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Article:

Zhao, X, Tillotson, MR, Liu, YW et al. (2017) Index decomposition analysis of urban crop water footprint. *Ecological Modelling*, 348. pp. 25-32. ISSN: 1872-7026

<https://doi.org/10.1016/j.ecolmodel.2017.01.006>

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Index decomposition analysis of urban crop water footprint

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Abstract

Rapid urbanization has resulted in often unplanned increases in population, and food demand in cities. Historically, hinterlands to these cities have acted as breadbaskets producing food to the urban residents. Accordingly, a large amount of available freshwater has been needed to support these croplands. However, the rapid expansion of cities in developing countries has significantly changed both the croplands around cities and the water demand. It is thus important to quantitatively investigate the water-food nexus of cities related to the changing hinterland agriculture. Water footprint is an indicator reflecting the human impact on water. In this study, we quantified both the blue and green water footprint of major crop products in Suzhou city, China using a bottom-up accounting method. A novel decomposition analysis was carried out with a Logarithmic Mean Divisia Index (LMDI) method to study the driving forces that changed the water footprint during the period 2001-2010. The drivers were designed to

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26 reflect the factors related to farmland, such as yield and crop area. This is different from
27 previous decomposition analyses, which focused on economic factors such as GDP. The
28 results show that the crop water footprint of Suzhou city has seen a general decreasing
29 trend between 2001 and 2010. The decomposition analysis showed that the decline of
30 crop area was the main driver that decreased the crop water footprint, followed by the
31 virtual water content (water consumption per unit of production). In contrast the
32 changes of crop combination and yield contributed to an increase in the crop water
33 footprint. Although the shrink of urban croplands decreased the water footprint of crop
34 products. Cities' increasing demand for food will increase the crop water footprint of
35 consumption. This will increase the dependence of cities on external water footprint of
36 crop products (water embodied in imported crops), which may impact upon food
37 security in cities in the long term.

38 **Keywords:** hinterland agriculture, crop water footprint, decomposition analysis, LMDI

39 **Highlights**

40 Redesign of driving forces for crop water footprint changes

41 Analysis of interaction between hinterland agriculture and water demand

42 Discussion of farmland impact upon urban water demand

43 **1. Introduction**

44 Cities constitute primary agglomerations of people. In 2014 54% of the world's
45 population lived in cities, and this is forecast to rise to 66% by 2050 (United Nations,
46 2014). One of the key challenges faced by cities around the world is to meet food
47 demand for residents (Barthel and Isendahl, 2013; Lynch et al., 2013). Traditionally,
48 farmlands around cities, also known as hinterlands, have supported this food demand
49 (Zezza and Tasciotti, 2010). Such urban agriculture has historically been critical to
50 achieving food security in cities (Lynch et al., 2013). However, the huge water demand
51 associated with agricultural production conflicts with the increasing water demand due
52 to urban population growth. Current trends of rapid expansion of cities, especially in
53 developing countries, has significantly changed both the croplands around cities and
54 the associated water demand. To the best of our knowledge, few studies have focused
55 on the interactions between hinterland agriculture and the water demand associated with
56 urbanization.

57 The water-food nexus of cities related to changing hinterland agriculture can be
58 evaluated using the water footprint (WF) concept. The WF is defined as the volume of
59 freshwater used during the production process (Hoekstra et al., 2011). It has been
60 widely used in quantifying and assessing freshwater consumption in crop production
61 (e.g. Chapagain and Hoekstra, 2011; Mekonnen and Hoekstra, 2011; Vanham et al.,
62 2013). Freshwater refers to both green water and blue water. Green water is the
63 precipitation on land which does not run-off or recharge groundwater but is stored in
64 the soil or remains on the surface of the soil or vegetation. The accounting of green
65 water footprint is closely related to crop growth. The blue water for crop growth can be
66 substituted by green water, so a complete picture can be obtained only by accounting
67 for both (Hoekstra et al., 2011). A bottom-up method is widely applied to accounting
68 for the crop WF, which starts from the smallest unit feasible in assessing the WF and
69 aggregates each unit to the desired scale and period (Yang et al., 2013).

70 The changes in the WF of crops can be related to crop production and changes in

71 hinterland usage, with drivers such as water productivity, yield, agricultural area etc.,
72 to understand the interactions between hinterland agriculture changes and freshwater
73 consumption. In recent years, decomposition analyses has been applied to study the
74 driving forces or determinants that underlie changes to the WF (Feng et al., 2015). For
75 example, Zhang (2012) decomposed the effects of contributing factors to Beijing's WF
76 changes during 1997-2007. The contributing factors were technological, economic
77 system efficiency, scale, and structural effects. Zhao et al. (2014) investigated the
78 impact of population, affluence, urbanization level, and diet factors on the WF of
79 agricultural products in China based on an extended STIRPAT model. The above
80 decomposition analyses, however, were not designed to reflect the factors related to
81 changing farmland, such as crop yield or area, and thus were unable to identify the
82 interrelationships between hinterland agricultural changes and associated water
83 consumption. In addition, green water was excluded from most decomposition analyses
84 of WF changes.

85 In the context of increasing urbanization in developing countries, this study has
86 quantitatively investigated the water-food nexus in Suzhou city, China by performing a
87 novel decomposition analysis with a Logarithmic Mean Divisia Index (LMDI) model.
88 The aim was to study the contributing factors to urban crop WF changes, including
89 virtual water content (reciprocal of water productivity), yield, crop structure, and crop
90 area. To best of our knowledge the driving forces related to crop production that
91 changes both green and blue WF has been rarely reported. The driving forces and the
92 implications to water-food security at urban scale are also discussed.

93 **2 Water endowment and water stress in Suzhou city**



94

95

Fig. 1. Location of Suzhou city, China

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Suzhou city is located in the Taihu Lake Basin, which is a subtropical humid area of plentiful rainfall. The annual available water resource in Suzhou is 2.98 billion m³ (in 2010). The total administrative area of Suzhou is 8,488 km², with 3,609 km² covered by water (Suzhou Water Resources Bureau, 2010). Lake Taihu, a large shallow freshwater lake in the lower Yangtze Delta, is close to Suzhou (Fig. 1), and is the main water resource for Suzhou. Significant nutrient pollution from wastewater discharges, along with agricultural run-off from the northwestern shores flows into Lake Taihu. Nutrient concentrations decrease with the current towards the eastern and southern

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104 reaches of the lake which, as a result, have better water quality i.e. the reaches close to
105 Suzhou city, despite extensive blue-green algae problems in the northwestern part of
106 the lake (Hu et al., 2010).

107 Suzhou is an ideal case for illustrating how hinterland agriculture can be changed
108 through urbanization and industrialization. Although in contemporary China, Suzhou
109 is known as an industrialized city with many high-tech industries, it was until the 1980's
110 on of China's grain production center. The Taihu Lake Basin has long been known as
111 "the land of rice and fish" in China. Agriculture in the Taihu Lake Basin sustained high
112 productivity for more than nine centuries (Ellis and Wang, 1997). As such, Suzhou has
113 historically had a large amount of hinterland agriculture dedicated to producing rice and
114 other grain products for both local consumption and export to other regions in China.
115 After the foundation of the People's Republic of China in 1949, Suzhou was established
116 as a grain production base (Wang et al., 2015). In 1984, the sown area was about 5000
117 km² with grain production peaking at 3.1 million tons (Suzhou Statistics Bureau, 2011).
118 Since then Suzhou has accelerated its industrialization transformation process by
119 creating a series of industrial park and development zones to stimulate industrial
120 development and attract Foreign Direct Investment (Wang et al., 2015). Today, Suzhou
121 has become one of the wealthiest industrial cities in China. In 2010, GDP in Suzhou
122 ranked 5th among China's 337 cities, following the mega-cities of Beijing, Shanghai,
123 Guangzhou, and Shenzhen. Per capita GDP was about 87,607 CNY (about 12,800 US
124 dollars) (Suzhou Statistics Bureau, 2011). Urbanization in Suzhou, as with other
125 Chinese cities, has experienced land grab and population growth, which have
126 substantial impacts on hinterland agriculture.

127 Despite its location in a subtropical and humid area, Suzhou as a developed city in
128 China faces water stress. We evaluated water stress in Suzhou during 2007-2010 with
129 two well-known water scarcity indices. The Falkenmark Index evaluates water stress
130 through the total annual renewable water resource per capita (Falkenmark et al., 1989),
131 and the "Criticality ratio" evaluates water stress using the ratio of total annual

132 withdrawals to renewable water resources (Alcamo et al., 2000). The classification of
 133 both indices was adjusted according to Zeng (2013) and Zhao (2016) following China's
 134 water endowment. As a result, four classifications were generated with C as the
 135 "Criticality ratio" and F as the Falkenmark Index: Absolute Scarcity ($C > 1$ or $F < 500$
 136 $m^3/capita$); Scarcity ($1 > C > 0.4$ or $1000 m^3/capita > F > 500 m^3/capita$); Stress ($0.4 >$
 137 $C > 0.2$ or $1700 m^3/capita > F > 1000 m^3/capita$); and No Stress ($C < 0.2$ or $F > 1700$
 138 $m^3/capita$). The results for the Criticality ratio show the highest level of water stress in
 139 Suzhou (Table 1), while the results for the Falkenmark Index show the second highest
 140 level of water stress during 2007-2009, and the highest level in 2010. These results
 141 suggest that intensive water use and high population density are the main causes of
 142 Suzhou's water stress.

143 **Table 1 Results of water scarcity indices in Suzhou city**

Year	Annual renewable water resources (billion m^3)	Population	Water withdrawal (billion m^3)	Falkenmark Index (F)	Criticality Ratio (C)
2007	3.2	6244311	7.7	515	2.3
2008	3.3	6297530	7.5	522	2.3
2009	4.4	6332903	7.7	702	1.7
2010	3.0	6376558	7.8	468	2.6

144 3. Method and data

145 3.1. Quantification of blue and green water footprint of crop products

146 The WF of crop products in this study refers to the WF of crop growth. The indirect
 147 water requirement for crop production, i.e. the water required in production of upstream
 148 products only takes a small share of the total crop WF (Zhao et al., 2009), thus is ignored
 149 in this study. A bottom-up method to quantify the WF of crop products can be expressed
 150 as follows:

$$151 \quad WF_{tot} = WF_g + WF_b = \sum_i [CWR_{g,i} \cdot A_i] + \sum_i [CWR_{b,i} \cdot A_i] \quad (1)$$

152 Where WF_{tot} , WF_g and WF_b refer to the total, green and blue water footprint of crops,
 153 i is the type of crops planted, A_i is the plant area of crop i , $CWR_{g,i}$ and $CWR_{b,i}$ are

154 annual green and blue crop water requirements per hectare of crop *i*. Crop water
155 requirement can be calculated using the CROPWAT model developed by the Food and
156 Agriculture Organization (FAO) (available at <http://www.fao.org/nr/water/infores>
157 [databases cropwat.html](http://www.fao.org/nr/water/infores)). The CROPWAT model takes into account both rainfed and
158 irrigated conditions. So in the CROPWAT model, the green crop water requirement is
159 obtained through quantifying effective rainfall, while the blue crop water requirement
160 is obtained through quantifying irrigation.

161 3.2. LMDI model

162 We used the LMDI model to decompose the WF of crops in Suzhou city. The
163 LMDI method was initially developed by Ang and Liu (2001), and has been widely
164 used in analyzing the driving forces of carbon dioxide (CO₂) emissions or energy
165 efficiency (e.g. Ang, 2004; Dai and Gao, 2016; Fernández González et al., 2014; Liu et
166 al., 2012), and a small number of applications in analyzing WF changes (Xu et al., 2015;
167 Zhao and Chen, 2014). The method has the advantages of expressing in a simple form
168 with no residual errors, so has been recommended for general use (Ang, 2004).

169 In this study, we redesigned the driving forces of the crop WF to reflect the
170 interrelationships between urban agriculture and associated freshwater consumption.
171 The total WF of crops in Suzhou was decomposed into four driving forces: virtual water
172 content, yield, crop structure, and crop area. Virtual water content (VWC) is the amount
173 of water consumed to produce a unit of each crop, which is also the reciprocal of water
174 productivity. Yield is production volume per unit area. Crop structure is the proportion
175 of specific crop area to total area of all crops, and crop area is the total planting area for
176 all crops. The total WF of crops can be expressed with the above four driving forces as
177 follows:

$$178 \quad WF(t) = \sum_i [V_i(t) \cdot Y_i(t) \cdot S_i(t) \cdot A(t)] = \sum_i \left[\frac{WF_i(t)}{P_i(t)} \frac{P_i(t)}{A_i(t)} \frac{A_i(t)}{A(t)} A(t) \right] \quad (2)$$

179 Where $WF(t)$ is the water footprint of all crops, $V_i(t)$, $Y_i(t)$, and $S_i(t)$ represent
180 VWC, yield, and crop structure for crop *i* in year *t* respectively. $A(t)$ is the total crop

181 area in year t . $P_i(t)$ is the production volume of crop i in year t , and $A_i(t)$ is the crop
 182 area of crop i in year t .

183 According to LMDI, the variation of WF (ΔWF) from year 0 to year t can be
 184 decomposed into four parts: the variation of WF caused by change in VWC (ΔWF_v),
 185 the variation of WF related to change in yield (ΔWF_y), the variation of WF which is
 186 due to change in the proportion of a crop area in the total area (ΔWF_s), and the variation
 187 of WF caused by changes to the total area (ΔWF_a). The decomposition form is shown
 188 in Eq. (3):

$$189 \quad \Delta WF = WF(t) - WF(0) = \Delta WF_v + \Delta WF_s + \Delta WF_y + \Delta WF_a \quad (3)$$

190 The four driving forces in Eq. (3) can be quantified as:

$$191 \quad \Delta WF_v = \sum_i [\phi[WF_i(t), WF_i(0)] \ln \frac{V_i(t)}{V_i(0)}] \quad (4)$$

$$192 \quad \Delta WF_s = \sum_i [\phi[WF_i(t), WF_i(0)] \ln \frac{S_i(t)}{S_i(0)}] \quad (5)$$

$$193 \quad \Delta WF_y = \sum_i [\phi[WF_i(t), WF_i(0)] \ln \frac{Y_i(t)}{Y_i(0)}] \quad (6)$$

$$194 \quad \Delta WF_a = \sum_i [\phi[WF_i(t), WF_i(0)] \ln \frac{A(t)}{A(0)}] \quad (7)$$

195 where function $\phi[WF_i(t), WF_i(0)]$ is the logarithmic average of two positive numbers
 196 $WF_i(t)$ and $WF_i(0)$ which are given by:

$$197 \quad \phi[WF_i(t), WF_i(0)] = \begin{cases} \frac{WF_i(t) - WF_i(0)}{\ln WF_i(t) - \ln WF_i(0)}, & WF_i(t) \neq WF_i(0) \\ WF_i(0), & WF_i(t) = WF_i(0) \end{cases} \quad (8)$$

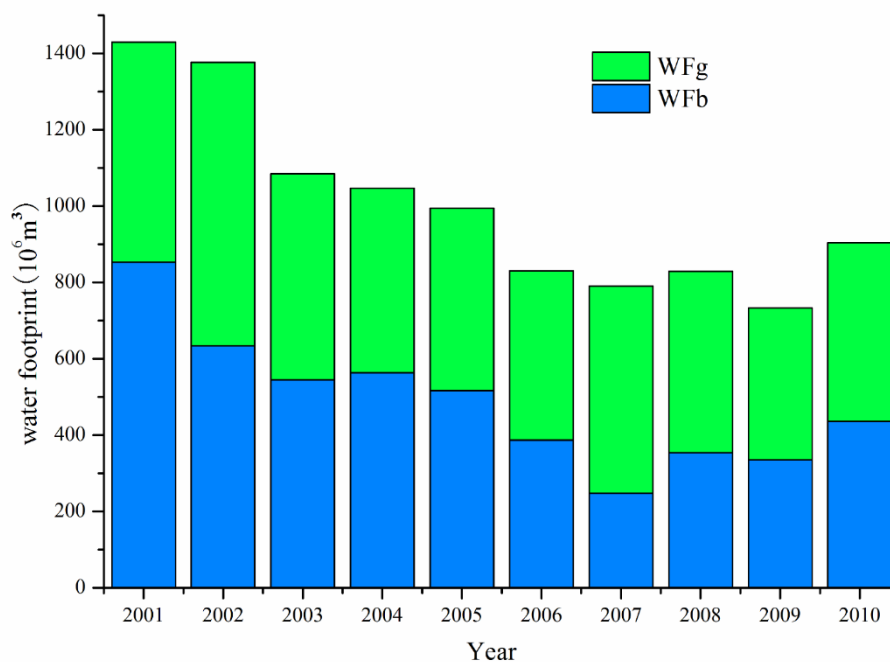
198 3.3. Data source

199 In this study, the four main crops in Suzhou were considered: wheat, rice, cotton,

200 and rapeseed. The total cultivated area of the four crops accounted for about 70% of the
201 total cultivated area in Suzhou (Suzhou Statistics Bureau, 2011). The input data of the
202 CROPWAT model included climatic, crop and soil parameters. Climatic inputs included
203 average maximum and minimum air temperature, precipitation, relative humidity,
204 sunlight duration, radiation and wind speed, which were obtained from the China
205 Meteorological Data Sharing Service System (<http://data.cma.cn/>). Crop and soil
206 parameters were taken from the default values in the CROPWAT software provided by
207 FAO. The data for crop production and crop areas were obtained from the Suzhou
208 Statistical Yearbook (Suzhou Statistics Bureau, 2011).

209 4. Results and Discussion

210 4.1. Water footprint of major crops in Suzhou from 2001-2010

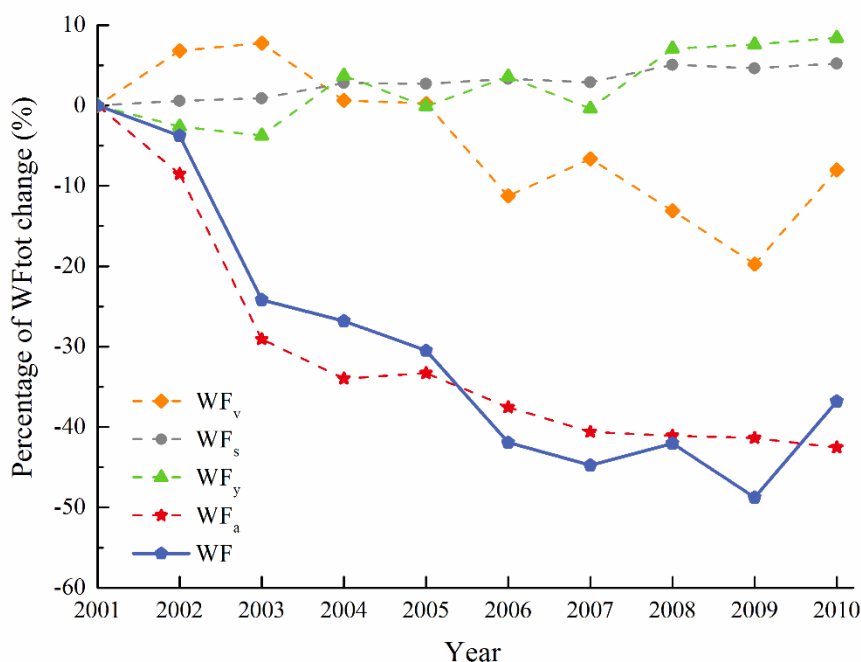


211
212 **Fig. 2. Changes of blue and green water footprint of crop products in Suzhou**
213 **(2001-2010)**

214 The average crop WF in Suzhou was 1001.9 million m³ during 2001-2010,
215 incorporating 487.5 m³ of blue WF and 514.4 m³ of green WF. Green WF dominated

216 the WF for wheat, cotton, and rapeseed, accounting for 73%-79% of the total WF on
 217 average for these three crops. Blue WF dominated the WF of rice, accounting for 62%
 218 of the total WF on average. The average WF for rice took the greatest share amongst
 219 the WF of the four crops studied, accounting for 63% of the total, followed by the WF
 220 of wheat which accounted for 29% of the total. As shown in Fig. 2, the crop WF
 221 experienced a general decreasing trend from 2001 to 2010. Specifically, the crop WF
 222 experienced continued reduction between 2001 and 2007, before fluctuating slightly
 223 from 2007 to 2010. Blue WF decreased from 853.04 million m³ in 2001 to 247.53
 224 million m³ in 2007, before increasing to 436.38 million m³ in 2010. Green WF
 225 fluctuated between 397.41 million m³ to 742.75 million m³ during the 10 study years.
 226 The biggest share of the blue WF to total WF of crop products was 59.64% in 2001,
 227 and the smallest share was 31.32% in 2007.

228 4.2. The driving force analysis of crop water footprint changes in Suzhou



229

230 **Fig. 3. Driving forces of crop WF during the study period of 2001-2010**

231 As shown in Fig. 3, the total crop WF decreased by 526 million m³ during 2001-

232 2010, with total area contributing the most to this reduction. The decrease of total area
233 would have decreased the crop WF by a total of 608 million m³, if other factors (VWC,
234 crop structure, and crop yield) had remained static at 2001 levels. In the study period
235 (2001-2010), area changes were the main driving forces in crop WF reduction.
236 According to Fig. 3, area changes sharply reduced crop WF from 2001 to 2004,
237 continued to cause a gentle reduction between 2004 and 2007, finally having less
238 impact between 2007 and 2010. The impact of VWC fluctuated over the study period,
239 but decreased by a total of 115 million m³ of the crop WF during 2001-2010. For
240 example, the VWC decreased the crop WF by 164.52 million m³ during 2005-2006, but
241 increased by 167.68 million m³ of the crop WF during 2009-2010. The change in crop
242 yield and crop structure would have increased the crop WF by 120 and 75 million m³
243 respectively. It is obvious that the crop WF growth due to the effects of crop yield and
244 crop structure could not offset the crop WF reduction owing to the effects of crop area
245 and VWC.

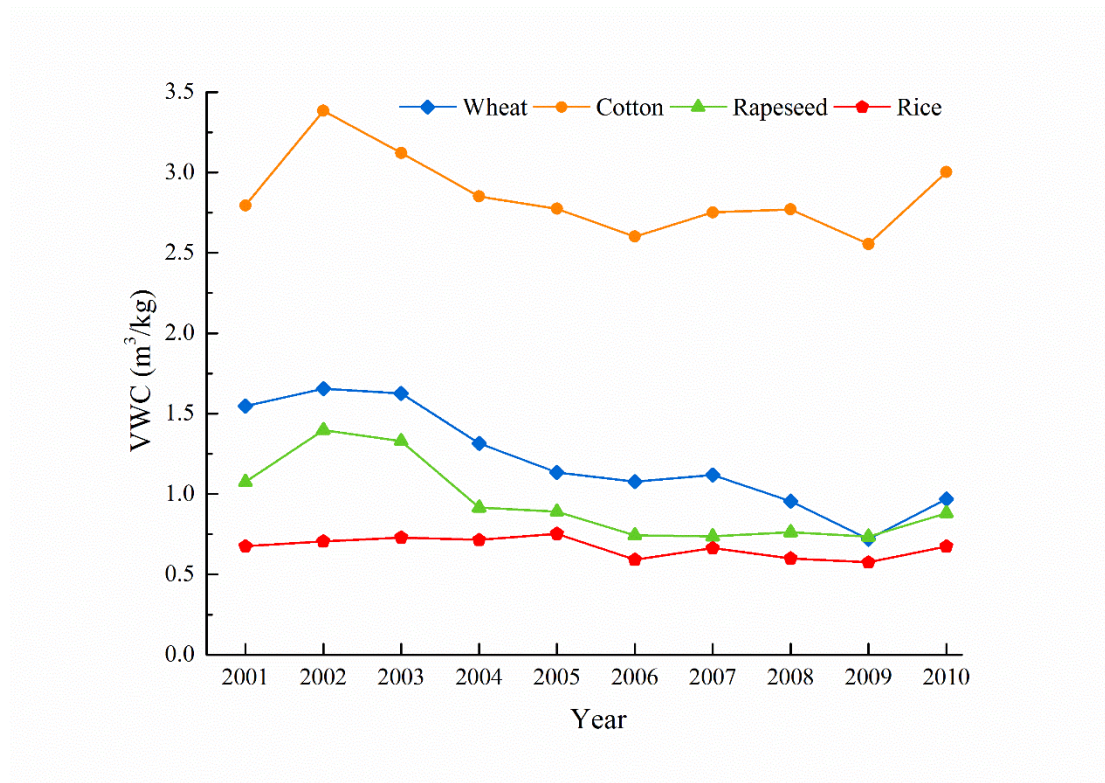
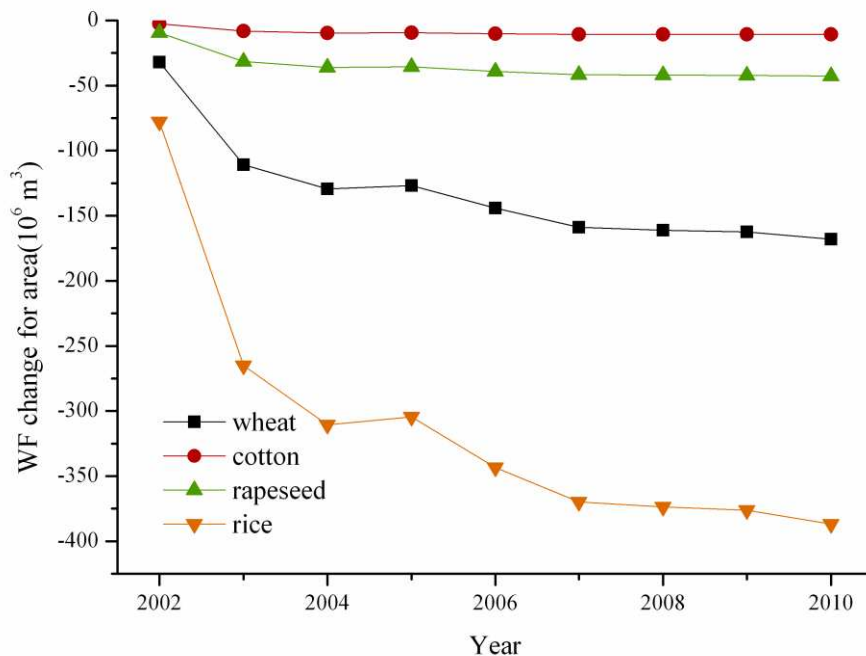


Fig. 4. Virtual water content changes for four major crops

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249 Fig. 3 shows that the pattern of crop WF change is highly related to the change of
 250 the VWC which fluctuated over the study period. Such fluctuation can be linked to
 251 changes in climatic factors such as temperature, sunlight, and precipitation etc. Climatic
 252 factors can change both crop output and associated water consumption, and as a result,
 253 have impact on the VWC. For example, Bocchiola and Soncini (2013) found that crop
 254 yield decreased and the WF increased with increasing temperature and decreasing
 255 precipitation. Kang et al. (2009) found that climate change led to changes in soil
 256 evaporation and plant transpiration and consequently the crop growth period may be
 257 changed having influence on crop water productivity, i.e. the reciprocal of the VWC.
 258 Some previous studies assumed the same VWC for different years e.g. (Liu et al., 2007),
 259 which ignored the impact of the changing VWC on the crop WF. However, our results
 260 show that ignoring the difference of the VWC will lead to noticeable bias for crop WF
 261 accounting.



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Fig. 5. Contribution of crop area to crop WF changes

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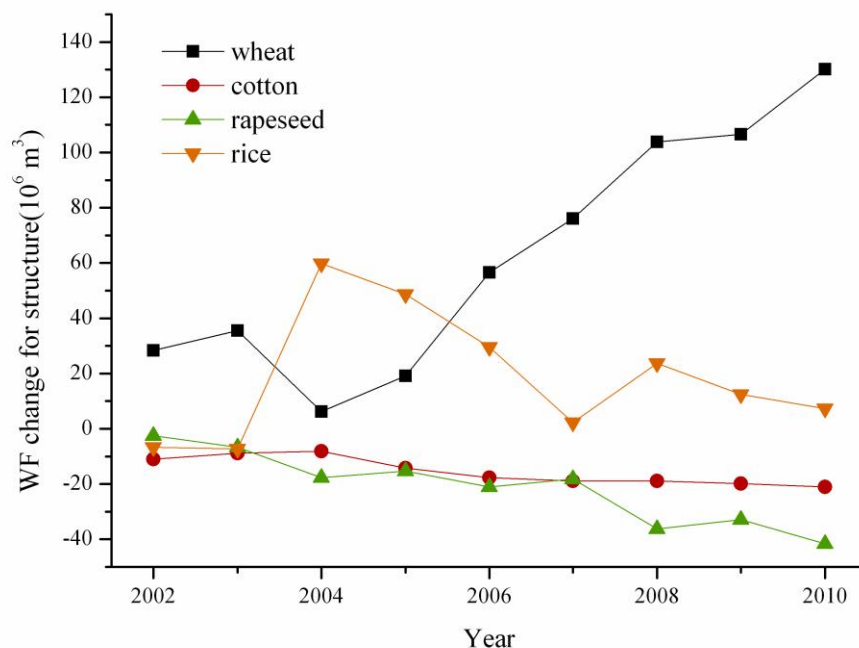
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During the study period (2001-2010) area changes were the main driving force in crop WF reduction. According to Fig. 3, area changes sharply reduced crop WF between 2001 and 2004, continued to cause a gentle reduction between 2004 and 2007, and had less impact from 2007 to 2010. The above changes correlated with crop area changes in Suzhou. The crop area reduction per annum was 136.6 km² from 2001 to 2004, 76 km² from 2004 to 2007, and 31.6 km² from 2007 to 2010. The main cause of crop area reduction is attributed to rapid urbanization in China, along with urban land expansion. In urban expansion it is common to see crop land occupied by newly built urban infrastructure, such as dwellings and factories. Consistent with China's national urbanization trend, the urban land take around Suzhou in the early 21st century has also undergone rapid expansion (Wang et al., 2015). As a result, agricultural land around Suzhou has shrunk rapidly since 2001. Such reductions have attracted the attention of government and scientists: a major concern is that rapid urban expansion will threaten food security in China. In 2006, 0.12 billion ha of arable land area was set as a cap, i.e.

279 a redline to limit arable land reduction (State Council of the People's Republic of China,
280 2006). Consequently, the downward trend of crop area has slowed since 2007.

281 4.2.3. Crop structure effect



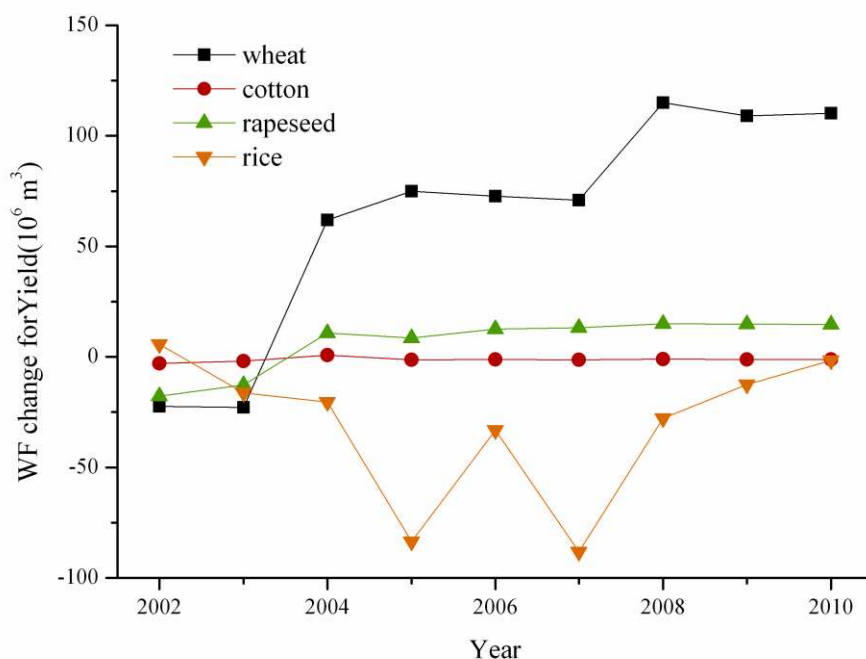
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283 **Fig. 6. Contribution of crop structure to WF change**

284 The overall impact of crop structure on crop WF was small but resulted in a steady
285 increase in crop WF during the study period. As shown in Fig. 6, the proportion of
286 wheat area amongst the major crop areas increased between 2004 and 2010, while the
287 area proportion for the other crops decreased. The increasing crop area proportion of
288 wheat possibly reflects a decreased labour force for Suzhou's crop production. In 2010,
289 labour costs for wheat production in Suzhou was the lowest of the four crops at about
290 1950 CNY/ha (285 dollars/ha), whilst labour costs for rapeseed was highest, at about
291 4440 CNY/ha (650 dollars/ha) (National Development and Reform Commission, 2010).
292 Since the population working on Suzhou's hinterland agriculture decreased by 218
293 thousand from 2001 to 2010, it is reasonable to infer that more farmers chose to
294 cultivate wheat to overcome labour shortage. Since wheat had the second largest VWC

295 among the four crops studied, and the largest plant area, the increased proportion of
296 wheat also increased the total WF.

297 4.2.4. Yield effect



298

299

Fig. 7. Contribution of yield to WF changes

300 From 2001 to 2010 yield generally increased crop WF for Suzhou. As shown in
301 Fig. 7 the yield of wheat contributed most to crop WF increase, rising from 3,136
302 ton/thousand ha to 4,727 ton/thousand ha, about a 51% increase during the study
303 period. It can be inferred that the increase in wheat yield also stimulated the increased
304 proportion of wheat planting area to the total areas of the four studied crops. The
305 yield for rice decreased in 2005 and 2007, and then increased to reflect the general
306 trend in subsequent years. Crop yield is highly related to climatic factors such as
307 radiation, temperature, and precipitation etc. (Liu et al., 2016), and will thus be
308 considered in the decomposition analysis of crop WF in future work.

309 **5. Conclusions**

310 China has long advocated food self-sufficiency; even developed cities take a
311 significant stake in governing agricultural land use. Such efforts provide an effective
312 way of supporting food security, but also increase the pressure on urban water supplies.
313 This study has proposed a new set of parameters including virtual water content, yield,
314 crop structure, and crop area to reflect the interactions of hinterland agriculture and
315 water demand on a developed Chinese city. Our attempt highlights the importance of
316 incorporating drivers related to agricultural land changes into urban land and water
317 management, thus can support decision making in balancing the trade-offs between
318 local food demand and water resource allocation. Decreased WF of crop products
319 mitigate urban water stress to an extent, but increase the reliance of the city on external
320 water supplies which can be acquired through both physical and virtual forms. Research
321 and modelling on the sustainability and equity for large cities relying on external water
322 supply is an urgent issue.

323 **Acknowledgement**

324 The research was supported by the Fundamental Research Funds for the Central
325 Universities (2016B13814), Chinese National Science Foundation (51579071,
326 51379061, 41323001, 51539003), Jiangsu Province National Science Foundation
327 (BK20131370), and National Science Funds for Creative Research Groups of China
328 (No. 51421006); the program of Dual Innovative Talents Plan and Innovative Research
329 Team in Jiangsu Province, and the Special Fund of State Key Laboratory of Hydrology-
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