

Trans-regional rice supply paradigm reveals unsustainable water use in China

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Abstract

Rice is an important staple food for more than half of the global population and one of the largest water consumers on earth. Improving the efficiency of water embedded in rice production and supply could have great implications for food and water security. This study starts from Yunnan, a traditional rice producing and consuming province in southwest China, and analyses its rice supply structure and dynamics, together with embedded water footprints (WFs) of three other regions: Northeast China, South and Southwest China and Southeast Asia. The results show that Yunnan has been through drastic food change in the past decades, leading to an increasing production and supply gap. Yunnan is found to have the least WF (778.2 m³/t) for rice production across the study regions, while Northeast China consumes the highest blue WF (364.6 m³/t) and blue to total WF ratio (97.7%). The study indicates that Northeast China is at risk of groundwater deficit due to rice production and export and the current rice production and consumption pattern is inefficient. The study suggests that policies for groundwater extraction, water resource price and international trade need to be in place to ensure sustainable food supply and water use at regional and national levels.

Keywords: Food trade; Rainwater use efficiency; Rice supply; Sustainability; Water footprint

Highlights

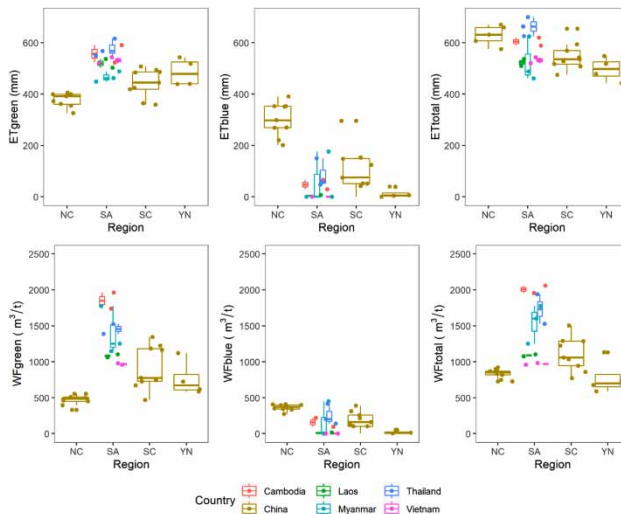
- Yunnan's rice supply and its water footprint from different transboundary regions are analyzed from the food-water nexus perspective.
- Rice supply in Yunnan is found to have a cascading effect on water security in Northeast China, and the current rice supply paradigm could be both unsustainable and inefficient for water use.
- This study shows the incremental needs to manage groundwater use and adjust the trading policy in China.

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Graphical Abstract



1. Introduction

Food and water insecurity are two of the biggest challenges for Earth and its people are working to reach the 2030 agenda for sustainable development goals (SDGs), which was adopted by all United Nations Member States in 2015. By 2030, the global food system would have to grow enough food to support over 8.5 billion people on limited water resources, while other water demands, such as residential needs, industrial requirements and environmental functions, are also growing fast (Heilig *et al.*, 2000; Vaux, 2012; Davis *et al.*, 2017; United Nations, 2019). Furthermore, changing precipitation patterns and overuse of surface water and groundwater in some of the cropping regions will further threaten food distribution and availability in the near future (Lam *et al.*, 2013; Dalin *et al.*, 2015; Huang *et al.*, 2015).

China's per capita water demand is only a quarter of the global average level (Heilig *et al.*, 2000; Dalin *et al.*, 2015; Huang *et al.*, 2015; Cao *et al.*, 2018). However, the challenges in food production in China lie not only in water scarcity but also in the temporal and spatial mismatch of water resources, which have resulted in imbalanced as well as low-efficient food production and supply patterns (Dalin *et al.*, 2015). In the past four decades, agricultural intensification has transformed China's Northern and Northeast plain regions into grain warehouses, while rapid industrialization and modernization have transformed the economic structure and population distribution pattern, which means that massive crops are growing in the water-deficient north, but are consumed in the water-sufficient south, leading to mismatch of food production and water consumption pattern, and increase of food trade between the north and the south, and between the east and the west (Ma *et al.*, 2006; Huang *et al.*, 2017; Chen *et al.*, 2018; Cai *et al.*, 2019).

Rice (*Oryza sativa*) is a staple food for more than half of the world's population and is amongst the three major staple grains in China, with annual production exceeding 200 million tons in the past decade (data from the National Bureau of Statistics). It is also the most water consuming crop in China, accounting for about 51.1% of the total water consumption of all crops (Han *et al.*, 2019). In the past two decades, as Northeast China (NC) has become a major rice producer and exporter, the Northeast rice products have dominated the domestic market owing to its gigantic production, high quality and competitive price. Meanwhile, the agricultural water consumption pattern of the country has also shifted northward, leading to escalating water risks in this region.

There is consensus that, in a commercialized and modernized world, more and more regions are connected by complex webs of information, goods, services and capital (Eakin *et al.*, 2017). International food trade has been identified as an important reason for groundwater depletion worldwide, with 11% of nonrenewable groundwater use for irrigation being embedded in international food trade (Dalin *et al.*, 2017). However, most studies that relate food with water footprint (WF) have been focusing on either international trade (Biewald *et al.*, 2014; Ali *et al.*, 2017; Rosa *et al.*, 2019) or intra-provincial trade (Faramarzi *et al.*, 2010; Dalin *et al.*, 2014, 2015, 2017; Wu *et al.*, 2018), but very little work has crossed the border to cover both (but see Dalin *et al.* (2014)). Another category of studies focused on spatial cropping patterns and the roles of international trade in saving water and bridging the gap between water demand and supply countries or regions (Hoekstra & Hung, 2005; Chapagain *et al.*, 2006).

The concept and techniques of WF have been applied in most of the above-mentioned studies and have proved to be very useful in linking the environmental, societal and economic characteristics of water and food production (Chapagain *et al.*, 2006; Chapagain & Hoekstra, 2011; Hoekstra *et al.*, 2011; D'Odorico *et al.*, 2020). The WF of crop production is the total amount of freshwater that is consumed and used during the crop growing process, and it includes green, blue and gray WFs (Hoekstra *et al.*, 2011; Li *et al.*, 2018). Green WF refers to the volume of precipitation consumed, blue WF refers to the volume of surface water or groundwater consumed, while gray WF is a measure of pollution, which is expressed as the volume of freshwater required to assimilate the load of pollutants to meet ambient water quality standards during the process of crop growth (Hoekstra *et al.*, 2011; Li *et al.*, 2018). Over the last decade or two, a majority of the studies worldwide that have arisen to mitigate or overcome the problem of water scarcity have been focusing on the issue of total WFs, for instance, by improving irrigation efficiency, using better agricultural practices like mulching and drip irrigation and enhancing water productivity, whereas other suggested solutions focused on changing diets and reducing food losses to diminish water consumption, etc. (Bouman, 2007; Chukalla *et al.*, 2015; Deng *et al.*, 2018; Chouchane *et al.*, 2020). Less focus has been put on the components of WF, especially the WF_{blue} (Chapagain & Hoekstra, 2011).

In this study, provincial and international rice trades are linked by the food balance sheet of Yunnan (YN) province of China, and transboundary virtual WFs embedded in rice production are investigated. YN is selected as an entry point because it is located in the southwest border of China, and has been a traditional rice planting and consuming province. However, during the past decade, it has been importing rice from NC, rather than its neighboring provinces or its neighboring countries of Southeast Asia (SA). This rice production and supply pattern might have significant impacts and implications for enhancing the food provision and water resources of associated regions, and for optimizing agricultural and trade policies across these regions.

2. Materials and methods

2.1. YN's rice supply

YN's rice production and supply structure and dynamics between 1978 and 2017 are recovered based on YN's Statistic Year Books and the provincial rice balance sheet offered by the Bureau of Grain Administration of YN. Four sources are identified for YN's rice supply, i.e., YN province, NC provinces, South and Southwest China (SC) provinces and SA countries (Figure 1). NC includes Heilongjiang, Jilin and Liaoning provinces, SC includes Guangxi, Guizhou, Hunan, Chongqing and Sichuan provinces, whereas all five countries in the Indo-China Peninsula, that is Vietnam, Laos, Cambodia, Myanmar and Thailand are grouped as SA. This treatment is based on the fact that, in China, most of the *Jing*¹ rice is produced in the northern regions, including NC, Jiangsu and Anhui provinces, while most *Xian* rice is produced in the southern region, including YN and its neighboring provinces. Rice produced in the Southeast Asian countries can also be categorized as *Xian* rice due to its tropical origin, grain shape and non-sticky features when cooked (GRSP, 2013). Rice production in NC, SC and YN is highly dependent on irrigation to maintain yield, wherever surface water is not available or sufficient to cover water needs, groundwater is extracted. In SA, most water comes from either rainwater or floods.

The reason to include SA in the analysis is because this region has a comparative advantage in terms of rice production, such as fewer chemical remnants and cheaper prices, and is therefore regarded as an important player in the global rice market. The SA countries are also willing to sell rice to China in exchange for cash and industrial products. However, the Chinese government has been strictly limiting rice import in order to protect the domestic rice sector, and has restrained YN from importing rice from these countries, and indirectly pushed YN to buy rice from other provinces, such as NC provinces, to meet their increasing demands for rice.

2.2. WF for food consumption

A top-down approach is used to calculate the WF of YN's supply of rice (Hoekstra et al., 2011; Kalvani et al., 2019). The provincial WF of rice supply is decided by three parts:

$$WF_{yn, cons} = WF_{yn, prod} + V_i - V_e \quad (1)$$

In which, $WF_{yn, prod}$ refers to the WF of YN's supply of rice that is produced and consumed in YN, while V_i and V_e refer to the imported or exported WF that are either produced or consumed outside of YN, respectively, including trades with both other countries and provinces. Both V_i and V_e can be

¹ There are mainly two systems of rice production: wetland systems and upland systems. About 85% of the rice harvest area in the world is derived from wetland systems. In China, most rice plantation is in wetland, but could generally be classified into two varieties with regard to chemical composition, shape and taste, i.e. *Jing* rice and *Xian* rice, which corresponding to *Oryza sativa ssp. Japonica* and *O. sativa ssp. Indica*, respectively. The *Jing* rice is more adapted to the temperate regions and tropical uplands, with major distribution regions in NC and northern part of Jiangsu and Anhui provinces. The *Xian* rice is more adapted to tropics, with major distribution regions in southern China. Due to mountainous geography, YN also has a marginal production of *Jing* rice under upland system; however, its commercial production is quite limited.

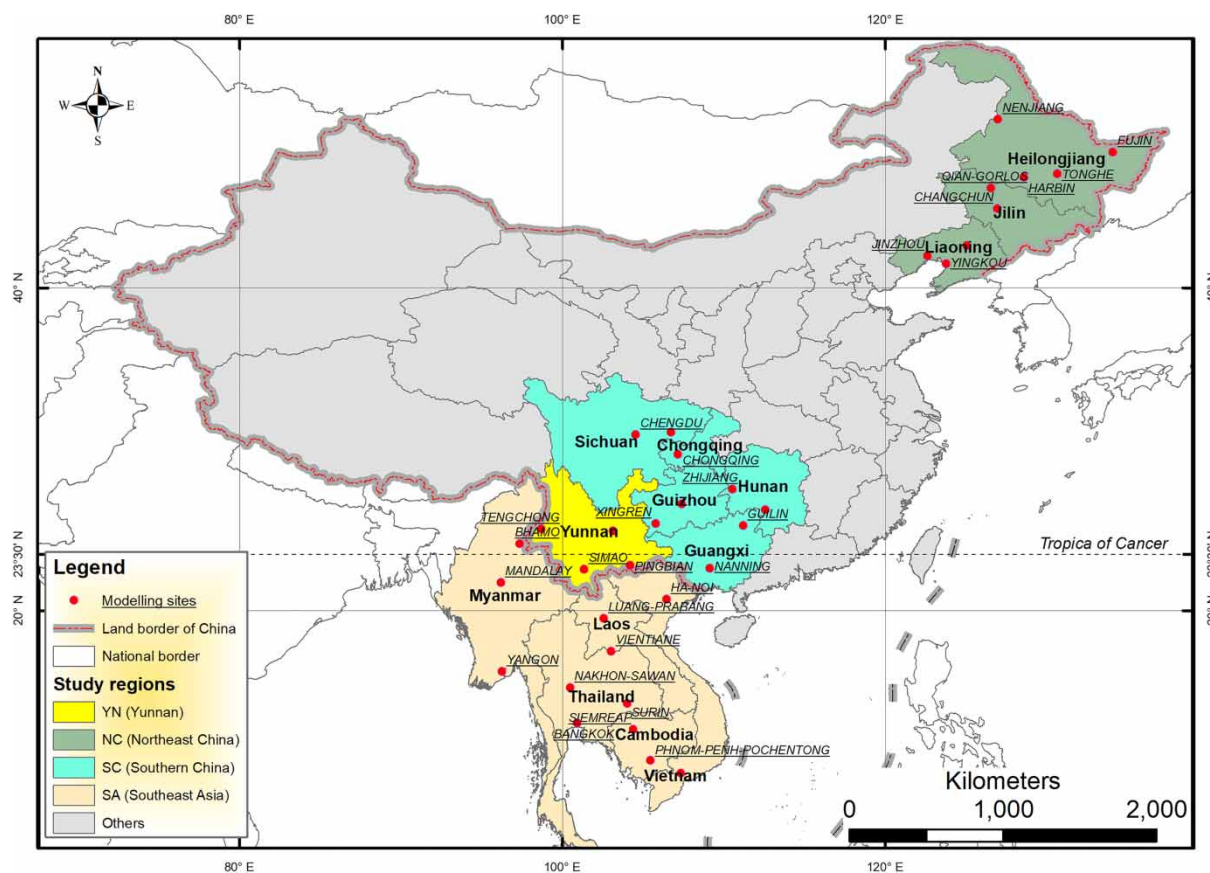


Fig. 1. Illustrative map showing the four study regions (YN, NC, SC and SA) and spatial distribution of selected modeling stations in the study. The stations are selected from the CLIMWAT database (FAO, 2010a).

determined by multiplying the trade volume and the WF of the rice as in the original production regions, respectively:

$$V_x = \sum_n T_x \times WF_{orig} \quad (2)$$

In which, V_x represents either WF_{orig} , V_i or V_e , T_x represents either imported or exported rice quantity from partner country or province n , and WF_{orig} represents the WF of rice as in the original country or province n . Rice stock change as well as smuggling are not considered here due to data unavailability.

2.3. WF for rice production

Like in many other agricultural products, total WF (WF_{total}) for the process of growing rice can be categorized into green (rainwater), blue (surface and groundwater) and gray (polluted water) WFs (Hoekstra et al., 2011). The gray WF (WF_{grey}) is not included in this study due to a lack of information.

The green and blue WFs in the process of producing rice can be calculated as the green and blue components in crop water use (CWU) divided by crop yield (Y), respectively:

$$WF_{proc, green} = \frac{CWU_{green}}{Y} \quad (3)$$

$$WF_{proc, blue} = \frac{CWU_{blue}}{Y} \quad (4)$$

The green and blue components in CWU can be calculated by the accumulation of daily evapotranspiration (ET) over the complete growing period:

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green} \quad (5)$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue} \quad (6)$$

In which, ET_{green} and ET_{blue} are green and blue ETs, respectively. A factor of 10 is meant to convert water depths in millimeters into water volumes per land surface in m^3/ha , and the summation is done over the whole length of the growing period (lgp) in days.

Subsequently, green and blue ETs are calculated as follows:

$$ET_{green} = \min(ET_C, P_{eff}) \quad (7)$$

$$ET_{blue} = \max(0, ET_C - P_{eff}) \quad (8)$$

In which, ET_C is daily ET (mm) and P_{eff} is the effective precipitation over the rice growing period (mm), estimated by the USDA S.C. method (FAO, 2010b). The percolation water loss is not included in the WF because percolation is water loss from an individual field, but there is great scope for reuse of these flows within a landscape that consists of many interconnected fields (Bouman et al., 2007).

2.4. Analyze methods and data sources

Both green and blue ETs and crop water requirements (CWRs) during the rice-producing periods are estimated by the FAO 56 approach implemented in the CROPWAT (ver. 8.0) software (Allen et al., 1998; Hoekstra et al., 2011; FAO, 2010b). The locations are selected from the CLIMWAT 2.0 database (FAO, 2010a) based on GYGA's rice distribution map (van Ittersum et al., 2013). Only those sites that fell inside the rice distribution areas are selected for CROPWAT modeling. In China, 2–4 locations are selected for each of the selected 10 provinces in YN, SC and NC, while 2–3 locations are selected for each selected country in SA. Meteorological data such as rainfall, sunshine time, relative humidity, average wind speed, daily high and low temperatures are extracted from the CLIMWAT database and used as inputs for CROPWAT calculations. Data comparison

between the CLIMWAT database and datasets from the National Climate Center of China is conducted to avoid data bias. Soil parameters for different soil types (black clay, red loamy and red sandy) are adjusted based on local conditions. The planting dates and irrigation schedules are compiled based on field trip visits together with literature review of the study regions. When two or more production seasons exist, only the major production seasons are modeled and extrapolated to national scale (for SC, YN and SA). Rice production data for other provinces are from the National Statistical Bureau of China, while data for Southeast countries are from either the statistical and agricultural websites of respective countries or from the FAOSTAT database. Household income, food expenditure and cereal consumption datasets are from the national household survey carried by the National Bureau of Statistics of China (Department of Household Surveys of the National Bureau of Statistics of China, 2013, 2014, 2015, 2016, 2017, 2018).

3. Results

3.1. Rice supply in YN and its sources

YN has witnessed significant rice production and supply change in the past decades. Rice production increased from around 4 million tons in 1978 to over 6.4 million tons in 2005, and then declined to 5.3 million tons in 2017, indicating a 1.69% increase and a 1.68% decline between 1978 and 2005 and between 2005 and 2017, respectively (Figure 2). Meanwhile, external inputs have increased from about 2 million tons in 2005 to 4.18 million tons in 2017, indicating a 6.3% increase. In 2017, around 8.1 million tons of rice were supplied to YN, in which 5.29 million tons are produced locally, 2.67 million tons from other provinces, including 2.39 million tons of *Jing* rice from NC and 0.28 million tons of *Xian* rice from neighboring provinces. Around 0.18 million tons of *Xian* rice were exported from YN to other provinces, leading to 0.1 million tons of net provincial import of *Xian* rice. YN imported 0.14 million tons of rice from Southeast Asian countries, but no rice was exported (Table 1).

Of the 7.92 million tons of rice consumed, 7.04 million tons go to food, while the other 0.88 million tons to feed, industrial or seed. *Xian* and *Jing* rice show similar structures of consumption, but the spatial patterns might differ due to distinct consumption schemes in urban and rural areas (Table 1).

3.2. ET and WF of rice production

A total of 34 locations from the four regions are selected for the entire study (Figure 1). Of the four rice-producing regions, YN showed smaller crop ET (ET_c) compared with other regions, followed by SC, SA and NC (Table 2). Effective precipitation (P_{eff}) was highest in SA, followed by YN, SC and NC (Table 2).

The green component of ET, i.e., ET_{green} , follows a similar trend to ET_c ; however, for ET_{blue} , the NC region showed the highest value (300.3 mm), followed by SC (104.3 mm). The ET_{blue} in YN and SA is significantly less, implying that precipitation is sufficient in the two regions.

The green component of WF of growing rice, or WF_{green} , is the highest in SA (1,454.9 m³/t), followed by SC (922.8 m³/t), YN (760.5 m³/t) and NC (471.0 m³/t), corresponding to latitudinal distribution of WF_{green} and close relationship with precipitation. The WF_{blue} is the highest in NC (364.6 m³/t), followed

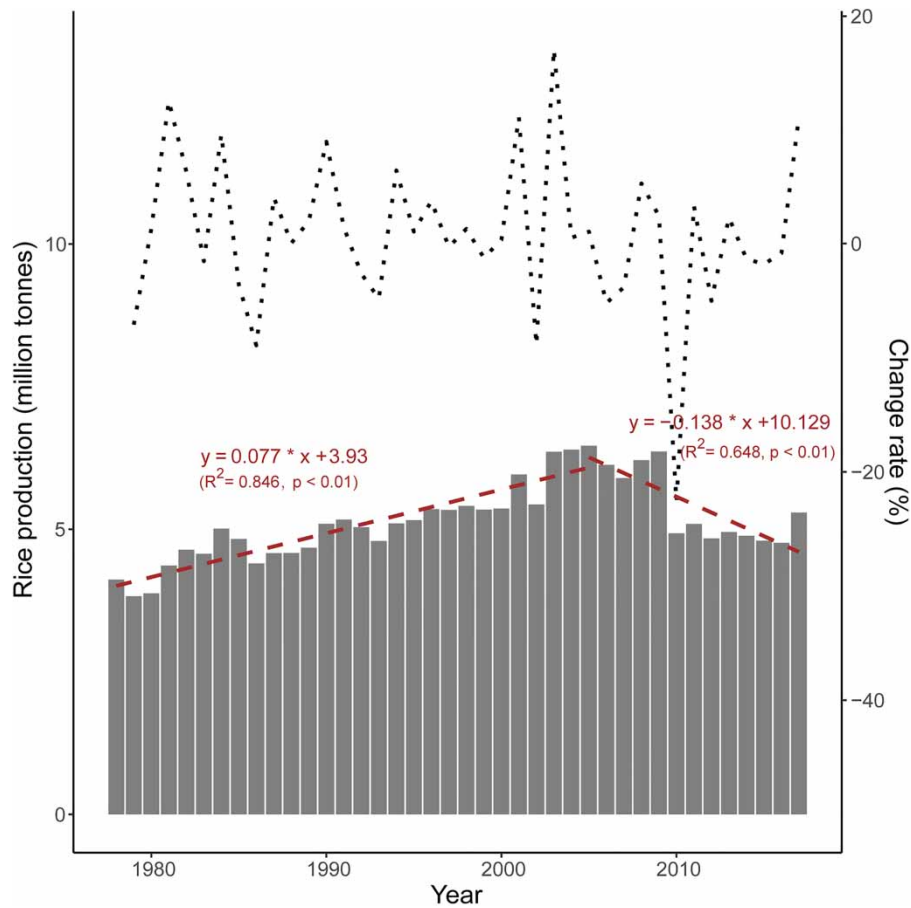


Fig. 2. Rice production (bar) and yearly change rate (dot line) in YN between 1978 and 2017. The red slash lines indicate that the whole period can be categorized into two parts, which broke out at 2005. Please refer to the online version of this paper to see this figure in colour: <https://doi.org/10.2166/wp.2021.168>.

Table 1. Aggregated rice balance sheet for YN province (2017, unit: million tons).

Category	Supply			Consumption					
	Production	From other province	Import	Food	Feed	Industrial	Seed	To other province	Export
<i>Xian</i> rice	4.10	0.28	0.14	3.78	0.20	0.16	0.02	0.18	0
<i>Jing</i> rice	1.19	2.39	0	3.26	0.14	0.11	0.01	0.06	0
All rice	5.29	2.67	0.14	7.04	0.34	0.27	0.03	0.24	0

Note: YN also produces *Jing* rice, but the major part is from other provinces, whereas for *Xian* rice, the major part is produced locally.

by SC (184.6 m³/t), SA (127.8 m³/t) and YN (17.7 m³/t), highlighting blue water consumption in NC. As a result, the WF_{total} of rice growth is the highest in SA (1,582.7 m³/t), followed by SC (1,107.4 m³/t), NC (825.7 m³/t), and YN (778.2 m³/t) (Table 2).

Table 2. Precipitation, ET, P_{eff} , irrigation and WFs of the study regions.

	Prec (mm)	P_{eff} (mm)	ET_c (mm)	ET_{green} (mm)	ET_{blue} (mm)	Avg. yield (kg/ha)	WF_{green} (m ³ /t)	WF_{blue} (m ³ /t)	WF_{total} (m ³ /t)	Rainwater use efficiency (WF_{blue}/WF_{total})
YN	1,414.1	644.6	496.8	484.8	12.0	6,666.6	760.5	17.7	778.2	97.7%
NC	560.5	388.4	671.7	378.4	300.3	8,192.3	471.0	364.6	835.6	56.4%
South & SC	1,252.2	502.7	546.5	442.2	104.3	5,212.3	922.8	184.6	1,107.4	83.3%
SA	1,512.4	673.2	573.1	528.8	44.3	3,923.2	1,454.9	127.8	1,582.7	91.9%

Note: the Prec, P_{eff} and ET are from CROPWAT outputs, whereas the WF and rainwater use efficiency are from calculations. The average yields are either from statistical reports, or from literature collections. Abbreviations: Prec, annual precipitation; P_{eff} , effective precipitation; ET_c , crop evapotranspiration; and WF, water footprint.

In terms of the percentage of WF_{blue} to WF_{total} , or rainwater use efficiency, YN is the highest, with 97.7% of water being green water, followed by SA (91.9%), SC (83.3%), while NC is the lowest, suggesting that NC uses the least proportion of water from rain (Table 2).

From the regional perspective, intra-regional variations for ETs are small, whereas the variations for WFs are higher, especially in SA (Figure 3). This could be mainly due to disparate rice production levels among the locations. The rice yields in SA can be as low as 3,000 kg/ha in Cambodia and some Myanmar locations, and as high as 5,660 kg/ha in Vietnam, suggesting different production capabilities (Table 2).

3.3. WF in YN's rice supply

A total of 7.81 billion m³ of water are embedded in the rice supply for YN in 2017, of which 67.7% is from YN, 25.5% from NC, and the rest 6.8% from SC and SA (Table 3). If compared with the agricultural water withdrawal of each study region, then over 50.2% of the total water withdrawn in YN are used for growing the corresponding quantities of rice for YN, 4.1% in NC, while the other two regions are below 0.5%. In total, the water for rice supply in YN accounts for around 2.7% of total agricultural water withdraw in the four regions (Table 3).

4. Discussion

4.1. YN's rice supply and demand change

YN has been under dramatic demand and supply changes in the past decades, leading to an increasing gap for rice supply, and expanding imports of rice and virtual water resources. The advantage of WF_{total} for YN (Table 2) suggests YN to be the most suitable region among the four to grow rice with regard to water use efficiency. However, in reality, both harvested area and production of rice have kept stagnating in YN in the past decades, while increasing drastically in NC and Southeast Asian Countries (Figure 4), suggesting water or water use efficiency could not be the determinant factor for rice plantation. The rice situation in YN can be explained from the following perspectives:

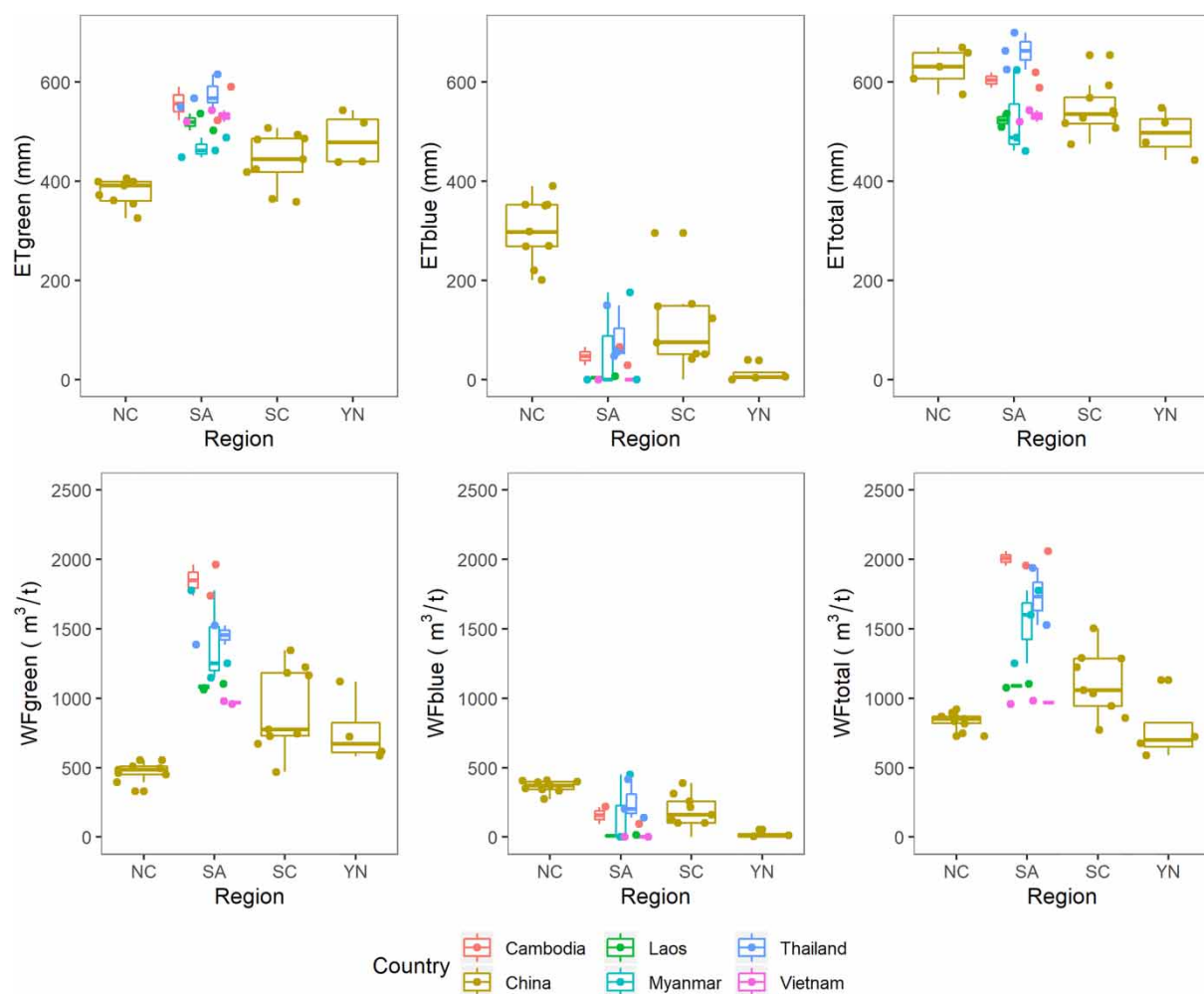


Fig. 3. Boxplot of the ETs and WFs of the study regions showing the inter- and intra-regional heterogeneity of crop WFs.

Table 3. WFs and the sources of YN's rice consumption.

Region	Rice supply to YN (million ton)	% of total rice supply	Water productivity (kg/m ³)	Total WF (million m ³)	% of total WF	Regional agricultural water withdraw (million m ³)	% of water withdraw
YN	6.79	70.7	1.285	5,285.3	67.7	10,520	50.2
NC	2.39	24.9	1.197	1,996.0	25.5	48,980	4.1
SC	0.28	3.0	0.903	313.9	4.0	63,120	0.5
SA	0.14	1.4	0.632	217.1	2.8	164,195	0.1
Summary	9.60	100.0	0.929	7,812.4	100	286,815	2.7

Note: In this study, the water productivity is defined as the production of rice product by a cubic meter of water. The regional agricultural water withdraw are from aggregation of statistic reports by governmental agencies.

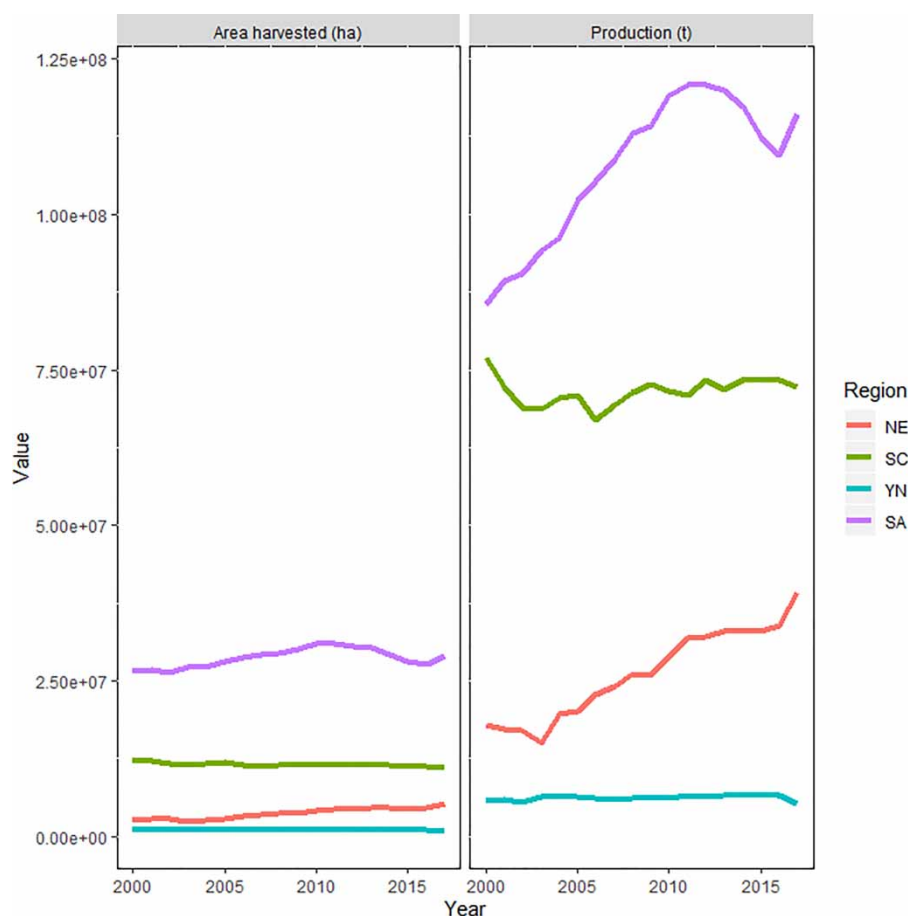


Fig. 4. Harvest area and production of rice in the four study regions between 2000 and 2017. *Note:* Abbreviations for the four regions can be found in the Material and Methods section.

Firstly, shifting of rice plantation to other high value-added cash crops. YN is very suitable for agricultural plantation. Since the 1980s, YN has been allocating more and more cropland for the planting of various cash crops, such as fresh flowers, tobacco and vegetables, among others. As land rents increased to levels that are even higher than the entire economic outputs of growing rice, more lands are gradually shifting from rice to non-rice crops, and rice has been dropped as a comparative disadvantageous crop for many farmers in YN in the past decades. When local production declined, import from outside has become a necessary option.

Secondly, consumption increase and dietary shift. In the past two decades, YN has witnessed a significant change in population, household income and food expenditure, leading to a dramatic change of dietary shift for rice. The population of YN has increased from 42.36 million in 2000 to 48.01 million in 2017. According to the national household consumption survey, per capita cereal consumption has dropped from 139.9 to 119.6 kg/year between 2013 and 2017 across the country (Department of Household Surveys of the National Bureau of Statistics of China, 2013, 2014, 2015, 2016, 2017, 2018). As disposable personal income also increased significantly, especially among urban citizens, household expenditure on food has since increased significantly (Figure 5). Furthermore, agricultural production,

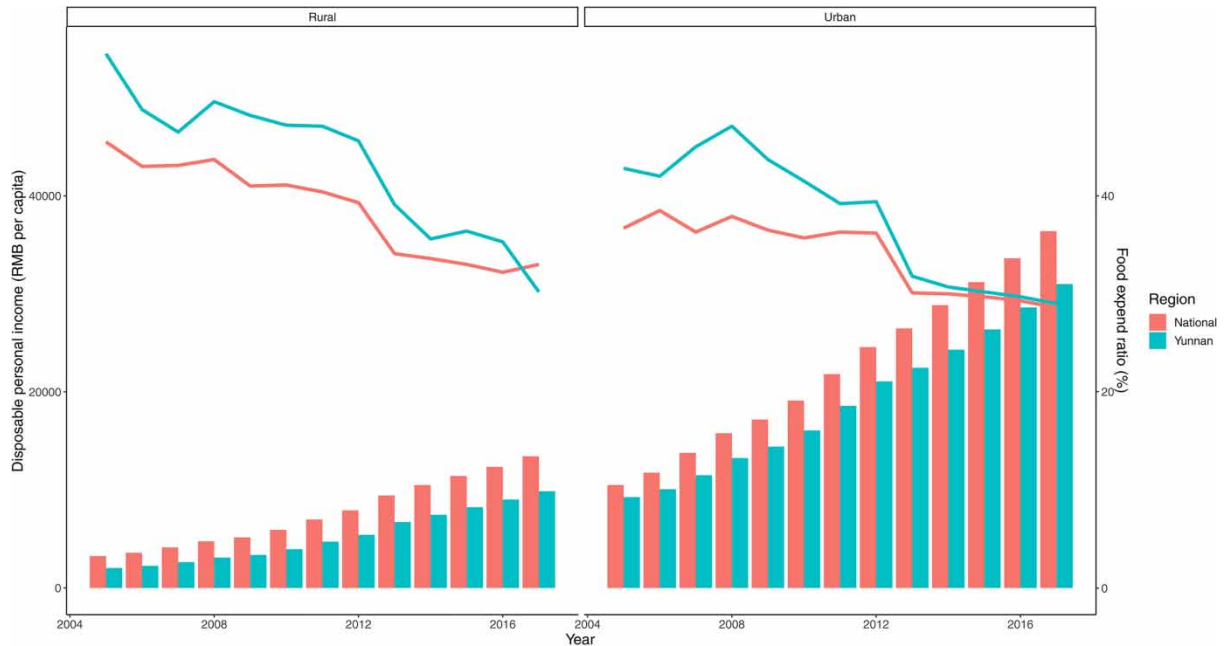


Fig. 5. Disposable personal income (bar) and house food expend ratio (line) for rural and urban citizens in YN and the whole country during 2005 and 2017.

transportation industry and food trade have transformed the national food provision system to a level in which most urban citizens could have access to abundant, qualified and diversified agricultural products at affordable prices. As a result, the dietary preference of the people has shifted toward less per capita rice consumption but more rice of higher quality, diversity and nutrition, especially for urban dwellers, a trend that is very similar in other developing regions (Bouman *et al.*, 2007; Lam *et al.*, 2013; Anderson, 2016). The Northeast *Jing* rice, which is regarded as one of the top rice varieties in China, has been dumping into the national rice market and gaining popularity in YN in the past decade.

Thirdly, development of tourism and immigration. Owing to YN's warm climate and comfortable environment, it is becoming one of the top destinations in China for both migration and tourism, especially for people from NC. As more and more Northeastern people flock in, the eating habits and structure are also changing, leading to more Northeast *Jing* rice consumption in YN, especially in urban cities like Kunming. This phenomenon has been reported in a couple of studies in recent years (Wang *et al.*, 2018; Gu *et al.*, 2019).

4.2. WF for YN's rice supply and its components

The model results indicate that YN consumes the least water to produce a unit of rice ($778.2 \text{ m}^3/\text{t}$), followed by NC ($835.6 \text{ m}^3/\text{t}$), South and SC ($1,107.4 \text{ m}^3/\text{t}$) and SA ($1,582.7 \text{ m}^3/\text{t}$) (Table 2). These WF_{total} results correspond to water productivities of between 0.632 and $1.285 \text{ kg}/\text{m}^3$, and are consistent with previous studies of between 0.6 and $1.6 \text{ kg}/\text{m}^3$ (Chapagain & Hoekstra, 2011; Li *et al.*, 2018; Ngo *et al.*, 2018; Table 4).

Table 4. Comparison of ETs and WFs with existing studies of rice water footprint.

Study region	Specific area	Study period	ET_c	P_{eff}	WF_{green}	WF_{Blue}	WF_{total}	Data source
YN	YN	–	496.8	644.6	760.5	17.7	778.2	This study
NC	Heilongjiang, Jilin, Liaoning	–	671.7	388.2	471.0	364.6	835.6	This study
	Jilin	2008	564.7	177.0	161.0	802.0	963	Li et al. (2018)
	Jilin	–	–	–	517.0	427.0	944	Chapagain & Hoekstra (2011)
	NC	–	–	–	527.0	758.0	1,285	Sun et al. (2013)
South and SC	Guangxi, Sichuan, etc	–	546.5	502.7	922.8	184.6	1,107.4	This study
	Guangxi	–	–	–	476.7	310.0	786.7	Yang et al. (2018)
China	National	2000–2004	530.0	–	1,077.0	826.0	1,903	Chapagain & Hoekstra (2011)
	National	1996–2005	–	–	1,087.0	–	–	Tuninetti et al. (2015)
SA	Vietnam, Myanmar, etc	–	573.1	673.2	1,454.9	127.8	1,582.7	This study
	Vietnam	–	–	–	–	–	1,437	Ngo et al. (2018)
	Vietnam	2000–2004	231.0	–	307.9	202.8	510.7	Chapagain & Hoekstra (2011)
	Thailand	2000–2004	401.0	–	942.1	559.0	1,501.0	Chapagain & Hoekstra (2011)
	Thailand	1976–2005	–	–	781.9	639.1	1,421.0	Shrestha et al. (2017)
	Myanmar	2000–2004	430.0	–	846.3	378.1	1,224.4	Chapagain & Hoekstra (2011)
	Cambodia	2000–2004	–	–	631.8	583.8	1,215.6	Chapagain & Hoekstra (2011)

Note: Bold texts and values indicate this study.

The distinction between WF_{green} and WF_{blue} could be of great importance because the hydrological, environmental and social impacts, as well as the economic opportunity costs of surface water and groundwater, or blue water use for production, differ distinctively from the impacts and costs of rainwater use (Hoekstra et al., 2011). In this study, the model results show that the blue WF of YN and neighboring regions are much lower than NC, indicating that NC is consuming a larger percentage of blue water, including groundwater, for rice production. Since the average annual precipitation in the NC is only about 560.5 mm, much less than the ET_c , which is 671.7 mm (Table 2), irrigation (blue water) is necessary to keep the fields from drying out and make sure that appropriate yields can be attained. When more and more blue water is consumed and the rice products are moved outside of the region for consumption, the NC region will be facing increasing water deficit and scarcity.

Rainwater allocated for rice production generally has no or very low opportunity cost for rice production, and this is because, in most river basins in China, rainfall accounts for over 50% of total water supply and over 80% of total water consumption goes to agriculture (MWR, 2019). Better use of rainwater will reduce both the fraction of blue water use and the production cost from the economic and ecological perspective. Very low blue water consumption could mean that the water use paradigm is sustainable and cost-effective in the region, and the demand for rice from areas where blue water is a necessary input can also be reduced (Chapagain & Hoekstra, 2011). For instance, for every ton of rice produced in NC, 56.4% of freshwater or groundwater (364.6 m³) is needed. Consuming one ton of rice in YN could mean around

0.25 tons are produced from NC, about 207.9 m³ of water embedded in rice is consumed and up to 90.7 m³ surface or groundwater has been used, which accounts for over 20% precipitation in the region. This 90.7 m³ blue water consumption in the Northeast could have been replaced by 4.4 m³ blue water in YN, 45.9 m³ in SC or 31.8 m³ in SA, if the same amounts of rice are produced in these regions. If this is the case, even though total WF might increase if the rice production is shifted from NC to SC and SA, the blue water consumption will drop significantly. As a result, the combined rainwater use efficiency of these regions should be higher than if most rice is grown and supplied from NC, let alone the embedded water cost for transportation from over 3,000 km away.

4.3. The cascading effect of YN's rice consumption

YN's consumption of *Jing* rice from NC suggests that China is producing rice in relatively water-poor regions and trading it to water-rich regions for consumption, suggesting a comparatively low-efficient water use paradigm nationwide and potential ecological risks in the rice exporting region. In NC, rice paddy fields amount to 5.3 million ha in the three provinces, which account for over 28.2% of grain production in the three provinces and 18.4% of national rice production in 2017. When more and more groundwater instead of rainwater is used for rice plantation and consumption, the aquifers will not be replenished before they are completely depleted. In 2018, the groundwater resources in the three provinces in NC account for over 32% of total water resources, larger than the 30% national average level, suggesting groundwater usage of the region comes at a critical status (MWR, 2019).

This trend is consistent with other Asian regions, such as the Ganges and Indus river basin in India and Bangladesh, where flooded rice or irrigated rice is the dominant cropping ecosystem (Bouman *et al.*, 2007). However, unfortunately, there is no systematic inventory or evaluation of water scarcity status in NC yet. A study by the China Geological Survey has collected the groundwater table between 1997 and 2017 from 15 wells in the Sanjiang Plain and found that the entire groundwater table in the studied area had been declining continuously, and ground table declines of between 1.60 and 9.29 m were discovered in the 20 years (Liu *et al.*, 2020). Zhong *et al.* (2018) found that groundwater storage in the West Liaohe River Basin has declined between 0.96 and 0.19 km³/year in *in-situ* observation and between 0.92 and 0.49 km³/year in the remote sensing approach. In some of the regions, such as west of Jilin and Heilongjiang, groundwater tables have dropped to over 70 m below ground level, drastically lower than just a few years back. If the current water consumption paradigm continues, more depletion of groundwater from the entire Northeast plain could be anticipated within a few decades, much alike the situation in China's Northern Plain.

4.4. Policy implications

Reducing blue water use as well as increasing the water use efficiency of rainwater would both conserve the surface and groundwater for environmental security purposes and offer sustainable benefits for the wellbeing of the cropping regions. However, this requires that the crop system be optimized to adapt to the climate, so less blue water will be required during the course of crop production, such as high water consuming crops being replaced by low consuming crops, and so on. This shift usually requires either financial investments in farmers and agriculture, or sacrificing of local farmers to give up economically more attractive crops and turning to economically less attractive crops, such as from rice to maize for the NC region, or from cash crops to rice for YN in the current study. If this is the case, then national or regional policies need to be in place, and financial support is also needed to facilitate

the transition. The promotion of aerobic rice could be a viable option for both Yunan and NC to bring down the WF, but more preliminary work should be done to test its suitability and profitability.

Incorporating water into the price of rice products should be taken as an immediate policy action. One of the reasons why groundwater is widely used in rice production in Northeast region is that agricultural intensification is heavily reliant upon irrigation (blue water) and the natural capital value for groundwater is not included in the production cost, leading to massive production of comparatively advantageous rice products. According to our field investigations in the Northeast region, a major part of the irrigation infrastructure receives investments from national or provincial governments and most of the farmers only need to pay the electricity bill to get the groundwater for irrigation, leading to very low irrigation cost and better earnings, compared with other crops such as maize. These rice products enter the markets of other provinces in China and become strong competitors against other rice products due to their better quality and taste, leading to the decline of local rice plantation, much like the situation in YN province. Strict groundwater management, such as surveillance and charges for the groundwater could possibly stop the abuse of groundwater extraction and conserve the water resource in the region. In this way, water will be incorporated into the price of the rice products, leading to a reduction of the comparative advantages of Northeast rice. However, the farmers will eventually benefit from this approach because rice prices will go up when total rice production is reduced. More importantly, these measures will conserve the valuable groundwater resources in the region and ensure sustainable production of rice in the long run.

Relaxation of the rice import policy could easily serve YN's need for rice, but might bring about unpredictable consequences for the domestic rice market, including discouraging rice plantation that had already been declining in YN. This is also the reason why the Chinese central government is putting a lot of effort into keeping rice import strictly under trade quota and fighting against rice smuggling. A compromise might be made to fix this problem by setting up special rice trade zones between YN and SA countries, thus allowing a larger amount of rice to be imported only to YN while blocking it from entering other parts of the country. This suggestion is based on the fact that, in YN, more and more lands are shifted to cash crops and fewer and fewer farmers are willing to grow rice for a living. How to balance the environmental, socio-economic and even diplomatic relationships is still a focal issue in ensuring food security in YN and, to a bigger extent, the whole country.

5. Conclusions

Linkages of rice supply and WFs among YN, its neighboring regions and NC have been investigated in this study. Rice has become such a common food in the domestic and global markets that agricultural development, policy restriction and dietary preference in one place can be reflected by land schemes and water resources in another distant region, i.e. the cascading effect. In this study, rice production and supply in YN has undergone dramatic changes in the past decades, and through trade, the impacts have reached thousands of kilometers away to the NC region, through expanding imports of rice and virtual water resources. The current rice supply paradigm is that rice being transported from NC to YN could be both unsustainable for the water resource cycle (by depleting blue water) and inefficient (by low green water use efficiency) for NC and beyond. As a result, there is an urgent for groundwater surveillance, for water to be included in the cost of rice production and for better trade policies to be put

in place to prevent water abuse, improve water use efficiency at regional and higher levels to ensure sustainable food and water security to meet the SDGs.

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Data availability statement

All relevant data are included in the paper or its Supplementary Information.

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