Niva, Venla; Cai, Jialiang; Taka, Maija; Kummu, Matti; Varis, Olli

China's sustainable water-energy-food nexus by 2030 : Impacts of urbanization on sectoral water demand

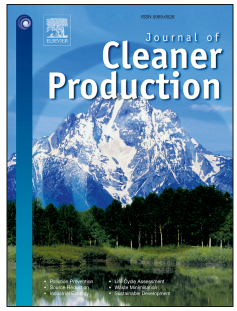
Published in:
Journal of Cleaner Production

DOI:
10.1016/j.jclepro.2019.119755

Published: 01/04/2020

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Journal Pre-proof



China's sustainable water-energy-food nexus by 2030: Impacts of urbanization on sectoral water demand

Venla Niva, Jialiang Cai, Maija Taka, Matti Kummu, Olli Varis

PII: S0959-6526(19)34625-6

DOI: https://doi.org/10.1016/j.jclepro.2019.119755

Reference: JCLP 119755

To appear in: *Journal of Cleaner Production*

Received Date: 4 March 2019

Revised Date: 21 November 2019

Accepted Date: 15 December 2019

Please cite this article as: Niva V, Cai J, Taka M, Kummu M, Varis O, China's sustainable water-energy-food nexus by 2030: Impacts of urbanization on sectoral water demand, *Journal of Cleaner Production* (2020), doi: https://doi.org/10.1016/j.jclepro.2019.119755.

China's sustainable water-energy-food nexus by 2030: Impacts of urbanization on sectoral water demand

Venla Niva, Jialiang Cai*, Maija Taka, Matti Kummu, Olli Varis

Water & Development Research Group, Department of Built Environment, Aalto University, P.O. Box 15200, FI-00076 Aalto, Finland

**Corresponding author*: Jialiang Cai (jialiang.cai@aalto.fi; caijialiang.pku@gmail.com)

Author Contributions

V.N., J.C., M.K., and O.V. conceived the original idea. V.N. and J.C. collected the data. V.N., M.K., and M.T. developed the methods and performed the numerical simulations. M.T., J.C., V.N., and M.K. carried out the figures. J.C. took the lead in writing the manuscript. All authors discussed the results, provided critical feedback, and helped shape the final manuscript.

China's sustainable water-energy-food nexus by 2030: Impacts of urbanization on sectoral water demand

Venla Niva, Jialiang Cai*, Maija Taka, Matti Kummu, Olli Varis

Water & Development Research Group, Department of Built Environment, Aalto University, P.O. Box 15200, FI-00076 Aalto, Finland

**Corresponding author*: Jialiang Cai (jialiang.cai@aalto.fi; caijialiang.pku@gmail.com)

Abstract: In the context of China's rapid and perennial urbanization, it is of profound importance to understand how to enable and accelerate progress towards achieving the country's sustainable water-energy-food nexus by 2030. In this study, a quantitative spatial scenario analysis was performed to identify the provinces that are expected to experience changes in water stress, under the competition for water between food and energy sectors. The results manifested an imbalance of water availability for meeting the demand between those two sectors. First, food sector played the leading role in the baseline water stress. Second, energy sector dominates the increases of the projected water stress index. Third, urbanization is projected to substantially affect the extent of water availability as well as food consumption and energy production, especially in the eastern provinces. Tackling imbalanced sectoral water demand is the key to China's sustainable water-energy-food nexus, which shall require some corresponding changes in national policy-making. China needs, first, policy coherence and synergies, second, ensuring the adequacy of any follow-up procedures, and third, embracing greater participation and transparency in policy-making.

Keywords: Water footprint; Blue water; Food security; Energy security; Urbanization; China

1 Introduction

Viewing night lights from the Earth's orbit illustrates how swiftly the patterns of human settlement change across our planet **(Carlowicz, 2017)**. These views on Earth at night resonate with the transition that our world is undergoing, i.e. global urban population growth is proportionally much faster than average population growth, and global urban population is expected to grow up to 6.68 billion by 2050 **(United Nations, 2019)**. The case of China is revealing; the combination of 6 % of global water resources, 9 % of global arable land, and 18 % of global population gives an insight of the challenges with regard to sustainable development that the country keeps facing **(World Bank, 2019)**. The growing population and economy, together with spreading consumeristic urban lifestyles, contribute to booming exploitation of natural resources. This puts increasing pressure on human well-being and environmental sustainability. At the same time, it is of pungent necessity to seek for means to balance between competing sectoral demands, between regional and provincial needs within a country, and between human desires and nature's sustainability. In particular, the inter-sectoral competition over water resources is expected to climb up and lead to overexploitation, as demographic and economic growth, along with growing consumption, lead to increased water stress significantly worldwide.

Urbanization is a process of concentration of population, and a key driver for various environmental changes **(van Ginkel, 2008)**. China has set urbanization as one of the core development strategies for economic growth and social development in its recent Five-Year plans **(Cui et al., 2019)**. This endeavor has resulted in rapid rural outmigration and corresponding growth of urban population, i.e. the degree of China's urbanization (percentage of urban population) has quadrupled in the last four decades **(National Bureau of Statistics of China, 2018)**. Urbanization contributes to not only changing consumption patterns such as the shift from plant to animal-based diet **(Dwivedi et al., 2017)** and the boom of construction activity **(Zhang et al., 2019)**, but also changing energy and water demand in households and industries **(Fukase and Martin, 2016)**. Owing to the fact that agriculture is the greatest water-use sector in China with 62 % of total water use in 2017 **(National Bureau of Statistics of China, 2018)**, the vast population, lifestyle transition, and limited water resources have triggered a concern of the country's national food security, with aims of food self-sufficiency up to 90 % by 2030 **(Fukase and Martin, 2016)**. Besides, urbanization puts pressure on land use, by diffusing to areas previously used for agriculture **(Li et al., 2013)**, thus decreasing the share of agricultural land and water availability **(Yan et al., 2015)**. Apart from food security, urbanization has a big influence on energy security, through electrical appliances, private transportation, and infrastructure **(Wang, 2014)**. China's coal-intensive energy production is the main and significant water consumer **(Gu et al., 2016)**, whereas the water footprint of renewable energy resources is much smaller **(Mekonnen et al., 2016)**. In light of water availability being the crucial issue in China's food consumption **(Huang et al., 2015)** and energy production **(Cai et al., 2018b)**, it is therefore of prime importance to address the changes in water demand under the effect of rapid urbanization.

China has been underlining sustainable development as an overarching objective for policy-making within the economic, social, and environmental dimensions. Also, the country has committed to play a leading role, to the best of its abilities, in implementing the 2030 Agenda (*Transforming our world: The 2030 Agenda for Sustainable Development*) comprehensively at national, regional, and global scales **(Ministry of Foreign Affairs of China, 2017)**. Due to the fact that water, in sufficient quantity and quality, is at the core of sustainable development **(United Nations Educational, Scientific and Cultural Organization, 2019)**, it is embedded in the majority of the Sustainable Development Goals (SDGs). It is crucial to food security

(SDG 2), health and well-being (SDG 3), energy security (SDG 7), cities and human settlements (SDG 11), consumption and production cycles (SDG 12), climate change (SDG 13), aquatic biodiversity (SDG 14), terrestrial biodiversity (SDG 15), and means of implementation (MoI) (SDG 17) **(United Nations, 2018)**.

The water-energy-food (WEF) nexus constitutes a framework for analyzing the dynamic interactions between water, energy, and food systems and developing strategies for resource sustainability and effective governance **(Liu et al., 2017)**. The interlinkages and interdependencies of SDG 6 (water), SDG 7 (energy), and SDG 2 (food) across the 2030 Agenda articulate the significance of the WEF nexus. Like most nexus cases, China's WEF nexus also has a clearly water-centric perspective, underlining the water use/withdrawal aspects of agriculture and coupling these with specific energy-sector issues **(Varis and Keskinen, 2018)**. Whilst such water-centrism may be seen to be natural due to the intensifying water stress and the crucial role that water plays in food and energy production **(Keskinen et al., 2016)**, it is likely to be the greatest single challenge for the nexus approach, as its implementation requires the engagement of both food and energy sectors **(Varis and Keskinen, 2018)**. Hence, it is of profound interest and great necessity to scrutinize the competition over water demand between food and energy sectors through the WEF nexus in the context of China's urbanization. To the authors' knowledge, hitherto only **Xiang et al. (2016)** examined this inter-sector competition in one river basin in China, with no attempt to address the country's spatial heterogeneity.

The aim of this study is consequently to comprehend the water demands of food and energy sectors nationwide, in particular their interlinkages and rivalries, and thereby to contribute to the progress towards achieving China's sustainable and balanced WEF nexus by 2030. To fill this knowledge gap, a quantitative spatial scenario analysis was conducted to investigate the competition for water between food and energy sectors in water stressed provinces, being the first study to systematically assess the role of these two sectors in future water stress. The future scenarios were developed on the basis of recent literature, and the concepts of blue water footprint and water stress index were then applied to assess these changes, in the context of China's urbanization. The specific objectives are to (1) investigate the sectoral water demand in China by 2030; and (2) assess the shares of blue water withdrawals of China's food and energy sectors and their corresponding contributions to water stress index in an array of scenarios for the development of those two sectors.

2 Materials and methods

The current water stress for each province was assessed by using blue water availability (BWA) and blue water withdrawals (BWW) of all water use sectors (irrigation, domestic, electricity generation, livestock, mining, and manufacturing). To understand how the changes of water demand in food sector (FS) and energy sector (ES) in 2030 might impact on the pressures on water resources, the changes of blue water footprint (BWF) were calculated based on the existing water demand scenarios of FS and ES. These changes in BWF were accordingly used to estimate the future BWW and thus water stress, including the sectoral impacts. Data and methods used for the analyses are elaborated below, also the detailed scripting can be found in **Supplementary information**.

2.1 Blue water availability and blue water withdrawals

The BWA in each province was estimated using the water availability data from **Kummu et al. (2016)**. They took into account the upstream water availability, on the basis of water allocation rules **(Kummu et al., 2016)**. In this study, the average BWA over 2001-2010, including surface water runoff and groundwater recharge (but not fossil groundwater sources) were used.

The BWW data for the current conditions (an average over 2001-2010) were extracted from **Huang et al. (2018)**. They provided global gridded (30 arc-min) dataset of water withdrawals of six sectors: irrigation, domestic, electricity generation, livestock, mining, and manufacturing. For current water stress calculations, a sum of the BWW of all the sectors was used; while for scenario calculations, the BWW of food (irrigation and livestock) and energy sectors were used with the changes in BWF. Year 2010 was used as the baseline for BWW in FS and ES, since newer data are not available.

2.2 Blue water footprint

Water footprint is a consumption-based indicator of water withdrawals **(Hoekstra and Chapagain, 2007)**. The BWF concentrates on the water intake from freshwater resources (rivers, lakes, and groundwater). The provincial BWF for food consumption was assessed by multiplying food consumption by each food category's BWF **(Jalava et al., 2014)**. The equation can be expressed as

$$BWF_{food} = pop_{province} \sum BWF_{food.item} \cdot m_{food.item.province} \qquad (1)$$

where BWF_{food} (m^3/province/year) is the provincial BWF for total food consumption in an average diet, $BWF_{food.item}$ (m^3/kg/year) is the BWF for per kilogram of consumed food, $m_{food.item.province}$ (kg/person/province/year) is the provincial per capita consumed food of each category in an average diet, and $pop_{province}$ (person/province/year) is the provincial total population of 2015 or 2030. Water consumption was calculated based on current food consumption data (Cons2015) **(National Bureau of Statistics of China, 2016)** and simulated consumption patterns (Cons2030) **(Zheng et al., 2019)**. Food consumption in 2030 was projected by applying annualized growth rates of food item expenditure on baseline food consumption in 2015. Growth rates were acquired from projections estimating the changes in expenditure on major foods under the impact of medium income growth, population aging, and urbanization **(Zheng et al., 2019)**. Here, it was assumed that the percentual change of food consumption is equal to the change in expenditure (i.e. annual growth of 0.46 % in expenditure on poultry equals to annual growth of 0.46 % in consumption of poultry). The population data for the 2015 provincial water consumption calculations was based on year 2015 population counts **(National Bureau of Statistics of China, 2016) (Table 1)**. The future scenarios for 2030 population projections were also performed by HYDE 3.2 data set **(Klein Goldewijk et al., 2010) (Table 1)**.

160 **Table 1. Summary of scenario input data.**

Data	Definition	Resolution	Unit	Source
Food	Per capita consumption of major foods in 2015	province	kg/person/year	(National Bureau of Statistics of China, 2016)
	Projections of expenditure on major foods in 2030	-	kg/person/year	(Zheng et al., 2019)
	Blue water consumption of produced food	-	l/g/year	(Jalava et al., 2014)
Electricity	Electricity production and water withdrawals for electricity production in 2015	province	TWh/year, m^3/MWh/year	(Cai et al., 2014)
	Projections of electricity consumption in 2030	province	TWh/year	(OECD/IEA, 2018)
Population	Provincial population counts in 2015	province	person/year	(National Bureau of Statistics of China, 2016)
	Projections of provincial population counts in 2030 (HYDE 3.2)	5 arc min	person/year	(Klein Goldewijk et al., 2010)
Water availability	Total blue water availability, excluding upstream water use	30 arc min	m^3/year	Kummu et al (2016)
Water withdrawals	Sectoral water withdrawals for irrigation, domestic, electricity generation (cooling of thermal power plants), livestock, mining, and manufacturing	30 arc-min	m^3/year	Huang et al (2018)

161

The provincial BWF for electricity production was assessed by the BWW for electricity production **(Cai et al., 2014)**, which is the common approach in water stress calculations **(Liu et al., 2017)**. The BWF for electricity production is thus a slight overestimation, due to lack of consideration for water returns. This approach does not consider the potential mutual benefice or complementary uses that may derive from water returns used for agriculture. The equation can be expressed as

$$BWF_{electricity} = \sum BWW_{electricity.type} \bullet PG_{type} \tag{2}$$

where $BWF_{electricity}$ (m^3/province/year) is the BWF for electricity production, $BWW_{electricity.type}$ (m^3/TWh (terawatt hours) /year) is the BWW for each type of electricity production, including coal, gas, biofuel, and nuclear, and PG_{type} (TWh/year) is the amount of generated power by each production approach. The BWF for electricity production was calculated for year 2015 and 2030 with three scenarios listed in **Table 2 (OECD/IEA, 2018)**. It was assumed that both the provincial share of electricity production and BWW per produced TWh would remain unchanged since 2015.

2.3 Water stress index

The inter-sectoral water competition between FS and ES was examined by the water stress index (WSI), which indicates the ratio between BWW and BWA **(Vörösmarty et al., 2000)**. The equation of the provincial WSI can be expressed as

$$WSI = \frac{\sum_i BWW_i}{BWA} \tag{3}$$

Where BWW_i (m^3/province/year) is the sectoral blue water withdrawals and BWA (m^3/province/year) is the blue water availability. The range of the WSI values can be divided as follows: (1) [0, 0.10[, which denotes no to low water stress; (2) [0.10, 0.20[, which means moderate water stress; (3) [0.20, 0.40], which represents medium water stress; and (4) > 0.40, which indicates high water stress **(Vörösmarty et al., 2005)**. For future scenarios, the WSI was calculated with **Eq. 3**, so that the BWW for food and electricity were changed according to the changes in BWF of FS and ES, while the BWW for other sectors were kept in current levels.

2.4 Scenario design

The impacts of provincial FS and ES on blue water resources were examined with six scenarios, on the basis of potential changes in diet and electricity production by 2030, i.e. by the end of the period of achieving SDGs (2015-2030) **(Table)**. The bottom-up approach for assessing water demand for FS was selected to analyze the BWF required for sufficient food supply. The future provincial per capita food consumption in 2030 was estimated by applying food expenditure projections for major food items **(Zheng et al., 2019) (Supplementary information)**. The BWF data for food produced in China were acquired from **Jalava et al. (2014)**, who used the original data from **Mekonnen and Hoekstra (2011)**. These data provided the BWF for each food item defined in this study **(Supplementary information)**.

ES was examined by assessing electricity production instead of consumption, to include several different sources for electricity production (i.e. coal, gas, biofuel, and nuclear) **(OECD/IEA, 2018)**. However, the direct consumption of gas or fuel for transportation, for instance, is excluded, because this study concentrates on BWF and water stress, and water consumption of these two energy forms in China is marginal, also the origin of these energy forms is not easy to track and thus it is difficult to allocate the BWF to correct places. Electricity demand is estimated to grow faster than any other types of energy, globally as well as in China, where the share of electricity in total energy demand at both residential and industrial levels is expected to grow due to urbanization **(International Energy Agency, 2019)**. In this sense, electricity provides a good proxy for examining the structural changes of the energy sector in the context of China's urbanization **(Supplementary information)**.

Table 2. Scenario design of food consumption and electricity production. (i) Cons2015 shows current food consumption patterns; (ii) Cons2030 denotes future food consumption patterns by 2030; (iii) CPS is a current policy scenario of electricity production before mid-2018; (iv) NPS denotes new policy scenario of electricity production reflecting the policy targets set after mid-2018; and (v) SDS indicates a sustainable development scenario which reflects the energy-related Sustainable Development Goals. This scenario includes measures for keeping the global temperature increase below 2 °C, ensuring accessible modern energy for all and preventing negative health impacts of energy-related pollution **(OECD/IEA 2018)**.

		Food consumption scenarios	
		Cons2015	**Cons2030**
Electricity production scenarios	**CPS**	**SC1** (Cons2015+CPS)	**SC4** (Cons2030+CPS)
	NPS	**SC2** (Cons2015+NPS)	**SC5** (Cons2030+NPS)
	SDS	**SC3** (Cons2015+SDS)	**SC6** (Cons2030+SDS)

With regard to food consumption scenarios, the year 2015 scenarios with current consumption patterns (Cons2015) contain no effect of urbanization, in comparison with the 2030 scenarios with the combined effect of income growth, demographic change, and urbanization (Cons2030). The estimated impacts of urbanization on food consumption were adopted from **Zheng et al. (2019)** who hypothesized future food expenditure patterns for major food items in China.

In terms of electricity production scenarios, current policy scenario (CPS) is based on policies implemented and adopted before mid-2018, new policy scenario (NPS) reflects policies implemented and adopted after mid-2018, and SDS indicates policies aligned with energy-related Sustainable Development Goals **(OECD/IEA, 2018)**. These scenarios note urbanization as an "overarching structural trend" and a possible catalyst concerning electricity production **(OECD/IEA, 2018)**, yet they do not examine the potential increases in electricity production indirectly caused by irrigated food production.

All the scenarios were tested with three potential population scenarios **(Supplementary information)**. Population projections for year 2030 followed Shared Socioeconomic Pathway (SSP) scenario 1-3 for total, urban, and rural population, and they were aggregated to provincial scales **(Jiang and O'Neill)**. SSP1 projects a sustainable future with low fertility, fast urbanization, rapid economic growth, and increased environmental awareness. SSP3 forecasts a complete opposite future of SSP1, whereas SSP2 stands a middle-way option between SSP1 and SSP3 **(O'Neill et al., 2014)**. Since none of the population projections of SSP 1-3 significantly affected the scenarios (SC1-6) **(Table 2 and Tables S3-18)**, the results are thus presented on the basis of SSP2, being the mid-way scenario **(Supplementary information)**.

The scenario results for the BWF of food consumption and electricity production were used to estimate the changes in blue water demand at the provincial scale. These estimates were then used to calculate the future BWW of FS and ES, while the BWW of other sectors, as well as the BWA, remained in current levels. This approach allowed the authors to calculate the impact of FS and ES on future water stress levels as well.

2.5 Study area

The spatial analysis was conducted by province to allow the applicability of the results to China's WEF-nexus policy-making **(Varis et al., 2014)**. For simplicity, the term *province* was used to represent all 34 provincial jurisdictions, namely to cover 23 provinces, 5 autonomous regions, 4 municipalities, and 2 special administrative regions. Due to lack of data, the provinces Hainan, Hong Kong, Macau, and Taiwan were excluded from the analysis. The data were thereby collected on 30 provinces located in the continental mainland China **(Figure 1)**. To ease interpretation, these 30 provinces were categorized into 4 regions as follows **(Figure 1)**:

1) Northeast China (Heilongjiang, Jilin, and Liaoning);
2) East China (Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, and Guangdong);
3) Central China (Shanxi, Henan, Hubei, Hunan, Anhui, and Jiangxi); and
4) West China with 12 provinces covered by the China Western Development Policy (Xinjiang, Inner Mongolia, Qinghai, Gansu, Ningxia, Shaanxi, Tibet, Sichuan, Chongqing, Yunnan, Guizhou, and Guangxi).

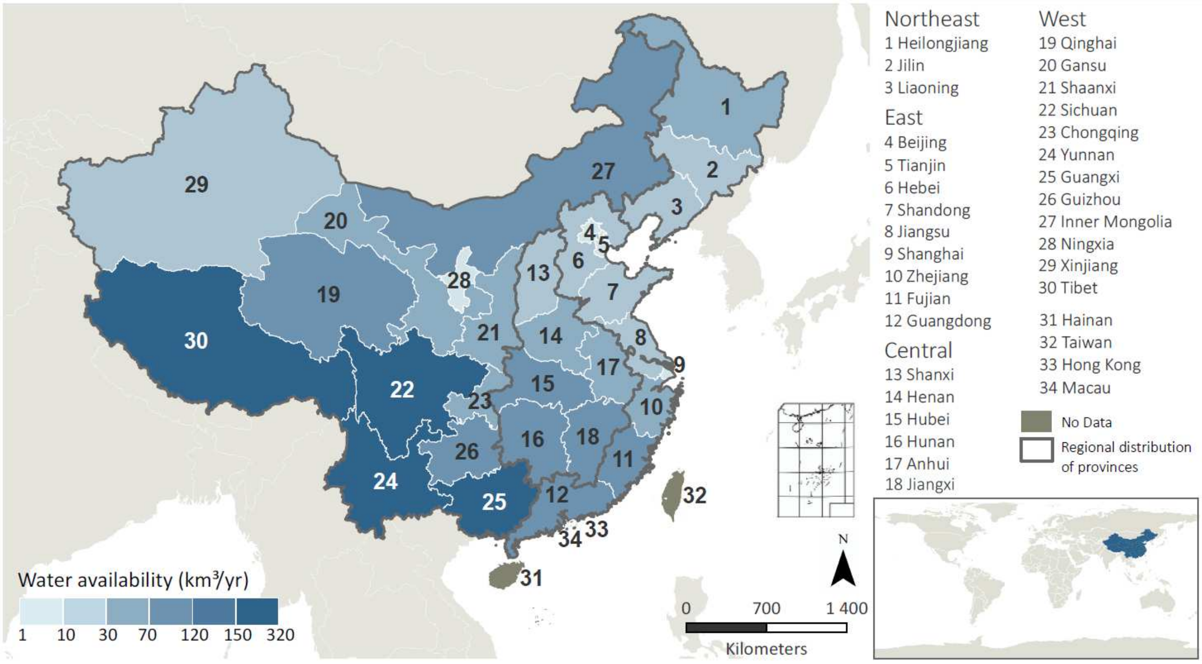


Figure 1. Study area. The study was conducted for thirty provinces in the continental mainland China (1-30). The other provinces with no data (31-34) are illustrated for clarity. This map also shows the average blue water availability for each province.

China's climate is highly diverse, ranging from humid southeast to arid northwest and polar tundra in the Tibet plateau. This spatial heterogeneity contributes to the local hydrology **(Chen et al., 2017)**. The most abundant water resources are located in the western provinces, including Tibet and Guizhou. In contrast, the scarcest available water resources, in relation to demand, are located in the coastal provinces on the Yellow Sea coast and on the belt from the bay to inland.

3 Results

The following sections elaborate the baseline status and projections of blue water withdrawals and water stress index.

3.1 Baseline status of blue water withdrawals and water stress index

In the baseline year 2010, there was a pronounced spatial heterogeneity in total BWW among provinces, e.g. Shandong's total BWW value was approximately 30 times greater than Tibet's **(Figure 2B; Table S1)**. The majority of the provinces with great total BWW values are located in East and Central China **(Figure 2B)**. When taking a closer look at the shares of the total BWW values, FS and ES accounted for a major proportion, ranging from 62.2 % to 94.6 % in these 30 provinces **(Figure 3; Table S1)**. Also, the contribution of FS surpassed ES nationwide **(Figure 3; Table S1)**. Therefore, FS played a leading role in intensifying water stress.

Altogether 27 out of 30 provinces suffered from different degrees of water stress. The WSI values of 30 % provinces (9 out of 30) were over 1 **(Figure 2A; Table S1)**. The provinces that experienced high water stress standing in the top tier included Tianjin (WSI = 3.63), Beijing (3.00), Shandong (2.36), and Hebei (2.06), which are mainly located in East China **(Figure 2A; Table S1)**. Whilst the provinces under no or low water stress are all from West China, namely Tibet, Qinghai, and Yunnan **(Figure 2A; Table S1)**.

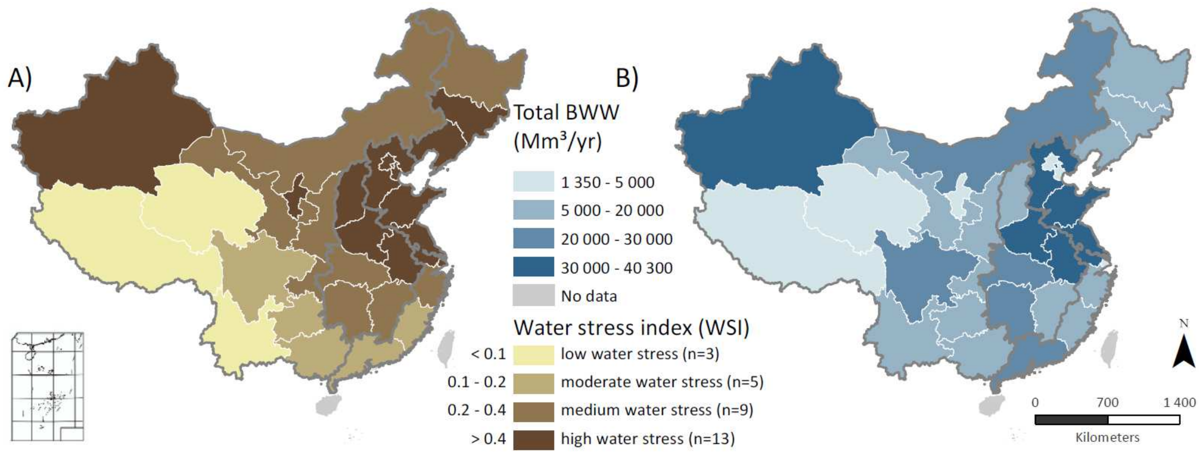


Figure 2. China's water stress index (WSI) (A) and total blue water withdrawals (BWW) (B) in the baseline year 2010.

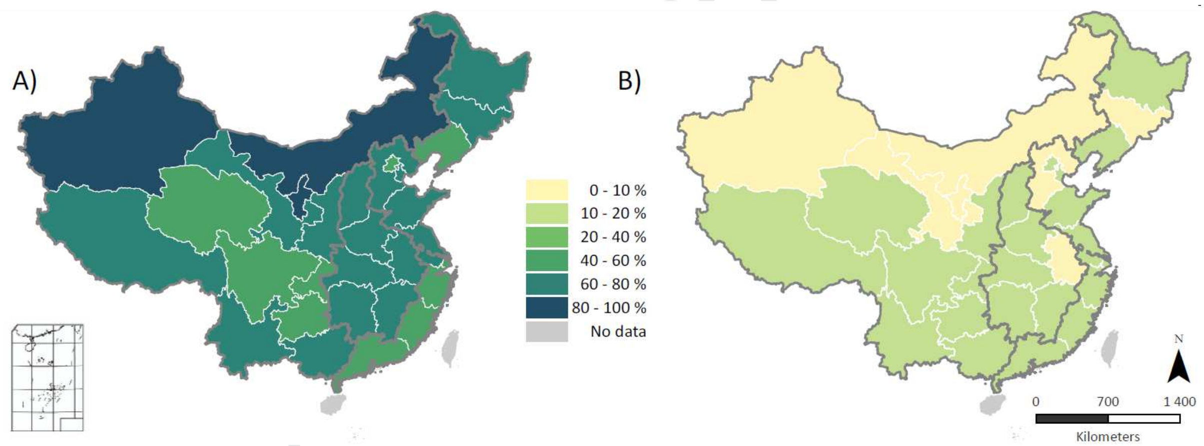


Figure 3. Shares of China's total blue water withdrawals (BWW) in food sector (A) and energy sector (B) in the baseline year 2010.

3.2 Projections of blue water withdrawals and water stress index

In order to display the envelope of the multitude of the scenario results, the best-case scenario (SC6) and worst-case scenario (SC1) are presented here. More detailed rationale of other scenarios can be found in **Table S2-18**.

With regard to the projected BWW, the best-case scenario (SC6) portrayed nearly nationwide decreasing or no changes in the total BWW (ranging from -16.2 % to 2.7 %), except for Hubei, while the worst-case scenario (SC1) manifested mostly increasing changes across the country (ranging from -11.8 % to 30.3 %), with the exception of Beijing, Tianjin, and Tibet **(Figure 4; Table S19)**.

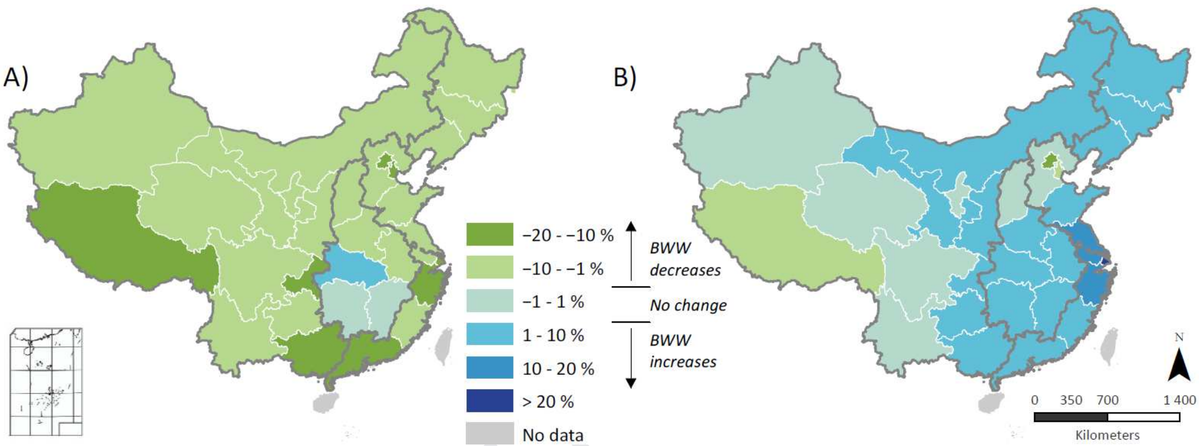


Figure 4. Relative changes of China's total blue water withdrawals (BWW) by 2030. A) Best-case scenario (SC6); and B) worst-case scenario (SC1). See scenario description in **Table 2**.

When zooming in on the sectoral BWF **(Table S22)**, the best-case scenario (SC6) showed that the BWF values in FS sunk in each province (ranging between -1.8 % and -43.8 %), whereas the values in ES dropping in the majority of the provinces as well (ranging from -7.2 % to -74.6 %). In contrast, half of provinces in Central China had soaring BWF changes in ES (ranging from 40.7 % to 90.3 %) **(Table S22)**. On the other hand, the worst-case scenario (SC1) indicated that the BWF values in ES climbed up nationwide, except for Tibet (-19.3 %), with a 42.3 % increase on average (ranging from 23.5 % to 95.8 %) **(Table S22)**. Whilst the BWF values in FS were diverse, as there were mostly decreasing changes in the eastern provinces (ranging from -36.6 % to 2.8 %) and increasing changes in the central and north-eastern provinces (ranging from -4.4 % to 15.4 %) **(Table S22)**. From the point of view of the absolute changes, most of eastern provinces had approximately 2-4 times greater increases in ES than other provinces **(Table S1-2)**.

In terms of the projected WSI, both the best-case scenario (SC6) and the worst-case scenario (SC1) unveiled that still 90 % of the provinces (27 out of 30) suffered from different degrees of water stress, and the WSI values of the same nine provinces remained over 1 **(Figure 2A; Table S13)**. Taking a closer look at the absolute changes of the WSI values, nationwide decrease or no changes were observed in the best-case scenario (SC6), except for Hubei, whereas the worst-case scenario (SC1) manifested mostly increasing changes, with the exception of Beijing, Tianjin, and Xinjiang **(Figure 5; Table S23)**. These results were in line with the changes in the total projected BWW.

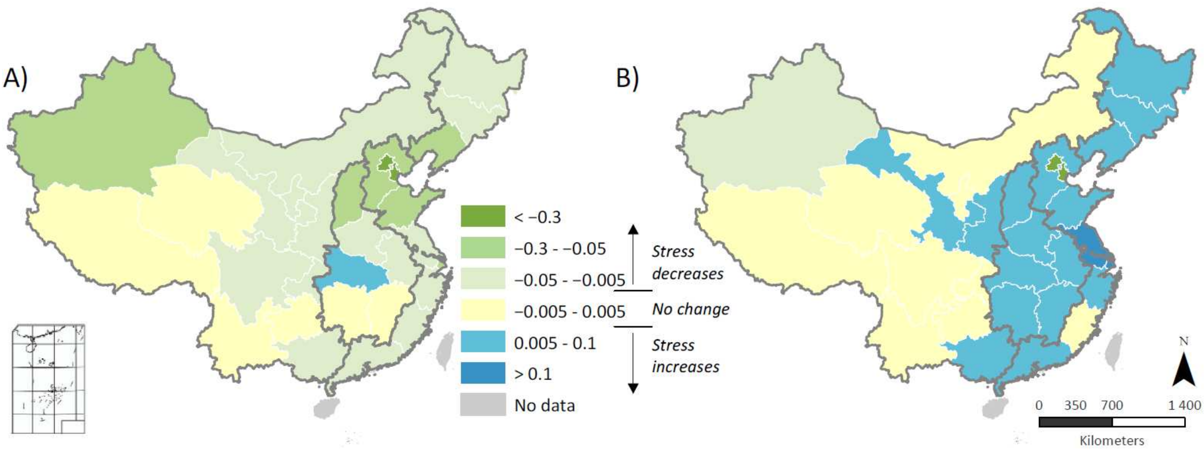


Figure 5. Absolute changes of China's water stress index (WSI) by 2030. (A) Best-case scenario (SC6); and (B) worst-case scenario (SC1).

Moreover, ES dominated in the best-case and worst-case scenarios across the country, especially in East China's provinces Beijing, Tianjin, and Shanghai **(Figure 6)**, when looking through the lens of the absolute changes of FS and ES contributions to WSI. It is noteworthy that ES is the sector that resulted in the substantial increases of the projected WSI, despite the fact that FS held the largest share of the total BWW in the baseline as well as in the scenarios **(Figure 3; Table S1 and S6)**.

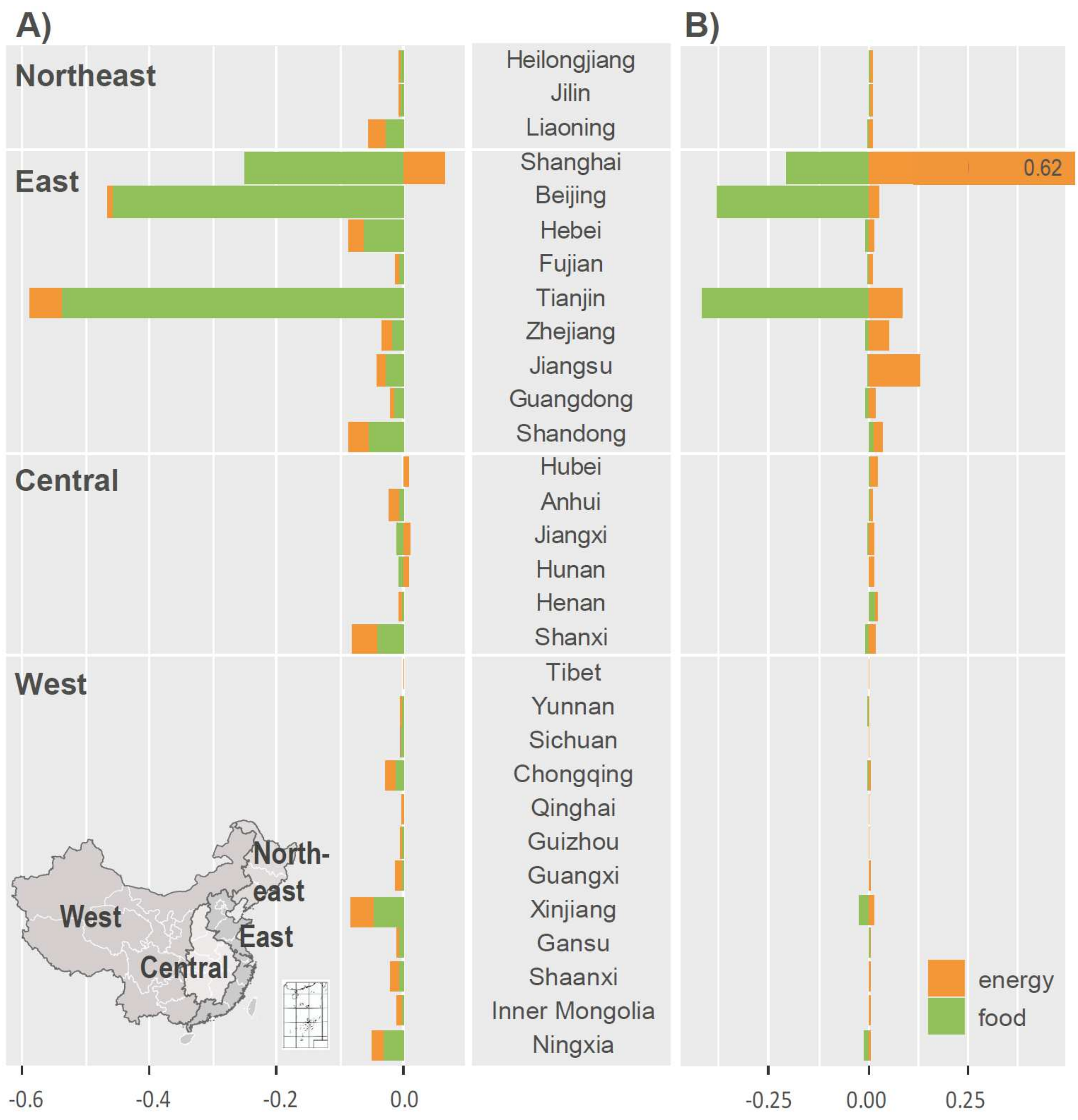


Figure 6. Absolute changes of contributions of food sector and energy sector to China's water stress index (WSI) by 2030. (A) Best-case scenario (SC6); and (B) worst-case scenario (SC1).

4 Discussion

The following sections focus on three aspects in detail: (1) sectoral water demand; (2) impacts of urbanization; and (3) limitations and the way forward.

4.1 Sectoral water demand

The results manifested distinct evidence of the imbalance of water availability for meeting the demand between FS and ES, which reveals that China's water, energy, and food security have been under duress. How to tackle this imbalance of sectoral water demand is thereby the key to enable and accelerate progress towards achieving China's sustainable WEF nexus by 2030.

A high level of water stress can affect food security as well as amplify competition and potential conflict among sectors **(United Nations, 2018)**. By far, agriculture accounts for 69 % of annual water withdrawals globally **(United Nations Educational, Scientific and Cultural Organization, 2019)**. In particular, irrigated agriculture is one of the main subsectors causing water stress **(Jägermeyr et al., 2015)**, thus increasing agricultural water productivity is an essential and efficient means of alleviating water use intensity **(Cai et al., 2016)**. The results unveiled that FS played a leading role in the baseline water stress, which is in line with the key findings of the previous study, i.e. primary industry (including FS) appeared to dominate the water use intensity and its water use intensity continued to be far higher than that of secondary industry (including ES) **(Cai et al., 2016)**. According to the projections, FS made less contribution to the WSI, even in the worst-case scenario (SC1) there was on average -3.9 % growth nationwide **(Figure 6; Table S22)**. However, the huge base quantity of FS shares shall be taken into account **(Figure 3)**.

In light of China's National Plan on Implementation of the 2030 Agenda for Sustainable Development (NPISD) **(Ministry of Foreign Affairs of China, 2016)**, the effective irrigation ratio is listed as one of three ''redlines" for the most stringent water resources management. This indicator is aimed to reach above 0.55 nationwide by 2020 **(Ministry of Foreign Affairs of China, 2016)**. The measures to achieve this goal are expected to include developing irrigation schemes and water-saving irrigation technologies to enhance agricultural water productivity as well as to upgrade manufacturing industry to accelerate the innovation-driven transformation on agricultural modernization **(Jägermeyr et al., 2017)**. Besides, China has issued the National Plan for Sustainable Agricultural Development (2015-2030) to ensure sustainable food production and to promote resilient agricultural practices **(Ministry of Foreign Affairs of China, 2016)**.

According to **Cai et al. (2016)**, China has been and will continue to experience industrial transition from primary industry towards secondary industry and tertiary industry, it is thus the reason why ES was the biggest contributor to both the increases of the total BWF and the WSI in the projections, given the fact that coal has been occupying an absolutely dominant proportion of energy sources for China's electricity production **(Cai et al., 2018b)**. In particular, the fundamental difference between the best-case scenario (SC6) and worst-case scenario (SC1) regarding ES is whether China would stick with the current policy scenario of electricity production before mid-2018 (SC1) or issue new sustainable-development policies that are adopted to the maximum of global temperature increase below 2 °C (SC6). The results showed that the coal-based electricity production within the worst-case scenario (SC1) exacerbated water stress across the country, whereas in the best-case scenario (SC6) the BWF in ES and the corresponding WSI were largely alleviated in most of the provinces **(Figure 6)**.

Low-carbon energy production usually saves water substantially **(Bridle and Attwood, 2015)**, and there is a clear shift in China's policies away from coal and towards cleaner alternative energy sources **(Zhou et al., 2019)**. In comparison with 2010 (20.0 %), the share of renewable energy, including hydropower, nuclear power, and wind power, in the electricity mix rose to 25.6 % and 26.8 % in 2015 and 2016, respectively **(National Bureau of Statistics of China 2018)**. According to China's NPISD **(Ministry of Foreign Affairs of China, 2016)**, the share of non-fossil fuels in primary energy consumption aims at increasing to about 20 % by 2030. However, the development of renewable energy for electricity production has been experiencing several following hindrances: (1) the widespread coal subsidies for producers and consumers **(Bridle and Attwood, 2015)**; (2) the worsening electricity waste generated by solar and wind power, due to insufficient grid construction and transmission **(Stanway, 2017)**; and (3) the promotion of gas-based electricity production, owing to the fact that natural gas will become China's main energy source, together with non-fossil fuels **(Ministry of Foreign Affairs of China, 2016)**.

As noted above, the interlinkages and interdependencies of SDG 6 (water), SDG 7 (energy), and SDG 2 (food) across the 2030 Agenda articulate the significance of the WEF nexus. Several challenges still remain for sound operationalization of this nexus, due to the lack of systematic tools that could address all the trade-offs involved **(Liu et al., 2017)**. To achieve the sustainable WEF nexus by 2030, China needs policy coherence and synergies, which remain missing in either its NPISD or other long-term action plans. Integrated thinking is required to place the nexus to the center in meeting the demands across water, energy, and food sectors. Moreover, policy-making is a dynamic process and its effects ought to be reviewed regularly to ensure the adequacy of any follow-up procedures **(Cai et al., 2016)**. It is heretofore of prime importance and necessity to comprehend how and when to synchronize those national targets representing water, energy, and food security in every stage of the timeline in order to contribute most to China's sustainable WEF nexus by 2030 **(Cai et al., 2016, 2018b)**.

4.2 Impacts of urbanization

China is at the midst of an unprecedented urbanization development, with approximately 20 million new urban dwellers per year **(Cai et al., 2018a)**. This rapid and perennial development has substantially affected the extent of water availability as well as food consumption and energy production. In line with the analysis of spatial heterogeneity, particularly the coastal provinces in East China have been experiencing substantial stress across water, energy, and food sectors. It is due to their more developed socioeconomics in comparison with inland provinces, by having advantages in geographical conditions and corresponding preferential policies **(Varis and Kummu, 2019)**.

While approaching to becoming a high-income country, consumption and living patterns in China's cities undergo a radical change towards a consumeristic culture, such as the shift to meat-rich diets including more dairy products, which is one of the key drivers for growing water demand **(Godfray et al, 2018)**. According to the estimation by **Gu et al. (2019)**, China would need to increase its cropland area by 40 % from 2010 levels to 227 million hectares. Apart from dietary changes, food waste is another critical concern regarding water and food security **(Kummu et al 2012)**, owing to the fact that China's cities dump 18 million tons of uneaten food each year **(Gu et al., 2019)**. Reducing food waste by three-quarters would cut this aforementioned requirement to 200 million hectares **(Gu et al., 2019)**. As **Hoekstra et al. (2014)** pointed out that meat and dairy consumption can be a blind spot in water policy, it is difficult for policy-makers to comprehend the interlinkages and interdependence between animal-based food products and water stress. China made a commitment in its NPISD to launch nuritition improvement projects, as well as to conduct publicity and education campaigns on health and nutritition knowledge **(Ministry of Foreign Affairs of China,**

2016), yet the nutrition guiance and intervention does not explicitly include the recommdations on dietary changes underscoring more plant-based food comsumption.

Many studies, such as **Jiang and Lin (2012)** and **Yuan et al. (2015)**, have revealed a positive relation between China's urbanization and energy-related CO_2 emissions, in particular with regard to residential consumption. Given the dominance of coal in energy production structure for a long time, China's water and energy security have been deeply intertwined **(Cai et al., 2018b)**. To achieve the transition away from coal to cleaner fuels as well as advance the low-carbon and green urbanization model **(Gass et al., 2016)**, China has set a bunch of ambitious goals in its NPISD, along with the National New-type Urbanization Plan (2014-2020), the action plan for 1000 low-carbon cities, and the regional pilot cap-and-trade programs **(Ministry of Foreign Affairs of China, 2016)**. It is still too early to envision what progress can be achieved and by when **(Cai et al., 2018b)**. However, implementing these measures shall be a participatory process on the basis of inter-sectoral coordination and greater engagement of citizens. For instance, China launched a pilot run of residential tiered electricity pricing reforms in 2012, to the authors' knowledge, which mainly lies in the price differences between rush hours and peak hours. In Finland, besides that, electricity companies also offer the price options for consumers to choose how electricity is generated, i.e. by renewable energy alone or combined with other energy sources. Where policy-making is prepared to move towards greater participation and transparency, significant policy gains in effectiveness can be achieved.

4.3 Limitations and the way forward

With regard to food production, it was assumed that all food would be produced in China, and thus food imports were excluded. It was also assumed that food would be produced locally, and therefore food trade inside China was not considered either. Also, other factors limiting food production were not taken into account, due to the fact that these results do not consider the quality of water and arable land, to mention a few. It should be noted that food security cannot be explained only in the context of water quantity, as water quality is another crucial factor **(Chen, 2007)**. For instance, food security has been exposed to threat, owing to harmful subsidies in dairy resulting from polluted waters **(Squires et al., 2015)**. **Cai et al. (2017)** pointed out that water quality deterioration is strongest in China's water scarce areas. Therefore, the inclusion of water quality in a WEF nexus analysis such as the present one would evidently exacerbate the seriousness of water problems, particularly in water stressed areas of China.

In terms of water withdrawals for electricity production, the share of each province in national production was assumed to remain unchanged in 2030. So, possible replacement of production was not considered. Also, water withdrawals per produced unit of electricity were not considered to change, and accordingly improvements in technology were not taken into account in the results. It should be noted that the scenarios only considered water required for generating electric power, and excluded water demands for, such as coal mining and washing as well as primary energy industry in general. Hence, the analysis underestimated the total water demand for China's energy industry.

Another limitation deriving from the approach is to consider only BWF for FS and ES, which denotes that green water was not addressed in this study. Green water footprint should be addressed more thoroughly given that biomass energy production has been strongly promoted **(Zhao, 2016)**. Also according to the scenario results, the consumption of dairy products is projected to grow. This may assign possible competition over land and green water between

FS and ES, which would help achieve more comprehensive understanding about the inter-sectoral dynamics and competition over water availability.

5 Conclusions

It was for the first time that a quantitative spatial scenario analysis was performed, for assessing the competition for water between food and energy sectors in China's water stressed provinces by 2030 in the context of urbanization. The scenario results unveiled an imbalance of water availability for meeting the demand between food and energy sectors. They can be summarized as follows: (1) food sector played the leading role in the baseline water stress; (2) energy sector substantially causes the increases of the projected water stress index; and (3) the rapid and perennial urbanization has substantially affected the extent of water availability, particularly in the eastern provinces.

As tackling the imbalance of sectoral water demand in the context of China's urbanization is the key in enabling and accelerating the progress towards achieving the country's sustainable water-energy-food nexus by 2030, it shall require the following three changes in China's policy-making.

- China needs policy coherence and synergies, with the integrated thinking of placing the nexus to the center in meeting the demands across water, energy, and food sectors.
- China needs to ensure the adequacy of any follow-up procedures, by synchronizing national targets representing water, energy, and food security in every stage of the timeline. Those targets should level water consumption to sustainable quantities.
- China needs to embrace its policy-making towards greater participation and transparency, to optimize important policy gains in effectiveness.

Acknowledgements

This study was funded by Aalto University core funds, Maa- ja vesitekniikan tuki ry, Emil Aaltonen Foundation funded project "Eat-Less-Water", and European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 819202). The thorough and insightful comments of the editor and anonymous reviewers are greatly appreciated.

References

Bridle, R., Attwood, C., 2015. Coal and Renewables in China: GSI Report. Winnipeg. www.iisd.org/gsi/sites/default/files/ffs_china_coalrenewablesreport.pdf (accessed 30.11.19).

Cai, B., Zhang, B., Bi, J., Zhang, W., 2014. Energy's thirst for water in china. Environ. Sci. Technol. 48, 11760–11768. doi.org/10.1021/es502655m

Cai, J., Kummu, M., Niva, V., Guillaume, J.H.A., Varis, O., 2018a. Exposure and resilience of China's cities to floods and droughts: a double-edged sword. Int. J. Water Resour. Dev. 34, 547–565. doi.org/10.1080/07900627.2017.1353411

Cai, J., Varis, O., Yin, H., 2017. China's water resources vulnerability: A spatio-temporal analysis during 2003–2013. J. Clean. Prod. 142, 2901–2910. doi.org/10.1016/J.JCLEPRO.2016.10.180

Cai, J., Yin, H., Varis, O., 2018b. Impacts of urbanization on water use and energy-related CO2 emissions of residential consumption in China: A spatio-temporal analysis during

2003–2012. J. Clean. Prod. 194, 23–33. doi.org/10.1016/J.JCLEPRO.2018.05.117

Cai, J., Yin, H., Varis, O., 2016. Impacts of industrial transition on water use intensity and energy-related carbon intensity in China: A spatio-temporal analysis during 2003–2012. Appl. Energy 183, 1112–1122. doi.org/10.1016/j.apenergy.2016.09.069

Carlowicz, M., 2017. New Night Lights Maps Open Up Possible Real-Time Applications. www.nasa.gov/feature/goddard/2017/new-night-lights-maps-open-up-possible-real-time-applications (accessed 30.11.19).

Chen, J., 2007. Rapid urbanization in China: A real challenge to soil protection and food security. Catena 69, 1–15. doi.org/10.1016/j.catena.2006.04.019

Chen, W., Wu, S., Lei, Y., Li, S., 2017. China's water footprint by province, and inter-provincial transfer of virtual water. Ecol. Indic. 74, 321–333. doi.org/10.1016/j.ecolind.2016.11.037

Cui, Y., Liu, J., Xu, X., Dong, J., Li, N., Fu, Y., Lu, S., Xia, H., Si, B., Xiao, X., 2019. Accelerating Cities in an Unsustainable Landscape: Urban Expansion and Cropland Occupation in China, 1990–2030. Sustainability-Basel 11(8), 2283. doi:10.3390/su11082283

Dwivedi, S.L., Lammerts van Bueren, E.T., Ceccarelli, S., Grando, S., Upadhyaya, H.D., Ortiz, R., 2017. Diversifying Food Systems in the Pursuit of Sustainable Food Production and Healthy Diets. Trends in Plant Science 22(10), 842-856. doi.org/10.1016/j.tplants.2017.06.011

Food and Agriculture Organization of the United Nations, 2016. AQUASTAT. www.fao.org/nr/water/aquastat/water_use/index.stm (accessed 30.11.19).

Fukase, E., Martin, W., 2016. Who Will Feed China in the 21st Century? Income Growth and Food Demand and Supply in China. J. Agric. Econ. 67, 3–23. doi.org/10.1111/1477-9552.12117

Gass, P., Duan, H., Gerasimchuk, I., 2016. Stories of Coal Phase-Out: Lessons learned for China. Winnipeg. www.iisd.org/sites/default/files/publications/stories-coal-phase-out-lessons-learned-for-china.pdf (accessed 30.11.19).

Godfray, C. H. J., Aveyard, P., Garnett, T., Hall, J. W., Key, T. J., Lorimer, J., Pierrehumbert, R. T., Scarborough, P., Springmann, M., Jebb, S. A., 2018. Meat consumption, health, and the environment. Science 361 (6399), aam5324. doi.org/10.1126/science.aam5324

Gu, A., Teng, F., Lv, Z., 2016. Exploring the nexus between water saving and energy conservation: Insights from industry sector during the 12th Five-Year Plan period in China. Renew. Sustain. Energy Rev. 59, 28–38. doi.org/10.1016/j.rser.2015.12.285

Gu, B., Zhang, X., Bai, X., Fu, B., Chen, D., 2019. Four steps to food security for swelling cities. Nature 566, 31–33. doi.org/10.1038/d41586-019-00407-3

Hoekstra, A.Y., 2014. Water for animal products: a blind spot in water policy. Environ. Res. Lett. 9, 091003. doi.org/10.1088/1748-9326/9/9/091003

Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: Water use by people as a function of their consumption pattern. Water Resour. Manag. 21, 35–48. doi.org/10.1007/s11269-006-9039-x

Huang, F., Liu, Z., Ridoutt, B.G., Huang, J., Li, B., 2015. China's water for food under growing water scarcity. Food Secur. 7, 933–949. doi.org/10.1007/s12571-015-0494-1

Huang, Z., Hejazi, M., Li, X., Tang, Q., Vernon, C., Leng, G., Liu, Y., Döll, P., Eisner, S., Gerten, D., Hanasaki, N., Wada, Y., 2018. Reconstruction of global gridded monthly sectoral water withdrawals for 1971–2010 and analysis of their spatiotemporal patterns. Hydrol. Earth Syst. Sci. 22(4), 2117-2133. doi.org/10.5194/hess-22-2117-2018

International Energy Agency, 2019. Global Energy & CO_2 Status Report 2018: The latest trends in energy and emissions in 2018. webstore.iea.org/global-energy-co2-status-report-2018 (accessed 30.11.19).

Jägermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M., Lucht, W., 2015. Water savings potentials of irrigation systems: global simulation of processes and linkages. Hydrol. Earth Syst. Sci. 19, 3073–3091. doi.org/10.5194/hess-19-3073-2015

Jägermeyr, J., Pastor, A., Biemans, H., Gerten, D., 2017. Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. Nat Commun 8, 15900. doi.org/10.1038/ncomms15900

Jalava, M., Kummu, M., Porkka, M., Siebert, S., Varis, O., 2014. Diet change—a solution to reduce water use? Environ. Res. Lett. 9, 074016. doi.org/10.1088/1748-9326/9/7/074016

Jiang, Z.J., Lin, B.Q., 2012. China's energy demand and its characteristics in the industrialization and urbanization process. Energ Policy 49, 608-615. doi.org/10.1016/j.enpol.2012.07.002

Jiang, L., O'Neill, B.C., 2014. Global urbanization projections for the Shared Socioeconomic Pathways. Glob. Environ. Chang. 42, 193–199. doi.org/10.1016/j.gloenvcha.2015.03.008

Keskinen, M., Guillaume, J.H.A., Kattelus, M., Porkka, M., Räsänen, T.A., Varis, O., 2016.

The Water-Energy-Food Nexus and the Transboundary Context: Insights from Large Asian Rivers. Water 8. doi.org/10.3390/w8050193

Klein Goldewijk, K., Beusen, A., Janssen, P., 2010. Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. The Holocene 20, 565–573. doi.org/10.1177/0959683609356587

Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., Ward, P.J., 2012. Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Sci Total Environ 438, 477-489. doi.org/10.1016/j.scitotenv.2012.08.092

Kummu, M., Guillaume, J.H.A., de Moel, H., Eisner, S., Flörke, M., Porkka, M., Siebert, S., Veldkamp, T.I.E., Ward, P.J., 2016. The world’s road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. Sci Rep-Uk 6, 38495. doi.org/10.1038/srep38495

Liu, J., Yang, H., Cudennec, C., Gain, A.K., Hoff, H., Lawford, R., Qi, J., Strasser, L. de, Yillia, P.T., Zheng, C., 2017. Challenges in operationalizing the water–energy–food nexus. Hydrol. Sci. J. 62, 1714–1720. doi.org/10.1080/02626667.2017.1353695

Liu, J., Yang, H., Gosling, S.N., Kummu, M., Flörke, M., Pfister, S., Hanasaki, N., Wada, Y., Zhang, X., Zheng, C., Alcamo, J., Oki, T., 2017. Water scarcity assessments in the past, present, and future. Earth's Future 5(6), 545-559. doi.org/10.1002/2016ef000518

Mekonnen, M.M., Gerbens-Leenes, P.W., Hoekstra, A.Y., 2016. Future electricity: The challenge of reducing both carbon and water footprint. Sci. Total Environ. doi.org/10.1016/j.scitotenv.2016.06.204

Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15(5), 1577-1600. doi.org/10.5194/hess-15-1577-2011

Ministry of Foreign Affairs of China, 2017. China’s Progress Report on Implementation of the 2030 Agenda for Sustainable Development. Beijing. www.chinadaily.com.cn/specials/China'sProgressReport2(CN).pdf (accessed 30.11.19).

Ministry of Foreign Affairs of China, 2016. China’s National Plan on Implementation of the 2030 Agenda for Sustainable Development. Beijing. www.fmprc.gov.cn/mfa_eng/zxxx_662805/W020161014332600482185.pdf (accessed 30.11.19).

National Bureau of Statistics of China, 2016. China Statistical Yearbook 2015. China Statistics Press, Beijing.

National Bureau of Statistics of China, 2018. China Statistical Yearbook 2017. China Statistics Press, Beijing.

O’Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2014. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. doi.org/10.1016/j.gloenvcha.2015.01.004

OECD/IEA, 2018. World Energy Outlook 2018. Paris. webstore.iea.org/world-energy-outlook-2018 (accessed 30.11.19).

Stanway, D., 2017. China renewable power waste worsens in 2016.

governorswindenergycoalition.org/china-renewable-power-waste-worsens-in-2016-greenpeace/ (accessed 30.11.19).

Squires, V.R., Hua, L., Wang, G., 2015. Food security : A multi-faceted and multi-dimensional issue in China. Journal of Food, Agriculture & Environment 13(2), 24-31. doi.org/10.1234/4.2015.3921

United Nations, 2017. Comprehensive Assessment of the Freshwater Resources of the World. New York. www.un.org/ga/search/view_doc.asp?symbol=E/CN.17/1997/9&Lang=E (accessed 30.11.19).

United Nations, 2018. Sustainable Development Goal 6: Synthesis Report on Water and Sanitation. New York. www.unwater.org/app/uploads/2018/12/SDG6_SynthesisReport2018_WaterandSanitation_04122018.pdf (accessed 30.11.19).

United Nations, 2019. World Urbanization Prospects: The 2018 Revision. New York. population.un.org/wup/Publications/Files/WUP2018-Report.pdf (accessed 30.11.19).

United Nations Educational, Scientific and Cultural Organization, 2019. The United Nations World Water Development Report 2019: Leaving no on behind. Paris. unesdoc.unesco.org/ark:/48223/pf0000367306 (accessed 30.11.19).

van Ginkel, H., 2008. Urban Future. Nature 456, 32. doi.org/10.1038/twas08.32a

Varis, O., Keskinen, M., 2018. Discussion of “Challenges in operationalizing the water–energy–food nexus.” Hydrol. Sci. J. 63, 1863–1865. doi.org/10.1080/02626667.2018.1545094

Varis, O., Kummu, M., 2019. The demanding quest for harmony: China's polarizing freshwater resilience map. Environ Res Lett 14(5), 054015. doi.org/10.1088/1748-9326/ab1040

Varis, O., Kummu, M., Lehr, C., Shen, D., 2014. China's stressed waters: Societal and environmental vulnerability in China's internal and transboundary river systems. Appl. Geogr. 53, 105–116. doi.org/10.1016/j.apgeog.2014.05.012

Vörösmarty, C.J., Douglas, E.M., Green, P.A., Revenga, C., 2005. Geospatial indicators of emerging water stress: an application to Africa. Ambio 34, 230–236. doi.org/https://doi.org/10.1579/0044-7447-34.3.230

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global Water Resources: Vulnerability from Climate Change and Population Growth. Science (80). 289, 284–288. doi.org/10.1126/science.289.5477.284

Wang, Q., 2014. Effects of urbanisation on energy consumption in China. Energy Policy 65, 332–339. doi.org/10.1016/j.enpol.2013.10.005

World Bank, 2019. World Bank Open Data. data.worldbank.org (accessed 30.11.19).

Xiang, X., Svensson, J., Jia, S., 2016. Will the energy industry drain the water used for agricultural irrigation in the Yellow River basin? Int. J. Water Resour. Dev. 0627, 1–12. doi.org/10.1080/07900627.2016.1159543

Yan, T., Wang, J., Huang, J., 2015. Urbanization, agricultural water use, and regional and national crop production in China. Ecol. Modell. 318, 226–235. doi.org/10.1016/j.ecolmodel.2014.12.021

Yuan, B.L., Ren, S.G., Chen, X.H., 2015. The effects of urbanization, consumption ratio and consumption structure on residential indirect CO2 emissions in China: A regional comparative analysis. Appl Energ 140, 94-106. doi.org/10.1016/j.apenergy.2014.11.047

Zhang, S., Yi, B.-W., Worrell, E., Wagner, F., Crijns-Graus, W., Purohit, P., Wada, Y., Varis, O., 2019. Integrated assessment of resource-energy-environment nexus in China's iron and steel industry. J Clean Prod 232, 235-249. doi.org/10.1016/j.jclepro.2019.05.392

Zhao, G., 2016. Assessment of potential biomass energy production in China towards 2030 and 2050. Int. J. Sustain. Energy 1–20. doi.org/10.1080/14786451.2016.1231677

Zheng, Z., Henneberry, S.R., Zhao, Y., Gao, Y., 2019. Predicting the changes in the structure of food demand in China. Agribusiness 35(3), 301-328. doi.org/10.1002/agr.21592

Zhou, N., Zhang, J., Khanna, N., Fridley, D., Jiang, S., Liu, X., 2019. Intertwined impacts of water, energy development, and carbon emissions in China. Appl. Energy 238, 78–91. doi.org/10.1016/J.APENERGY.2018.12.085

Appendix A. Supplementary information

Supplementary information associated with this article can be found, in the online version, at XXX.

China's sustainable water-energy-food nexus by 2030: Impacts of urbanization on sectoral water demand

Venla Niva, Jialiang Cai*, Maija Taka, Matti Kummu, Olli Varis

Water & Development Research Group, Department of Built Environment, Aalto University, P.O. Box 15200, FI-00076 Aalto, Finland

**Corresponding author*: Jialiang Cai (jialiang.cai@aalto.fi; caijialiang.pku@gmail.com)

Highlights

- The impacts of China's urbanization on sectoral water demand were assessed.
- An integrated and quantitative spatial scenario analysis was performed.
- Food sector played the leading role in the baseline water stress.
- Energy sector substantially causes the increases of the projected water stress index.
- Tackling imbalanced sectoral water demand is the key to sustainable water-energy-food nexus.

China's sustainable water-energy-food nexus by 2030: Impacts of urbanization on sectoral water demand

Venla Niva, Jialiang Cai*, Maija Taka, Matti Kummu, Olli Varis

Water & Development Research Group, Department of Built Environment, Aalto University, P.O. Box 15200, FI-00076 Aalto, Finland

**Corresponding author*: Jialiang Cai (jialiang.cai@aalto.fi; caijialiang.pku@gmail.com)

Declaration of Interest Statement

The authors declare that there is no conflict of interest.