Research Article

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Impacts of changing cropping pattern on virtual water flows related to crops transfer: a case study for the Hetao irrigation district, China

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Abstract

BACKGROUND: Analysis of cropping patterns is a prerequisite for their optimisation, and evaluation of virtual water flows could shed new light on water resources management. This study is intended to explore the effects of cropping pattern changes between 1960 and 2008 on virtual water flows related to crops transfer in the Hetao irrigation district, China.

RESULTS: (1) The sown area of crops increased at an average rate of 3.57×10^3 ha year^{-1} while the proportion of sown grain crops decreased from 92.83% in the 1960s to 50.22% in the 2000s. (2) Virtual water content decreased during the study period while net virtual water exports increased since the 1980s. (3) Assuming that the cropping pattern was constant and was equal to the average 1960s value, accumulated net virtual water export in 1980–2008 would have been 4.76×10^9 m^3 greater than that in the actual cropping pattern scenario.

CONCLUSION: Cropping pattern changes in the Hetao irrigation district could not only be seen as resulting from the pursuit for higher economic returns, but also as a feedback response to limited water resources. A systematic framework is still needed for future cropping pattern planning by taking food security, continued agricultural expansion and other constraints into consideration.

Keywords: cropping pattern; virtual water; grain crop; non-grain crop; irrigation area

INTRODUCTION

Water shortages are a worldwide problem and they have become increasingly severe mainly due to population growth, improving living standards and small-scale climatic changes.[1,2] Researchers in different disciplines have focused most of their attention on water shortage.[3–5] In the early 1990s, Tony Allan introduced the concept of virtual water, which describes the amount of water required to generate a product.[6] The concept of virtual water adds a new dimension to international trade and provides a completely new way of thinking about water scarcity and water resources management.[7] An inflow of virtual water through imported products reduces the pressure on domestic water resources; an outflow of virtual water through exporting products results in a water loss from regional perspective, thereby adding to the pressure on local water systems.[8–10]

Thus far, most studies have focused on the quantification of virtual water pertaining to crop trades and on its application to ensure water and food security, considering the large proportion of water withdrawn for crop production.[9,11–13] However, a systematic analysis of virtual water flows requires evaluation of impacts and feedbacks of various intertwined factors associated with these trades, which requires knowledge of many disciplines.[14] Accordingly, some researchers have tried to explore the relationship between virtual water flows and other factors. Liu *et al.* estimated global virtual water flows related to seven cereal crops for the period of 1998–2002 and found that low-income countries generally have a low level of net virtual water import.[15] According to the study by D'Odorico *et al.*, the global distribution of people and wealth, whose effects on virtual water trade are expressed through gravity models, are unable to explain the strength of virtual water communities observed in the past few decades.[16] In addition to the studies of global virtual water flows, effects of

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crop productivity and access to arable land on inter-regional or international virtual water flows have also been studied.[17,18] The cropping pattern of a region reveals the proportion of an area sown with different crops at a given point of time; thus, a change in the cropping pattern implies a change in that proportion.[19,20] A comprehensive cropping pattern plan takes into account the high degree of interrelation of the environmental, economic and social aspects of farming systems.[2] Thus, identifying and quantifying the impacts of cropping pattern changes on virtual water flows could contribute to the systematic analysis of virtual water flows and provide the possibility of alleviating increasing water scarcity from the perspective of the cropping pattern. However, there are few studies illustrating how virtual water flows are influenced by the cropping pattern.

In China, more than three-quarters of grain is produced by irrigation districts, which have been performing an increasingly important function for ensuring China's food safety and social economic development.[21] Compared with global or national scales, studies at smaller and more localised scales have greater pertinence to specific regional problems.[10] Thus, the aim of this study was to explore the influences of cropping pattern changes on virtual water flows from the irrigation district scale. This study could provide a new dimension to regional crops transfer and it would be helpful in fostering adaptive strategies to water scarcity through the alteration of existing cropping patterns.

MATERIAL AND METHODS

Study area

As the largest gravity irrigation district in Asia, the Hetao irrigation district is located in the west of Inner Mongolia, China (north 40° 13′ to 42° 28′, and east 105° 12′ to 109° 53′). It spans an area of 5.74×10^3 square kilometres.[22] This area generally slopes toward the north-east varying from 0.125 to 0.2 m km^{-1} and the average elevation is 1030 m above the mean sea level.[23] The Hetao irrigation district has a continental monsoon climate with hot and dry summers, and winters are cold with little snowfall. Rainfall in this area is scarce (yearly average is about 130–215 mm) and erratically distributed (70% in July, August and September) while the annual evaporation is 2100–2300 mm.[24] Annual sunshine time and frost-free days are approximately 3150 h and 135 days, respectively.[23] Annual accumulated temperature over 10°C ranges from 2700°C to 3200°C and the average wind speed is 2.5–3.4 m s^{-1}.[23]

The Hetao irrigation district is an important agricultural production region and the crops in this region include rice, wheat, corn, coarse cereals, oil bearing crops, sugar crops, vegetables and fruits. The population of this area is around 1.55 million, and 56% are farmers with incomes greater than 5000 yuan cap^{-1} in 2008.[25] Irrigation in this area mainly depends on water from the Yellow River. With the increasing pressure upon water resources in northern China, allowable Yellow River water diversions to the Hetao irrigation district have decreased from 5 billion m^3 per year to 4 billion m^3 per year.[24] The combination of increasing water requirements and severely constrained fresh-water resources undoubtedly has an adverse effect on this area's development.

Calculation of virtual water flows

When crops are transferred between the study area and other regions, water resources used in crop production processes would be exported from or imported to the Hetao irrigation district in virtual form. The calculation of the virtual water balance related to the transfer of crops was based on the values of virtual water export and virtual water import:

$$\mathrm{VWB} = \mathrm{VWE} - \mathrm{VWI} \quad (1)$$

where VWB is the virtual water balance (in m^3), whereas VWE and VWI are the virtual water export and virtual water import values related to crops transfer (in m^3), respectively. A positive VWB value indicates a net virtual water export and a negative value indicates a net virtual water import.

The calculation of VWE and VWI was based on the following method:[26]

$$\mathrm{VWE} = \sum_{i=1}^{n} \left(E_i \times \mathrm{VWC}_i\right) \quad (2)$$

$$\mathrm{VWI} = \sum_{i=1}^{n} \left(I_i \times \mathrm{VWC}_i\right) \quad (3)$$

where n is the type of crop, E_i is the export volume of crop i (in kg), I_i is import volume of crop i (in kg), and VWC_i is the virtual water content of crop i (in m^3 kg^{-1}), as measured at the point of production.

According to food balance sheets form the Food and Agriculture Organization (FAO), crop transfer volume is a function of production, consumption and stock change.[27] In this paper, we assumed crop storage was constant during the study period and export happens when local production exceeds the consumption volume, otherwise a net import occurs. Thus, the export and import volume of crops could be calculated as follows:

$$\text{If } P_i \geq C_i, \quad \begin{cases} E_i = P_i - C_i \\ I_i = 0 \end{cases} \quad (4)$$

$$\text{If } P_i < C_i, \quad \begin{cases} E_i = 0 \\ I_i = C_i - P_i \end{cases} \quad (5)$$

where P_i is the production of crop i (in kg) and C_i is the consumption of crop i (in kg).

The virtual water content value shows the water consumption per unit of crop production over the growing period. Two types of water resources were consumed in this period: green water and blue water. Green water was calculated according to the evapo-transpiration of water supplied by rain.[28] In the Hetao irrigation district, flood irrigation is widely used and most of the irrigation water is lost during the transmission and distribution process from water sources to field.[23] In order to reflect actual blue water consumption, a water balance equation was used to calculate the value of blue water.[29] Thus, the virtual water content for crops exported from the Hetao irrigation district was calculated as follows:[28,29]

$$\begin{cases} \mathrm{VWC}_i = \frac{\mathrm{GW}_i + \mathrm{BW}_i}{Y_i} \\ \mathrm{GW}_i = 10 \min\left(ET_{c,i}, P_{e,i}\right) \\ \mathrm{BW}_i = \mathrm{IWC}_i \end{cases} \quad (6)$$

where GW_i is green water consumed by crop i (in m^3 ha^{-1}) during the growing period, BW_i is blue water consumed by crop i (in m^3 ha^{-1}) during the growing period, Y_i is the yield of crop i (in kg ha^{-1}), the factor 10 converts water depths (mm) into water volumes per unit land surface area (m^3 ha^{-1}); $\mathrm{ET}_{c,i}$ represents evapo-transpiration of water (in mm) from crop i during the growing period, $P_{e,i}$ is the effective precipitation (in mm) falling on crop i during the growing period, and IWC_i represents the consumption of irrigation water (in $m^3\ ha^{-1}$) by crop i during the growing period.

For the calculation of ET_c, The FAO Penman–Monteith method and crop parameter (K_c) were used:[30]

$$ET_c = K_c \times ET_0 \tag{7}$$

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \times \frac{900}{(T+273)} \times U_2 \times \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \tag{8}$$

where K_c is the crop parameter, ET_0 is the reference crop evapo-transpiration (in mm), Δ is the slope of the vapour pressure curve (in kPa °C^{-1}), R_n is the net radiation at the crop surface (in MJ $m^{-2}\ d^{-1}$), γ is the psychrometric constant (in kPa °C^{-1}), T is the average air temperature (in °C), U_2 is the average wind speed (in m s^{-1}) at 2 m height, G is the soil heat flux density (in MJ $m^{-2}\ d^{-1}$), e_s is the saturation vapour pressure (in kPa), and e_a is the actual vapour pressure (in kPa).

The effective precipitation (P_e) is calculated using CROPWAT according to the method developed by the USDA Soil Conservation Service:[31]

$$P_{e,ten} = \begin{cases} P_{ten}\left(4.17 - 0.02P_{ten}\right)/4.17 & P_{ten} \le 83 \\ 41.7 + 0.1P_{ten} & P_{ten} > 83 \end{cases} \tag{9}$$

where $P_{e,ten}$ is the effective precipitation within a 10-day period (in mm), and P_{ten} is the precipitation within a 10-day period (in mm). CROPWAT uses monthly precipitation data from which 10-day averages are derived as input for the calculations.[32]

IWC_i is calculated according to the proportion of irrigation water consumed by crop i to the total irrigation water consumption in the irrigation district:[29]

$$IWC_i = \frac{W_A \times \delta_i}{S_i} \tag{10}$$

where W_A is the total irrigation water consumed in the irrigation district (in m^3), δ_i is the proportion of irrigation water consumed by crop i to the total irrigation water consumed by the irrigation district, and S_i is sown area of crop i (in ha).

W_A is calculated according to the irrigation district water balance equation. Three components were essential for a water balance: (1) inflows across the boundaries, (2) outflows across the boundaries and (3) changes in storage levels within the district boundaries.[33] Thus, the water balance of the Hetao irrigation district could be expressed as follows:[29]

$$\Delta W = W_D + W_P + W_G - W_{out} - W_C \tag{11}$$

where ΔW is the variation of water storage (in m^3), W_D is the volume of the water diverted from the Yellow River (in m^3), W_P is the precipitation recharge (in m^3), W_G is the lateral inflow of groundwater (in m^3), W_{out} is the volume of irrigation district outflows (in m^3), and W_C is the sum of all sources of water consumption (in m^3), which includes agriculture water consumption, industry water consumption, domestic water consumption and ecological water consumption.

Therefore, W_A can be calculated as follows:[29,34]

$$W_A = W_D + W_P + W_G - W_{out} - \Delta W - W_I - W_L - W_E \tag{12}$$

where W_I is industry water consumption (in m^3), W_L is domestic water consumption (in m^3), and W_E is ecological water consumption (in m^3).

δ_i is calculated as follows:

$$\delta_i = \begin{cases} \dfrac{(ET_{c,i} - P_{e,i}) \times S_i}{\sum_{i=1}^{n}\left[\left(ET_{c,i} - P_{e,i}\right) \times S_i\right]} & \left(ET_{c,i} \ge P_{e,i}\right) \\ 0 & \left(ET_{c,i} < P_{e,i}\right) \end{cases} \tag{13}$$

It was difficult to determine the origin of crops imported to the Hetao irrigation district over such a long period, thus the virtual water content of imported crop i was assumed equal to the virtual water content of the exported crop i in this study. A similar assumption has been made in other studies within this context; for decision making, the calculation of virtual water import could demonstrate how much water could be saved by importing crops rather than producing them locally.[35,36]

Scenario analysis

Scenario analysis is a tool to explore the consequences of possible decisions, measures and events.[37] It has been widely used in different research fields.[38] In terms of cropping patterns, George *et al.* have compared a crop diversification scenario with a baseline scenario to investigate the response of regional water allocation in the Musi sub-basin of India.[39] In order to explore the impact of changing cropping patterns in the Hetao irrigation district on regional virtual water flows, we compared the actual cropping pattern scenario with a constant cropping pattern scenario.

Since the early 1960s, the irrigation water supply in the Hetao irrigation district could be guaranteed because of the completion of Sanshenggong water conservancy project on the Yellow River.[40] Therefore, the Hetao irrigation district became an important agricultural export region, resulting in large volume of crop-related virtual water export. Taking inter-annual variation into account, the average cropping pattern in the 1960s was chosen as a reference of constant cropping pattern. The objective of this paper was to demonstrate the impacts of cropping pattern alone on virtual water flows, thus no differences were assumed for other variables between actual and constant cropping pattern scenarios.

The sown area of crop i in a constant cropping pattern scenario was calculated as follows:

$$S_i' = \frac{S_{i,1960s}}{\sum_{i=1}^{n} S_{i,1960s}} \times \sum_{i=1}^{n} S_i \tag{14}$$

where S_i' is sown area of crop i in a constant cropping pattern scenario (in ha), $S_{i,1960s}$ is the average sown area of crop i in the 1960s in an actual cropping pattern scenario (in ha), and S_i is the sown area of crop i in an actual cropping pattern scenario (in ha).

In this paper, the integrated crop yield and integrated virtual water content were analysed. The integrated crop yield was calculated as follows:

$$Y_{int} = \frac{\sum_{i=1}^{n}\left(Y_i \times S_i\right)}{\sum_{i=1}^{n} S_i} \tag{15}$$

where Y_{int} is the integrated crop yield (in kg ha^{-1}).

The integrated virtual water contents for export crops and import crops were calculated as follows:

$$\mathrm{VWCE_{int}} = \frac{\sum_{j=1}^{r} (\mathrm{VWC}_j \times E_j)}{\sum_{j=1}^{r} E_j} \quad (16)$$

$$\mathrm{VWCI_{int}} = \frac{\sum_{k=1}^{s} (\mathrm{VWC}_k \times I_k)}{\sum_{k=1}^{s} I_k} \quad (17)$$

where $\mathrm{VWCE_{int}}$ is the integrated virtual water content for export crops (in $m^3\ kg^{-1}$), r represents the types of export crops, VWC_j is the virtual water content for export crop j (in $m^3\ kg^{-1}$), E_j is the export volume of export crop j (in kg), $\mathrm{VWCI_{int}}$ is the integrated virtual water content for import crops (in $m^3\ kg^{-1}$), s is the type of import crops, VWC_k is the virtual water content of import crop k (in $m^3\ kg^{-1}$), and I_k is the import volume of import crop k (in kg).

Data sources

The data used in this paper included the following.

Meteorological data

Meteorological data (1960–2008) were taken from China Meteorological Data Sharing Service System, and included data from five meteorological stations (Dengkou, Hanghou, Linhe, Wuyuan and Qianqi).[41] The monthly meteorological data included maximum temperature, minimum temperature, relative humidity, wind speed, sunshine hours and precipitation.

Agricultural and irrigation data

Agricultural data (1960–2008) came from *Hetao Irrigation District Statistical Data*, *China Agricultural Statistical Data* and *Bayan Nur Water Resources Bulletin*.[42,43] These data include crop yield, sown area and yearly water diversions from the Yellow River, total outflow and groundwater depth.

Social and economic data

Social and economic data were obtained from *Bayan Nur Statistical Yearbook*, *Inner Mongolia Statistical Yearbook* and *China Statistical Yearbook*.[25] Population and consumption of crops per capita were used in this paper.

RESULTS

Change of cropping pattern

Figure 1 shows the three different stages of crop sown area changes during the study period. From 1960 to 1982, the value of crop sown area fluctuated around 323.65×10^3 ha. Then the crop sown area entered a stage of significant increase until 2000, before reaching a maximum value (458.28×10^3 ha). The average growth rate in this stage was 6.80×10^3 ha per year. Since 2001 the crop sown area underwent a fluctuating trend with an overall decrease. The sown area in 2008 was 443.36×10^3 ha, which was 1.35 times that of the 1960 value.

Figure 2 shows the variation of the cropping pattern during the study period. In the 1960s and 1970s, more than 80% of the sown area consisted of wheat and coarse cereals (Fig. 2a). Since the 1980s, the proportion of oil-bearing crops in the total sown area

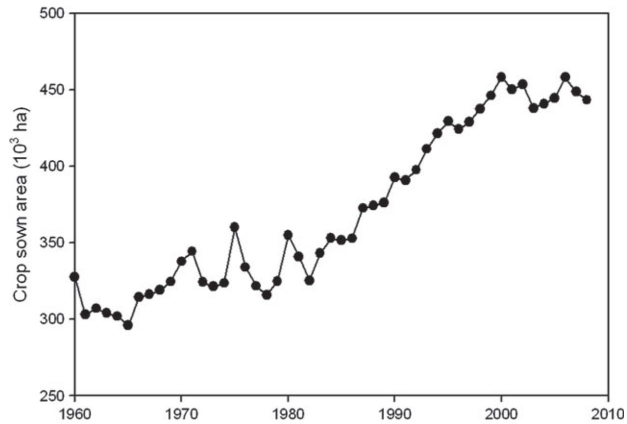

Figure 1. Temporal variation of the crop sown area in the Hetao irrigation district between 1960 and 2008.

increased significantly while the share of coarse cereals underwent a rapid decline. In the 2000s, the sown area of oil-bearing crops was the largest among all crops, and accounted for 33.93% of the total. The share of wheat (30.78%) took second place, followed by corn (15.33%).

In Fig. 2b, we divided different types of crops into two groups: grain crops (rice, wheat, corn and coarse cereals) and non-grain crops (oil bearing crops, sugar crops, vegetables and fruits). The percentage of the sown crop area for grain was stable around 93%, achieving its maximum during the study period (94.22%) in 1971. Since the 1980s, local farmers were more willing to choose non-grain over grain crops mainly due to variability of gross revenue. As a result, the sown area consisting of non-grain crops went through a trend of significant increases at a mean rate of 1.46% per year. It is notable that, in 2003, 2006, 2007 and 2008, the sown area of grain crops was smaller than that of non-grain crops, which was markedly different from the situation before the 2000s.

Change of virtual water flows

As can be seen from Table 1, the major export crops of the 1960s in the Hetao irrigation district were wheat and coarse cereals, whose export volume accounted for 80.84% of the total export volume. In the 2000s, about 3/4 of the export volume consisted of non-grain crops (fruits 35.54%, vegetables 19.55%, oil bearing crops 11.21% and sugar crops 8.03%), which was consistent with the variation of the cropping pattern. Rice was the dominant import crop and its import volume in the 2000s was more than triple of that in the 1960s.

Table 2 shows the variation of virtual water content for different crops during the study period. Decreasing trends were observed from the 1960s to the 2000s for different types of crops. For export crops, oil bearing crops had the largest decrease (16.69 $m^3\ kg^{-1}$), followed by rice (14.42 $m^3\ kg^{-1}$); the decrease in the virtual water content of coarse cereals were nearly 10 $m^3\ kg^{-1}$. For the major import crop rice, the virtual water content in the 2000s was less than 40% of that in the 1960s. Comparing the virtual water contents of exported crops with those of imported crops, we found that the virtual water contents of import rice, oil bearing crops and sugar crops were smaller than those of the exported crops; however, the opposite relation was found for corn, coarse cereals and vegetables.

We obtained the variation of virtual water flows by combining the changes in crop transfer volume and virtual water content (Fig. 3). The exported volume of virtual water increased from

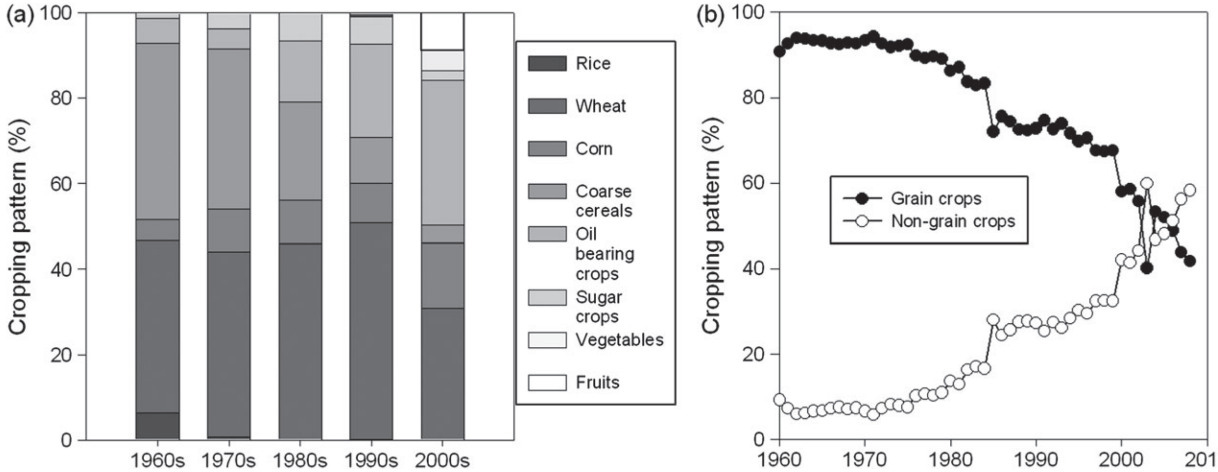

Figure 2. Temporal variation of cropping pattern in the Hetao irrigation district: (a) proportions of sown area for each crop in different periods; (b) proportions of sown area for grain crops and non-grain crops during the 1960–2008 period.

Table 1. Transfer volume (10^6 kg y^{-1}) of crops produced in the Hetao irrigation district for different periods

Export, import and decade	Rice	Wheat	Corn	Coarse cereals	Oil bearing crops	Sugar crops	Vegetables	Fruits
Export								
1960s	0.00	139.00	6.68	100.85	2.22	47.95	–	–
1970s	0.00	154.27	42.40	127.22	2.24	140.19	–	–
1980s	0.00	374.96	122.06	73.71	167.93	750.38	–	–
1990s	0.00	899.56	256.39	117.67	403.95	1014.38	–	220.21
2000s	0.00	628.32	524.13	25.45	514.28	368.67	897.11	1630.80
Import								
1960s	68.36	0.00	4.57	0.00	0.00	0.02	–	–
1970s	148.31	0.00	0.00	0.00	0.02	0.00	–	–
1980s	198.06	0.00	0.00	0.00	0.00	0.00	–	–
1990s	231.51	0.00	0.00	0.00	0.00	0.00	–	0.00
2000s	216.63	0.00	0.00	1.67	0.00	0.00	41.92	0.00

'—' indicates no data.

1.58×10^9 m^3 in 1960 to 3.29×10^9 m^3 in 1966, and then decreased to 2.08×10^9 m^3 by 1977. Afterwards, the virtual water export values fluctuated with an overall increasing trend, displaying an average growth rate of 34.24×10^6 m^3 per year. The virtual water import values showed an increasing trend from 1960 to 1971, when it reached a maximum value (1.24×10^9 m^3), which was mainly due to an increase in volume of imported rice. Since the 1980s, the volume of virtual water import has decreased at an average rate of 12.88×10^6 m^3 per year until reaching 740.85×10^6 m^3 in 2008. The net virtual water export values have fluctuated, with a mean value of 1.79×10^9 m^3 in the 1960s and 1.48×10^9 m^3 in the 1970s. Since the 1980s, the differences between virtual water export and virtual water import became larger and larger. As a result, the value of net virtual water export increased from 1.90×10^9 m^3 in 1980 to 2.59×10^9 m^3 in 2008, with an average growth rate of 34.57×10^6 m^3 per year. The volume of net virtual water export in 2008 was about 80 % larger than that in 1960.

Effects of cropping pattern on virtual water flows

Figure 4 shows the variation of integrated yield in different cropping pattern scenarios. The comparison was made from 1980 to 2008; during this period, the cropping pattern in the Hetao irrigation district was significantly different from that in the 1960s. Without considering the impacts of cropping pattern changes (constant cropping pattern scenario), the integrated yield increased from 2.05×10^3 kg ha^{-1} in 1980 to 6.68×10^3 kg ha^{-1} in 2008. After taking the changes of the cropping pattern into account (actual cropping pattern scenario), the integrated yield value was 3.07×10^3 kg ha^{-1} in 1980, which was 1.02×10^3 kg ha^{-1} greater than that in the constant cropping pattern scenario. The difference of integrated yield between these two scenarios displayed an increasing trend and it was as much as 9.61×10^3 kg ha^{-1} in 2008.

As can be seen from Fig. 5, shifting of the cropping pattern would lead to a decrease of integrated virtual water content for export crops and an increase of integrated virtual water content for import crops. Without considering cropping pattern changes (constant cropping pattern scenario), integrated virtual water content for export crops decreased from 5.68 m^3 kg^{-1} in 1980 to 1.41 m^3 kg^{-1} in 2008, and the mean rate of decrease was 0.13 m^3 kg^{-1} per year. After taking the cropping pattern changes into account (actual cropping pattern scenario), integrated virtual water content for export crops was 3.35 m^3 kg^{-1} in 1980 and 0.57 m^3 kg^{-1} in 2008. The shift in the cropping pattern decreased

Table 2. Virtual water content ($m^3\ kg^{-1}$) of crops produced in the Hetao irrigation district for different periods

Export, import and decade	Rice	Wheat	Corn	Coarse cereals	Oil bearing crops	Sugar crops	Vegetables	Fruits
Export								
1960s	17.80	8.91	7.79	11.85	19.32	1.49	–	–
1970s	9.46	7.55	3.93	7.23	13.56	0.82	–	–
1980s	8.98	4.17	2.36	6.69	3.57	0.34	–	–
1990s	4.56	2.10	1.08	2.65	2.26	0.24	–	0.18
2000s	3.38	1.62	0.93	1.88	2.63	0.18	0.16	0.21
Import								
1960s	8.96	NI	9.63	NI	NI	0.62	–	–
1970s	5.76	NI	NI	NI	6.75	NI	–	–
1980s	5.15	NI	NI	NI	NI	NI	–	–
1990s	3.79	NI	NI	NI	NI	NI	–	NI
2000s	3.33	NI	NI	3.79	NI	NI	0.34	NI

– indicates no data; 'NI' indicates no import.

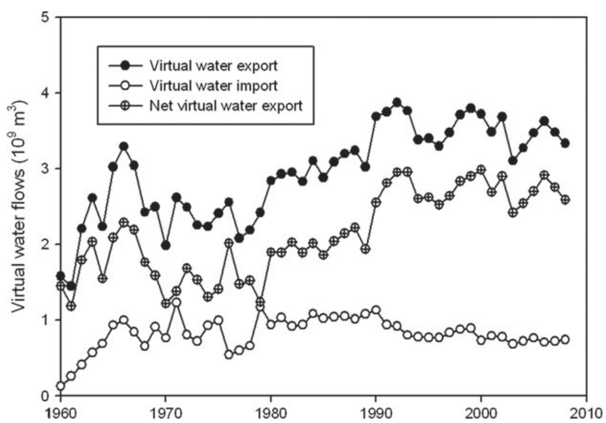

Figure 3. Temporal variation of virtual water flows in the Hetao irrigation district during 1960–2008.

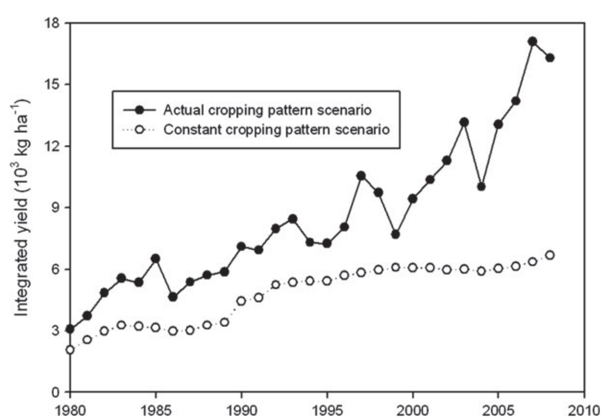

Figure 4. Integrated yield in actual and constant cropping pattern scenarios for the Hetao irrigation district during 1980–2008.

integrated virtual water content of export crops by 47%, 38% and 50% in the 1980s, 1990s and 2000s, respectively.

For import crops in the 1980s, the mean integrated virtual water content in the constant cropping pattern scenario was 4.20 $m^3\ kg^{-1}$ (Fig. 5). The value displayed a downward trend and the mean values in the 1990s and 2000s were 2.08 and 0.60 $m^3\ kg^{-1}$, respectively. Cropping pattern changes increased the integrated virtual water content for import crops by 0.94, 1.71 and 2.46 $m^3\ kg^{-1}$ in the 1980s, 1990s and 2000s, respectively.

When comparing the values of net virtual water export in actual and constant cropping pattern scenarios, we found that a decrease of $132.08 \times 10^6\ m^3$ net virtual water export was caused by cropping pattern changes during the 1980s (Fig. 5). The difference between these two scenarios in the 1990s was $2.53 \times 10^9\ m^3$. In the 2000s, the net virtual water export in the actual cropping pattern scenario was $2.10 \times 10^9\ m^3$ less than that in the constant cropping pattern scenario.

DISCUSSION

Increased demand for food in China has stimulated the enthusiasm of farmers in the Hetao irrigation district, where the fertile land, sunshine and heat provide good conditions for agricultural production. As a result, the crop sown area has increased from 327.64×10^3 ha in 1960 to 443.36×10^3 ha in 2008, with an average growth rate of 3.57×10^3 ha $year^{-1}$. It has been noted that changes in a region's cropping pattern occur for multiple reasons, including climate condition, resources endowments, agricultural technology, political motivation, consumption habits, economic development, social consideration among others.[44,45] In our study area, increasing numbers of local farmers have given up the traditional grain crops in favour of non-grain crops in order to achieve higher economic returns.

The values of virtual water contents for various crops were determined by their water consumption and yields.[28] In this study, a trend of decreases were observed for virtual water contents of different crops from the 1960s to the 2000s, which was due to falling crop water consumption and increases in crop yield mediated by improvements of agricultural production practices and water resources management. Imported rice, oil-bearing crops and sugar had lower crop water consumptions and larger yields compared with exported crops, thereby resulting in reduced virtual water content (excluding rice in the 2000s). Compared with exported rice, the mean crop water consumption and yield for imported rice in the 2000s were 0.35% and 1.87% larger, respectively; consequently, the virtual water content of imported rice in the 2000s was a little lower than that of exported rice. For corn, coarse cereals and vegetables, imported crops had higher water consumption values and lower yields than the respective exported crops;

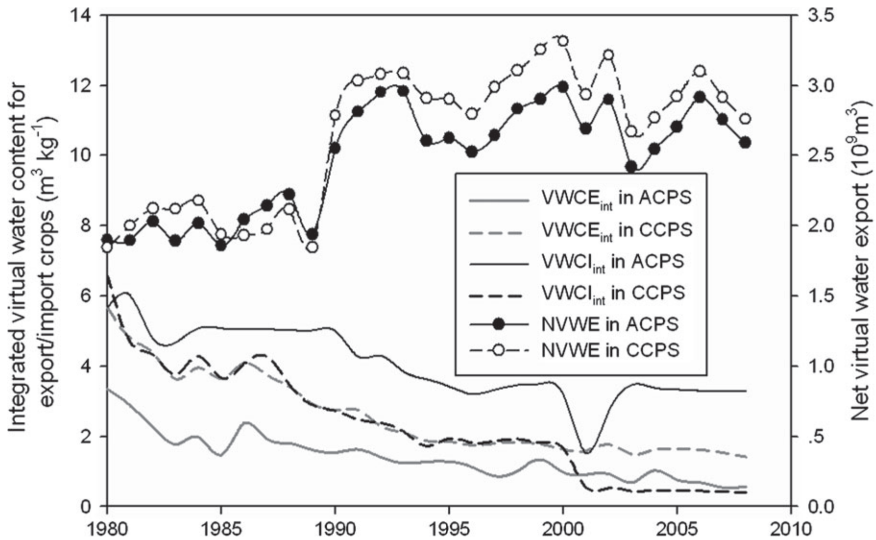

Figure 5. Integrated virtual water content for export/import crops and net virtual water export in actual and constant cropping pattern scenarios in the Hetao irrigation district during 1980–2008. VWCE$_{int}$ is the integrated virtual water content for export crops, VWCI$_{int}$ is the integrated virtual water content for import crops, and NVWE is the net virtual water export. ACPS means actual cropping pattern scenario; CCPS means constant cropping pattern scenario.

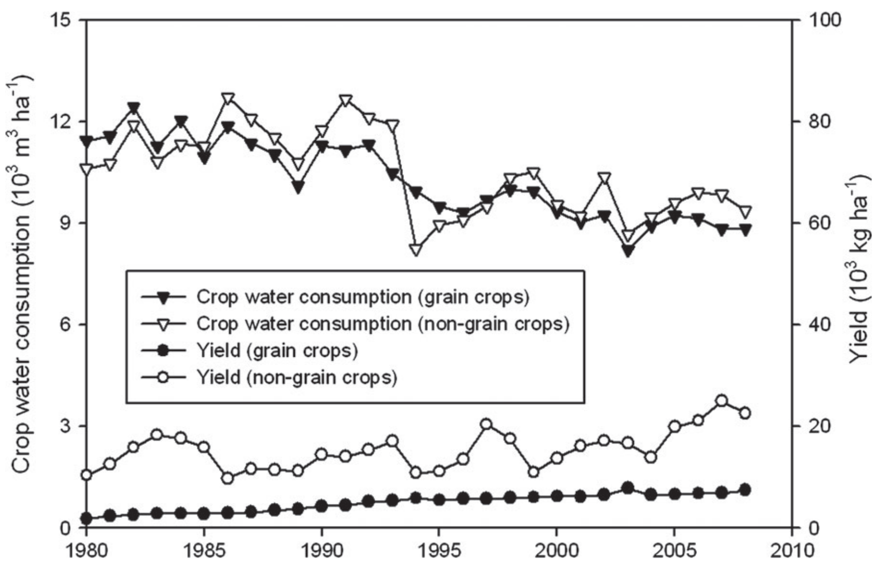

Figure 6. Crop water consumption and yield for grain crops and non-grain crops in the Hetao irrigation district during 1980–2008.

thus, these imports had greater virtual water contents than the exported crops. As indicated by Fig. 6, the volume of crop water consumption experienced a decrease of 22.83% for grain crops and a decrease of 11.77% for non-grain crops during 1980–2008 these changes were accompanied by large increases in yield, which were 294.01% (grain crops) and 116.66% (non-grain crops), respectively. The difference of virtual water content between grain and non-grain crops was mainly caused by changes in yield rather than changes in crop water consumption. Compared with grain crops, the higher yields of non-grain crops usually resulted in reduced virtual water content. Consequently, changes of the cropping pattern from grain crops to non-grain crops could bring an increase in crop water productivity for the Hetao irrigation district.

Virtual water trade does not only generate water savings for regions importing products, it also enhances the pressure on water resources in the regions producing the products for export.[8–10] Based on the results of this study, the Hetao irrigation district was a net virtual water exporter; an average of 2.72×10^9 m^3 $year^{-1}$ of water resources flowed out to other areas due to trading of crops in the 2000s, which created additional pressure on local water resources. According the results of this study, the shift of cropping pattern from grain crops to non-grain crops could decrease the net virtual water export. When the proportion of grain crops sown area in total sown area decreased from 86.23% in 1980 to 41.72% in 2008, a smaller net virtual water export was possible, along with reductions in pressure on local water resources. However, increases in crop water productivity, which were mainly driven by cropping pattern changes and adoption of agricultural technology, led to an incentive to expand agricultural production.[46,47] Consequently, more crops were produced and exported, and the value of net virtual water export experienced an increasing trend since the 1980s, adding more pressure to local water resources. In order to alleviate regional water pressure and reduce water competition between agriculture and other sectors, changing the cropping pattern from grain crops to non-grain crops is one of the means we could take, which should be coupled with measures that constrain the continued agricultural expansion.

Shifting the cropping pattern from grain crops to non-grain crops in the Hetao irrigation district could contribute to the export of water-extensive crops (such as vegetables and fruits) and the import of water-intensive crops (such as rice). If agricultural expansion is constrained as mentioned above, then scarce water resources might be allocated to those activities under serious water shortages which could generate greater economic value.[48] In this sense, cropping pattern changes in the Hetao irrigation district could not only be seen as the pursuit for higher economic return, but also as a form of feedback to water resource availability, which is the major limiting factor in sustainable development of the Hetao irrigation district. For China, the lack of food self-sufficiency would make it vulnerable to potential risks, such as war, national disasters etc.[49] Therefore, close attention should be focused on the dramatic falling trend of the proportion of grain crops in the total sown area of the Hetao irrigation district, as it is one of the important agricultural production regions. In the future, there will be a need for a systematic framework (usually a multi-objective optimisation model) to support policy makers in planning the structure of the regional cropping pattern to meet certain national goals of food production while taking many factors ranging from natural resources, ecological, socio-economic and institutional conditions into consideration.[45]

Owing to an absence of data, crop stocks used in this paper were deemed the same and no differences were assumed for virtual water content between export and import. Besides, many factors were difficult to include in the study, such as the influences of changing cropping pattern on other variables. Nevertheless, the results of this paper could provide insight into the potential for improving water resources management at the irrigation district scale by consideration of the existing cropping pattern.

CONCLUSION

During the study period, increasing amounts of traditional grain crops were replaced with non-grain crops. Due to the falling crop water consumption and increasing yield, the values for virtual water content for different crops decreased. Overall, the Hetao irrigation district was a net virtual water export region and the value of net virtual water export has increased since the 1980s.

Cropping pattern changes in the Hetao irrigation district could not only be seen as the pursuit for higher economic return, but also as a feedback response to limited water resources. The impact of cropping pattern change on net virtual water export was not sufficient to offset the effects of agricultural expansion; consequently, adjustment of the existing cropping pattern should be coupled with measures to constrain continued agricultural expansion. Additionally, a systematic framework is still needed for future cropping pattern planning by taking food security and other constraints into consideration.

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