al 2020) or importing water-intensive food products instead of producing locally (D’Odorico et al 2019) could also be beneficial.

This study quantified the environmental effects from the perspectives of production and consumption. This study had some limitations. There is a lack of official statistics or measurements about FLW over time. With data limitations, we must assume constant FLW ratios by food products as obtained from previous publications. This should be in caution when implementing current results. However, we believe that the current study can still show the temporal changes of FLW. Changes in both magnitude and constitution of the FLW in China were defined by considering inter-annual variations in food consumption, the food production and trade structure, the ratios of people eating out, and the ratio of rural to urban populations. The amounts of water and land resources were considered in this study; however, the water quality, land degradation, and economic and climate costs at the food waste treatment stage are important factors too. There are indeed differences between urban and rural diets, but the relevant data for the study period is still lacking in China’s official statistics. That is why such differences can only be considered for a certain year based on authors’ surveys for a few provinces in China (e.g. He et al 2018, Xue et al 2021), and only the national average data are finally reported. Therefore, we decided to use the globally accepted official data on diets at the national average level from the FAOSTAT (2022) to avoid unnecessary uncertainties from rough assumptions. The FAOSTAT contains the largest statistical database on food and agriculture in the world, with approximately 20 000 indicators covering more than 245 countries and territories, and around 2 million users each year (FAO 2021). However, the diet structure of different regions is different in reality because of diversity in education level, income, and local culture in the actual situation. Therefore, the specific implementation of policies should be based on the differences mentioned above. For example, improving infrastructure and promoting of policy is more urgent than other measures in rural regions. In urban regions, the actions of restaurants are crucial to avoid FLW and relevant resource consumption. Policy recommendations to reduce FLW can be provided from multiple perspectives. Although this study considered the difference in resource endowment at the provincial level, differences in scale remained within provinces (Mao et al 2021). There are some uncertainties in the estimation of the VW flows because of the lack of statistical trade data for calibration of the simulated trade matrix. However, these results are reliable compared with previous studies (Zhao et al 2015, Liu et al 2019b) in general VW transport directions and magnitudes. Local governments should develop policies based on further validation by field surveys.

5. Conclusions

This study estimated the WFs and LFs related to FLW considering associated inter-provincial VW and VL flows in China. The results demonstrate that FLW and embedded water and land resource in the driven inter-regional food logistics cannot be overemphasised. The main conclusions are as follows:

(a) The FLW and WF and LF related to FLW increased from 165.5 to 277.8 million t yr$^{-1}$, 107.3–159.2 billion m$^3$ yr$^{-1}$, and 37.8 to 47.2 million ha yr$^{-1}$, respectively, in the period 2000–2017. The FLW per capita and embedded WF and LF were 200.1 kg cap$^{-1}$, 229.5 m$^3$ cap$^{-1}$, and 34.0 ha cap$^{-1}$, respectively, in 2017. Vegetables, pork, and chicken had the largest FLW (118 million t yr$^{-1}$), WF (26.6 billion m$^3$ yr$^{-1}$), and LF (10.6 million ha yr$^{-1}$), respectively, in 2017. In the different consumption locations, eating at home in rural regions caused the most FLW and associated resource consumption, followed by eating at home in urban regions and eating out in urban and rural regions.

(b) The gross VW and VL flows related to FLW were 67.8 billion m$^3$ yr$^{-1}$ and 27.7 million ha yr$^{-1}$ in 2017, respectively, which had increased from 34 billion m$^3$ yr$^{-1}$ and 22.7 million ha yr$^{-1}$,
respectively, in 2000. The proportion of VW import in the total WF related to FLW ranged from 13.8% (Jiangsu province in 2001) to 96.1% (Tibet province in 2015). The highest proportions of VL imports in total LF related to FLW occurred in the Shanxi province in 2000 (91.5%) and Shanghai province in 2017 (98.7%). The VW and VL flows related to FLW under different consumption locations was same as the characteristics of FLW.

(c) The largest inter-provincial VW and VL flows related to FLW occurred in Henan to Sichuan province and Henan to Guangxi province (1.42 billion m³ yr⁻¹ and 0.40 million ha yr⁻¹) in 2017, respectively, which is different to the structure of crop trade because of differences in the unit WF and LF.

This study suggests that determining FLW throughout the life cycle is valuable, especially for the supply chain stage. Losses and wastage of resources caused by inefficient trade should not be ignored, and other combined effects should be considered in future research.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors declare that they have no conflict of interest.

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