Environmental Research Letters

LETTER

Effects of urbanization on food-energy-water systems in mega-urban regions: a case study of the Bohai MUR, China

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Abstract

The security of food-energy-water (FEW) systems is an issue of global concern, especially in mega-urban regions (MURs) with high-density populations, industries and carbon emissions. To better understand the hidden links between urbanization and FEW systems, the pressure on FEW systems was quantified in a typical rapidly urbanizing region—the Bohai MUR. The correlations between urbanization indicators and the pressure on FEW systems were analyzed and the mechanism of the impact of urbanization on FEW systems was further investigated. The results showed that approximately 23% of cropland was lost, 61% of which was lost via conversion to construction land and urban areas expanded by 132.2% in the Bohai MUR during 1980–2015. The pressure on FEW systems showed an upward trend, with the stress index of the pressure on FEW systems (FEW_SI) ranging from 80.49% to 134.82%. The dominant pressure consisting of that has converted from water system pressure to energy system pressure since 2004. The FEW_SI in the Bohai MUR was enhanced with cropland loss and increases in urbanization indicators. Additionally, land use, populations, incomes, policies and innovation are the main ways that urbanization affects FEW systems in MURs. This study enhances our understanding of the variation in pressure on FEW systems in MURs and the effects of urbanization on FEW systems, which will help stakeholders to enhance the resilience of FEW systems and promote sustainable regional development.

1. Introduction

The food-energy-water (FEW) crisis is the most prominent non-traditional security issue in the 21st century and is listed one of the top three global risks in terms of impact (Hendry et al 2012). Despite gaining increased access to food, energy and water resources within the past fifteen years, billions of people still lack these resources worldwide (Godfray et al 2010, McGuire et al 2015, International Energy Agency IEA 2016, United Nations 2016, Scanlon et al 2017). Approximately 40%, 50% and 35% more food, energy and water resources will be needed by 2030, respectively, and further resources will be needed to support the growing global population (9.7 billion) by 2050 (United States National Intelligence Council US NIC 2012, United Nations 2015, Vora et al 2017). This crisis is more significant in urban areas with high-density populations and industries. Previous studies indicated that urban areas in accounted for 50%–80% and approximately 80% of the total amounts of energy consumption and carbon emissions, respectively, and only 27–621 times the physical urban scale met water resource requirements (Jenerette and Larsen 2006, Heinenon and Junnilia 2011, Heard et al 2017). It was also forecasted that 46% of the urban population will suffer water stress by 2050 (Boretti and Rosa 2019). However, food, energy and water resources are the core
materials and lifeblood of urban development. Therefore, investigating FEW systems pressure in urban areas can help develop measures for relieving the FEW crisis and promoting regional sustainable development (Schlör et al. 2018, Zhang et al. 2019).

Notably, the exacerbation of pressure on FEW systems is mainly caused by external factors and internal characteristics of the system (Fang et al. 2017, Li et al. 2019a). Some previous studies focused on the FEW flows and nexus in watersheds, cities, megacities and regions (Kennedy et al. 2015, Endo et al. 2017, Cai et al. 2018, Gragg et al. 2018, Taniguchi et al. 2018, Yang and Wi 2018, Liang et al. 2019), which furthered our understanding of the internal characteristics of the system. Studies have also shown that changes in one system have profound effects on other systems, because of the interdependencies and interactions between food, energy and water subsystems (Hoff 2011, Al-Saidi and Elagib 2017, Scanlon et al. 2017, Cai et al. 2018, D’Odorico et al. 2018). In addition, the external factors, such as rapid population growth, urbanization, economic development and climate change, will affect the production and supply of these resources and enhance the demands for food, energy and water (Hanjra and Qureshi 2010, Allan et al. 2013, Seto and Ramankutty 2016, Qin et al. 2019). These conclusions help us understand how the pressure on FEW systems responds to changes in the internal characteristics of FEW systems and external factors.

Urbanization, an important external factor affecting FEW systems, involves multiple changes, including urban population growth, urban area expansion, economic development and technological advances (Seto and Ramankutty 2016, Song et al. 2019). Urbanization is rapidly occurring worldwide. According to the United Nations’ report (2014), the urban population will increase to 5 billion by 2030 and will account for 75% of the global population by 2050. Urban areas around the globe are also predicted to increase twofold in 2000–2030 (Seto et al. 2013). Specifically, previous studies showed that urban population growth and urban land expansion will mostly occur in Asian and African countries, such as China and India (United Nations Department of Economic and Social Affairs UN-DESA 2014, Bren d’Amour et al. 2017, Fei and Zhao 2019). In China, the urbanization rate increased from 42.99% to 56.1% during 2005–2015, and the size of the urban population will increase by 2.9 billion by 2030. Urban areas also increase at a rate of 20 000 km² yr⁻¹ because of conversion from cropland, forest and grassland during this same period. As a result of rapid urbanization, mega-urban regions (MURs), e.g. the Bohai MUR, Yangtze River Delta MUR and Pearl River Delta MUR, are becoming a major trend in city development.

How urbanization is transforming food, energy and water systems directly or indirectly is of the utmost concern. Some studies have investigated the hidden links between urbanization and food systems, energy systems or water systems (Seto and Ramankutty 2016, Fang et al. 2017, Avtar et al. 2019, Liu and Sun 2019). One of the remarkable effects of urbanization on FEW systems is that cropland loss, especially the loss of the most productive cropland, caused by urban land expansion, leads to changes in food production and the amount of agricultural water resources (Seto and Ramankutty 2016, Bren d’Amour et al. 2017, Yu et al. 2019). Hot spots of cropland losses in MURs have been reported (Bren d’Amour et al. 2017, Yu et al. 2019). Another notable aspect of the effect of urbanization on FEW systems is the increased demands and consumptions of food, energy and water as a result of rapid increases in urban population size and industries (Esfandiari-Baiat et al. 2014, Fan et al. 2019). Although the effects of urbanization on food, energy and water systems have been widely studied, the mechanism of how urbanization affects FEW systems is not well understood from a holistic perspective. Hence, it is necessary to further study the impact of urbanization on FEW systems, especially in hot spots such as MURs.

The Bohai MUR is a typical region located in northern China with a high level of urbanization, a high population density, a serious FEW crisis and rapid economic development (Ren et al. 2018, Zeng et al. 2019). In addition, due to drastically growing demands, the uneven spatio-temporal distribution of food, energy and water and incompatibilities between the population, ploughed land, the gross domestic product (GDP), energy and water, FEW systems in most of China at serious risk, which restricts regional socio-economic development (Jiang 2015, Wang et al. 2018, He et al. 2019, Li et al. 2019b, Xiao et al. 2019). Therefore, the Bohai MUR was selected as a case study. This study aimed to (1) assess the urbanization effect and pressure on the FEW systems at an MUR scale in 1980–2015, (2) quantify the spatio-temporal variation in FEW systems pressure and (3) explore the mechanisms by which urbanization affects FEW systems. This study will shed light on the dynamics of how urbanization affects FEW systems in MRUs.

2. Data and methods

2.1. Study area

The Bohai MUR (113°20′E ~ 125°45′E, 34°20′N ~ 43°30′N), one of forty such regions in the world, is located in Northeast China as shown in figure 1. The Bohai MUR covers an area of 518 000 km² that includes Beijing, Hebei, Tianjin, Liaoning and Shandong provinces. Most of the region is in the warm temperate zone and exhibits a half-moist monsoon climate, with an annual mean precipitation and temperature ranging from 560 mm to 916 mm and 8 °C–12 °C, respectively. The Bohai MUR has a high population density (18.6% of the nation’s population in 2015) and is the third economic growth pole of China (representing 25.8% of
The urbanization rate in the region has grown considerably, increasing at an average rate of 1.19% during 2005–2015. However, rapid economic development and urbanization processes are causing problems related to cropland loss and resource use in the Bohai MUR (Fei and Zhao 2019). Cropland loss, in most productive croplands, inevitably affects food security. In 2015, the per capita food production of the Bohai MUR was 406.8 kg, which was lower than the national per capita grain yield (481.76 kg). In recent years, the per capita water resources (430 m³) in the region were always below the level used internationally to denote a severe water shortage (500 m³). In addition, the gap in regional energy consumption and production was greater than 87.74 million tons of standard coal in 2015, which was four times that in 1995. Therefore, the Bohai MUR is an ideal zone for studying the effect of urbanization on FEW systems in MURs.

2.2. Data sources and processing
The land use data for 1980–2015, with a 5 year interval and a 1 km spatial resolution, were provided by the Data Centre for Resources and Environmental Sciences, Chinese Academy of Sciences (http://resdc.cn). The statistics for urbanization indicators and related factors reflecting the pressure on FEW systems were obtained from the Statistical Yearbooks of China, the China Energy Statistical Yearbooks, the Statistical Yearbooks and Water Resources Bulletins of each city from 1980 to 2015 (http://stats.gov.cn/, http://mwr.gov.cn/). Food consumption was calculated with the data on average per capita food consumption of urban and rural households and urban and rural populations. The energy production and consumption data were converted into standard coal according to the related reference coefficient provided in table A2 in the supplementary materials is available online at stacks.iop.org/ERL/15/044014/mmedia. The available water resources were calculated by the total water resources and the available water resource coefficient. In particular, food included only cereals, beans and tubers, energy resources included only local energy production and the total water resources did not include water transferred from other regions.

2.3. Methodology
2.3.1. Indicators for mapping urbanization levels
Land use change, population growth, economic development and other socio-economic indicators are applied to characterize urbanization levels (Wang et al 2019a, Zhou et al 2019). In this study, three aspects were considered for mapping urbanization levels: land use change, demography and economic development. Changes in cropland, construction areas and urban areas were used to describe land use change. With the aid of GIS technology, we analyzed the temporal and spatial variation in land use in the Bohai MUR during 1980–2015 (details in supplementary material (S1)). The total population size (permanent resident population) and urbanization rate (the proportion of urban people) were used to reflect population urbanization. Per capita GDP was applied to represent economic urbanization (Fang et al 2017). We performed normalization and scaled the values to a range of 0–1 before correlation analysis (table A.3 in S1).

2.3.2. Quantifying pressure on the FEW systems
To reflect the pressure on the FEW systems, we constructed a composite index of FEW system pressure (FEW_SI), which is described in equation (1). Because interdependencies and nonlinear interactions exist between food, energy and water subsystems (Hoff 2011, Al-Saidi and Elagib 2017, Scanlon et al 2017,
Cai et al. 2018, D’Oodorico et al. 2018), a geometric average value was adopted in equation (1) to represent the pressure on the FEW systems

\[ \text{FEW}_\text{SI} = \frac{\text{FSI} \cdot \text{ESI} \cdot \text{WSI}}{[3]} \]

(1)

The pressures on food systems (FSI), energy systems (ESI) and water systems (WSI) were constructed on the basis of the resource supply and demand balance. WSI is defined as the ratio of water consumption to locally available water resources, which improves on the water resource vulnerability index. The water resource vulnerability index is a widely used water scarcity index, defined as the ratio of total annual water withdrawal to available water resources (Raskin et al. 1997, Pedro-Monzonís et al. 2015). ESI is defined as the ratio of energy consumption to local energy production. FSI is defined as the ratio of staple food consumption to local staple food production. FSI, ESI and WSI were calculated by equations (2)–(4), respectively

\[ \text{FSI}_j = \frac{C_{F_j}}{P_{F_j}} \]  
(2)

\[ \text{ESI}_j = \frac{C_{E_j}}{P_{E_j}} \]  
(3)

\[ \text{WSI}_j = \frac{C_{W_j}}{P_{W_j}} \]  
(4)

where \( C_{F_j} \) represents the total food consumption (including only cereals, beans and tubers), and \( P_{F_j} \) represents the total local food production; \( C_{E_j} \) represents the total energy consumption and \( P_{E_j} \) represents the total local energy production; \( C_{W_j} \) represents the total water consumption and \( P_{W_j} \) represents the amount of available water resources in the jth year.

2.3.3. Relationship analysis between urbanization and FEW systems

To analyze the relationship between urbanization and the pressure on FEW systems, Pearson correlation test was adopted, and the mechanism of how urbanization affects FEW systems was further analyzed by combining these results with those from previous studies. In this study, statistical analysis was performed using the free software R (R Core Team 2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://r-project.org/), and other graphs were produced using Origin 2017 (OriginLab, Northampton, MA, USA).

3. Results

3.1. Land use change and urban expansion from 1980 to 2015

During 1980–2015, notable spatial changes in land use occurred in the Bohai MUR. In 1980, cropland (including irrigated land and paddy land, 54% of land use types) comprised an area of 27,996 km² in the Bohai MUR, which was mainly distributed in the southern part of the region (figure 2). The construction land area, including urban land, rural residential land and other construction land, occupied only approximately 7.6% of the entire region (figure 2). However, the area of construction land increased, while that of the other land use types decreased in the past thirty-five years (figure 2). In particular, the percentage of urban land in the initial area increased by 132.14% (with an area of 6,907 km²), making urban land become the land use type with the largest change. Meanwhile, there was a 6,424 km² decrease in the area of cropland in this period (figure 2). The spatial pattern of land use change from 1980 to 2015 suggested that cropland loss occurred mainly around urban areas and continued to expand outwards (figure 2). In addition, approximately 36,058 km² of cropland was occupied, 61.07% of which was covered by construction land, but only 10% of the cropland was supplemented through land transfer between 1980 and 2015 (figure 2). Figure 2 also demonstrates that the loss of cropland was a common phenomenon in each period from 1980 to 2015 and the rate of urban expansion continued to increase and then decrease.

3.2. Change in FSI, ESI and WSI during 1980–2015

The pressure on the food, energy and water systems in the Bohai MUR changed greatly from 1980 to 2015 (figure 3). In this period, the values of FSI, ESI and WSI were 27.05%–72.33%, 87.09%–267.86% and 92.55%–307%, respectively (figure 3). Specifically, the FSI values decreased by more than half during 1980–2015 (figure 3(A)), while the energy system and water system pressures were enhanced at rates of 6.29% and 1.32% each year respectively (figures 3(B) and (C)).

The strengths of the food system pressure, energy system pressure and water system pressure differed greatly among the five provinces of the Bohai MUR (figure 4). Beijing (FSI: mean ± SE, 121.34% ± 10.07%) and Tianjin (FSI: mean ± SE, 88.73% ± 2.91%) suffered greater food system pressures than the other three provinces during 1980–2015. Hebei (ESI: 238.26% ± 20.85%) and Liaoning (ESI: 214.77% ± 17.49%) displayed high pressures on the energy system. In addition, Beijing, Tianjin and Hebei suffered more serious water resource shortage pressure than the other two provinces in 1980–2015. In particular, Tianjin suffered the greatest water shortage pressure in this period that the mean WSI value was five times that in Liaoning Province. Overall, figure 5 shows that the pressures on water system and energy system were stronger than that on food system in each province in the Bohai MUR.

3.3. Variation in the pressure on FEW systems and the dominant pressure

The pressure on FEW systems in the Bohai MUR showed great temporal and spatial variation (figure 5). During 1980–2015, the pressure on FEW systems showed an upward tendency, with FEW_SI increasing from 980.49% to 116.82% in the entire region. In particular, the pressure on FEW systems in Beijing first decreased and then increased, while that in Tianjin first increased and then decreased, and that in the other three provinces had an upward tendency in 1980–2015. Meanwhile, the values of FEW_SI varied.
across provinces in the region. Specifically, the pressure on the FEW system in Beijing was significantly greater than that in the other four provinces and that in Liaoning (FEW_SI : 84.5% ± 3.2%) was the weakest. In addition, the FEW_SI in Tianjin was higher than that in Hebei and Shandong. Figure 5 illustrates that the amplitudes of FEW system pressures in Beijing and Tianjin were greater than those in the other three provinces in the temporal series.

Figure 6 shows the spatio-temporal heterogeneity in the dominant pressure in the Bohai MUR. The dominant pressure on the FEW system has been converted from water system pressure to energy system pressure since 2004, which is supported by the results of Li et al (2019b) to some extent. In addition, the dominant pressure exhibited noticeable spatial heterogeneity in the provinces. The dominant pressure in Beijing was caused by the water system until 2005, at which point it changed to the food system, while that in Tianjin and Liaoning were always the pressure on the water system and energy system, respectively. Nevertheless, in Hebei and Shandong, FEW system pressures were mainly dominated by the water system but then switched to the energy system in 2006 and 2004, respectively. Of particular note, the pressure on the food

Figure 2. Spatio-temporal distribution of land use and Statistics of land use change in the Bohai MUR from 1980 to 2015.
system was another source of pressure on FEW systems in the 1980s that cannot be ignored.

3.4. Urbanization effects on FEW systems in the Bohai MUR

The correlation analysis results between the urbanization indicators and variables of the FEW system are shown in figure 7. The results suggested that the FEW_SI in the Bohai MUR was enhanced with cropland loss and an increase in the urbanization indicators construction area, urban area, urbanization rate, population and per capita GDP. The ESI and WSI exhibited similar correlations with the urbanization indicators (figure 7). However, the FSI in the Bohai MUR was significantly positive correlated with crop land area and significantly negative correlated with other indicators of urbanization, which may have been caused by technological innovation with urbanization. More specifically, although the area of crop land decreased and food consumption increased in the Bohai MUR, technological advances increased food production, thereby reducing the pressure on the food system. Importantly, domestic and other water

Figure 3. Temporal variation in food, energy and water stress index and its resource and consumption in the Bohai mega-urban region during 1980–2015.
consumption and energy consumption both increased with urbanization, and there was a significant correlation between them (figure 7).

4. Discussion

4.1. Urbanization effects on FEW systems in typical MURs
Pressure on FEW systems is common and evident in MURs. The index of pressure on FEW systems in the two typical MURs—the Bohai MUR and Yangtze River Delta MUR—were calculated as shown in figure 8. The results showed that the pressure on FEW systems was initially enhanced and then weakened in the two MURs (figure 8). The pressure on the FEW systems showed obvious heterogeneity in the two MURs. The mean value (97.92%) of FEW_SI in the Bohai MUR during 1980–2015 was smaller than that (119.58%) in the Yangtze River Delta MUR and the value of FEW_SI each year was smaller in the Bohai MUR than in the Yangtze River Delta MUR (figure 8). As shown by the correlation between the urbanization rate and FEW_SI, heterogeneity mainly occurred because the urbanization process in the Yangtze River Delta MUR was consistently faster than that in the Bohai MUR. The mechanism of urbanization effects on the FEW systems in the MURs can be determined in the sector of 4.2.
4.2. The mechanism of how urbanization affects FEW systems in MURs

Urbanization can affect FEW systems, including changes in land use patterns, households and demography, economy and development, and innovation and related policies (figure 9) (Seto and Ramankutty 2016, Fang et al 2017). In this section, how urbanization affects FEW systems was analyzed.

Figure 6. The change in the dominant pressure index of the food-energy-water system in the Bohai MUR during 1980–2015.
from perspectives of demand, production and consumption.

As one aspect of urbanization, land use change, especially urban land expansion was proven to cause cropland loss ($r = -0.97$, $p < 0.01$ in the Bohai MUR, figures 2 and 7) (Shi et al. 2016, Ju et al. 2018). Similarly, rapid urban area expansion has led to the loss of some highly productive croplands worldwide, especially in MURs in Asia and Africa (Brend’Amour et al. 2017). However, the loss of cropland, as an essential element of food production, will further decrease food yield, thus imposing stress on the food system (from the perspective of production) (Martellozo et al. 2015, He et al. 2017). Urban land expansion also causes a loss in water body area, including the loss of wetlands (figure 2). A decrease in water body area during the urbanization process will directly reduce surface water resources, and these losses will become serious pressures affecting water systems in MURs (from the perspective of production). An increase in urban land has also been shown to increase urban runoff and reduce infiltration, which affect groundwater and available water resources (Chen et al. 2018, Wang et al. 2019b).

In households and demography, with the increase in urbanization, an increasing number of people have moved to urban areas. Households were reported to consume more energy during urbanization process (Lin and Ouyang 2014, Sun and Ouyang 2016). Rapid population growth and economic development not only increase the consumption of food, energy and water but also change the composition of food, energy and water consumption (from the perspectives of demand and consumption) (figure 9) (Fang and Chen 2016, He et al. 2019, Song et al. 2019). Previous studies also showed that higher-income societies consume more meat, which results in a change in diet composition; for example Chinese per-capita meat consumption was twice as high in 2015 compared with 1970, with an increase in the urbanization rate over this period from 17.4% to 55.6% (Seto and Ramankutty 2016, Song et al. 2019). Such a change eases the demand for staple foods (the correlation between GDP_pop and FC in the Bohai MUR: $r = -0.85$, $p < 0.01$, figure 7). The regional GDP also affects the consumption of energy and water (Li et al. 2019a).

Innovation, including new technologies and ideas related to merging FEW systems during the urbanization process, also affects production, transportation, processing, trade, and food, energy and water consumption. Urban land planning and other policies related to food, energy and water are non-negligible factors that can reduce or increase the FEW system pressure (Zhao et al. 2015, Gu et al. 2016, Kattel et al. 2019). Innovation and policies may be the reasons that the FEW_SI values in the two MURs in this study showed a tendency to decrease when urbanization increased (figure 8). In addition, when urbanization affects one subsystem, it will affect the other two

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**Figure 7.** The correlation relationships between urbanization indicators and food-energy-water system pressure. Food in this study includes cereal, beans and tuber crops. The blue shaded color bar represents a negative correlation and the red represents a positive correlation. The blank parts indicate that there was no significant correlation ($p > 0.05$). The indicators’ names are in table A1 of S1 and data are in table A3 of S1.
subsystems because there is a nexus of synergy and a trade-off effect among food, energy and water systems (Bazilian et al 2011, Hoff 2011, Cai et al 2018). Thus, various forms of urbanization effects comprehensively act on FEW systems and subsystems, resulting in the mechanism shown in figure 9.

5. Conclusion and suggestions

We proposed an index of pressure on FEW systems for quantifying and further analyzing variation in the pressure on FEW systems. The pressure on the studied FEW systems increased from 80.49% to 134.82% during 1980–2015, and the dominant pressure on the FEW systems in the Bohai MUR transformed from water system pressure to energy system pressure with a tipping point in 2004. These conclusions imply that some measures need to be taken to decrease energy system pressure, e.g. increasing water and energy efficiency and adjusting regional industrial structures to reduce water and energy consumption. We also analyzed the relationships between urbanization indicators and pressure on FEW systems and explored the mechanisms by which urbanization affects FEW systems in MURs. We found
an obvious positive relationship between urbanization and the pressure on FEW systems. Urbanization generally affects FEW systems in terms of land use change, urban population growth, economic development, policies and innovation in MURs. Especially, land use change was identified as having a stronger impact than other factors on FEW systems. An increased understanding of the spatio-temporal heterogeneity in the pressure on FEW systems and the effects of urbanization on the FEW systems in MURs can help stakeholders take effective measures to enhance FEW system resilience in MURs and ensure sustainable development during the urbanization process in similar regions.

In future work, other non-negligible influential factors affecting FEW systems, such as climate change and other aspects of urbanization should be considered. Various linkage quantification methods such as system dynamic models or multi-agent models presenting the interaction of urbanization on FEW systems could be applied. In addition, how urban expansion will affect future FEW systems in MURs is worthy of exploration in further research.

Acknowledgments

We are grateful for financial support from the National Natural Science Foundation of China (Grant No. 51879010, 51479003), the National Key Research and Development Program of China (2018YFC0407900) and the 111 Project (Grant No. B18006). We thank anonymous reviewers and editors for very helpful comments and suggestion of the manuscript.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Please also see supplementary materials for further information.

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