High potentials of water and land efficiency in agricultural production and trade for rich food supply by Central Asia

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Key Points:

- Agricultural water and land efficiency in Central Asia are much lower than China.
- Water and land in agricultural production and trade are shown for Central Asia.
- Visible trade-offs are shown between water and land efficiencies for food.
- Central Asia shows high potential of more food supply for feeding 387 million people.

Abstract

Besides posing soaring pressure on water and land resources, the ever-intensifying agricultural production redistributes these pressures trough increasingly intensive trade. Environmental consequences are complicated and unprecedented, and postulate thorough scrutiny. Little attention is paid to developing regions which are small nodes in global trade however of visible gaps in water and land productivities. Here we evaluate, among five Central Asian nations (CANs) and China, the water and land footprints, virtual water and land trades, as well as potentials in enhancing water and land efficiency related to agricultural production and trade. We find that the blue water footprint and land footprint per unit product in CANs were up to 61- and 17-times higher than in China. Through enhancing water and land efficiency without further intervention in water and land endowments, the scenario for CANs shows an additional food supply for feeding 387 million people or half the starving population in the world.

1 Introduction

Increasing demand for agricultural products and the soaring global trade are putting unprecedented pressure on agricultural systems as well as water and land resources, the base for agriculture, worldwide (D'Odorico et al., 2019; Hoekstra & Wiedmann, 2014; Wiedmann & Lenzen, 2018). A quarter of the global water (WF) (Hoekstra & Mekonnen, 2012) and land footprint (LF) (Weinzettel et al., 2013) in agricultural systems is embodied in international agricultural trade, forming the growing virtual water (VWT) and virtual land trade (VLT). Various studies have discussed how the management of virtual water or land resource trade can drive resource allocation towards a more sustainable pattern (Abdelkader et al., 2018; D'Odorico et al., 2019; Dalin et al., 2012; Hoekstra & Mekonnen, 2016; Wu et al., 2018; Zhuo et al., 2019). Optimizing agricultural trade structure by increasing exports from resource-affluent areas and improving productivity of particularly water-thirsty crops are widely recommended solutions (B. Cai et al., 2020; Dalin et al., 2012; Hoekstra & Mekonnen, 2016). However, a bulk of arable lands keep suffering from high crop yield gaps (Mueller et al., 2012) and low water efficiency (Mekonnen & Hoekstra, 2014) especially in many less developed countries. Among them, many of those that are not major players in global VWT and VLT have still been largely ignored (Hoekstra & Mekonnen, 2016; Lenzen et al., 2012; Liu et al., 2018) in constructing sustainable food supply scenarios with curbed environmental pressure, both locally and globally.

Here, we aim to address this knowledge gap with a focus on five Central Asian nations (CANs) (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan), which are small nodes in global agricultural trade however suffering the most serious environmental havoc with low efficiencies (Qadir et al., 2009; Varis, 2014), and one of their biggest trade partner and neighbour China. CANs are in favourable geographical positions for several markets such as China, Russia, the Middle East, and Europe. CANs use over 90% of its water resources to irrigate water-intensive crops (FAO, 2018; Varis, 2014) with strikingly low productivity (Varis, 2014). This leads to ecosystem degradation, seriously threatening local human water security and biodiversity (Vörösmarty et al., 2015; Varis, 2014). CANs' total agricultural land area equals to 57% of China's, while CANs' population is the mere 5% of China's. In 2017, the average yields of cotton and wheat in CANs were only at 43% and 29% of the Chinese level, respectively (FAO, 2018). Thus, it is not surprising that Turkmenistan has the largest blue WF per capita worldwide (Hoekstra & Mekonnen, 2012). Here we address three questions zooming in CANs and China. First, how are the magnitudes of WFs and LFs and their trade-offs related to agricultural products. Second, how sustainable are their VWT and VLT patterns. Third, what is the potential in enhancing agricultural efficiency in CANs?

In particular, we (i) evaluate national level trade-offs between annual consumptive WF and LF in agricultural production; (ii) assess patterns and sustainability of agricultural trade related VWT and VLT by country over 2000-2014; and (iii) investigate the potential for efficiency improvement in agriculture via scenario analysis. We include 16 primary crop products, 4 primary animal products, and 12 derivative products, which altogether account for 93% of agricultural land in CANs and 83% of total agricultural trade volume between CANs and China (FAO, 2018).

2 Materials and Methods

2.1 Overview

The concept of VW was introduced by Allan (1993), which refers to the water resources needed to produce agricultural products, also known as “embedded water” (Allan, 1998). Hoekstra (2003) further came up with the concept of WF, which is the total amount of water resources required by all products and services consumed by a country, region, or person in a certain period of time. Then, the concept of VL and LF (Erb, 2004) emerged. They are new tools for us to measure and manage natural resources use.

2.2 Water footprint calculation

We use the Fast Track approach (Tuninetti et al., 2017), which is based on the negative relationship between crop yield and corresponding WF per unit mass of crop, to calculate annual WF per unit of primary or derivative crop products considering the product ratio and value ratio of derivatives (assuming the product ratio and value ratio both constant) (Mekonnen & Hoekstra, 2011). We make use of the available product WF database (Mekonnen & Hoekstra, 2011) and crop yield levels at year 2000 (FAO, 2018) to obtain the inter-annual variations in WF for crop production at national level.

$$WF_{c,i,t} = \frac{WF_{c,i,2000} \cdot Y_{c,i,2000}}{Y_{c,i,t}} \tag{1}$$

$$WF_{dp}(p) = \frac{WF_{pp}(p) \cdot f_v(p)}{f_p(p)} \tag{2}$$

where $WF_{c,i,t}$ is the WF per unit of crop *c* in country *i* in year t, m^3 t^{-1} ,and $Y_{c,i,t}$ is the yield of crop *c* in country *i* in year *t*, in units of t^{-1} ha^{-1}. $WF_{dp}(p)$ and $WF_{pp}(p)$ are the WF per unit of derivative product *p* and its primary product, in units of m^3 t^{-1}, respectively. $f_p(p)$ and $f_v(p)$ are the product ratio and value ratio of derivative products, respectively.

The WF of animal products (WF_a) includes feed crop WF (WF_f), service water, and drinking water. The proportion of feed crop WF is approximately equivalent to 98% of total water consumption of raising animals (Mekonnen & Hoekstra, 2011). In this study, using available dataset on WF of animal products (weighted average production system) (Mekonnen & Hoekstra, 2010), the effects of annual change on WF in main feed (ΔWF_f), animal productivity (Bouwman et al., 2005; Zhuo et al., 2016) and animal product productivity (FAO, 2018) are considered in terms of inter-annul variability, as follows:

$$WF_{a,i,t} = \frac{WF_{a,i,2000} + \Delta WF_{f,a,i,t}}{(1+\Delta ap_{a,i,t}) \times (1+\Delta pp_{a,i,t})} \tag{3}$$

$$\Delta WF_{f,i,t} = \sum\nolimits_{c} (WF_{a,i,2000} \times m_c\% \times (\frac{Y'_{c,i,2000}}{Y'_{c,i,t}} - 1)) \tag{4}$$

$$Y'_{c,i,t} = \begin{cases} \dfrac{P_{c,i,t} - E_{c,i,t} + I_{c,i,t}}{\dfrac{P_{c,i,t} - E_{c,i,t}}{Y_{c,i,t}} + \dfrac{I_{c,i,t}}{Y_{c,global\ average,t}}}, & I_{c,i,t} \geq 0 \\ Y_{c,i,t}, \quad I_{c,i,t} < 0 \end{cases} \tag{5}$$

where, $WF_{a,i,t}$ is the WF of animal product a in country i in year t, in units of $m^3\ t^{-1}$. $\Delta WF_{f,a,i,t}$ is the change on WF in main feed used to fed animal to produce animal product a in country i in year t compared to year 2000, in units of $m^3\ t^{-1}$. $\Delta ap_{a,i,t}$ and $\Delta pp_{a,i,t}$ (%) are rates of change in animal production output per unit mass of feed and animal product production output per head of product a in country i in year t, respectively. When the animal product a is a primary animal product namely live animal, $\Delta pp_{a,i,t}$ is equal to 0. In the calculation of $\Delta WF_{f,a,i,t}$, $m_c\%$ is the proportion of WF for each forage crop in the total WF of animal production (Mekonnen & Hoekstra, 2011). As it is uncertain whether the origin of feed is domestic or foreign, according to the domestic production and import and export volume of feed crops, we calculate $Y'_{c,i,t}$, which is the corrected yield of feed crop *c* used in country *i* in year *t*, in units of t ha^{-1}. $P_{c,i,t}$ refers to the crop production in country *i* in year *t*, in units of t. $I_{c,i,t}$ and $E_{c,i,t}$ are import and export volume of crop *c* in country *i* in year *t*, in units of t, respectively.

2.3 Land footprint calculation

The LF per unit of crop of each country is the area of cultivated land required for unit quality crop products, that is, the reciprocal of yield, as follows:

$$LF_{c,i,t} = \frac{1}{Y_{c.i,t}} \tag{6}$$

where $LF_{c,i,t}$ is the LF per unit of crop *c* in country *i* in year *t*, in units of ha t^{-1} and $Y_{c.i,t}$ refers to the yield of crop *c* in country *i* in year *t*, in units of t ha^{-1}. Derivative crop product LF is calculated from the LF of the primary product by considering the product ratio and value ratio (in the same manner as WF (Mekonnen & Hoekstra, 2011)).

The LF of animal product is the sum of grazing land and forage crop planting land (Bosire et al., 2015). Grazing land is calculated by the density of livestock in the agricultural area (FAO, 2018). In this study, the main forage crops were divided into four categories: grain, oil crops (oil crops, oil meals, and pulses), sugar crops (sugar crops, molasses) and roughage (Mekonnen & Hoekstra, 2011). The LF of roughage is included in grazing land.

$$LF'_{a,i,t} = \frac{LF_{a,i,t}}{W_{a,i} \times R_{a,i,t}} \tag{7}$$

$$LF_{a,i,t} = \frac{ST_{a,i,t}}{\mathrm{LD}_{a,i,t}} + \sum\nolimits_{c} (L_{c,i,t} \times \omega_{c,a,i,t}) \tag{8}$$

where the subscripts a, i, t and c denote animal product, country, year and forage crop, respectively. LF' and LF refer to the LF per unit of animal product and the LF total production of animal product, in units of ha t^{-1} and ha, respectively. W is the average live weight of animal product (FAO, 2003), in units of t $head^{-1}$ and R is the amount of animal product raised (FAO, 2018), in units of head. ST represents the stock of animal product, in units of LSU (Chilonda & Otte, 2006; FAO, 2018) and LD is the density of animal product in the agricultural area, in units of LSU ha^{-1}. L is the planting area of forage crop required for raising animal products, in units of ha, and ω is the ratio of animal product consumption of forage crop to the all animals consumption of forage crop. The above two parameters were calculated via equations (9-11):

$$L_{c,i,t} = \left(\frac{P_{c,i,t} - E_{c,i,t}}{Y_{c,i,t}} + \frac{I_{c,i,t}}{Y_{c,global\ average,t}}\right) \times f_{c,i,t} \tag{9}$$

$$f_{c,i,t} = \frac{F_{c,i,t}}{P_{c,i,t} + IM_{c,i,t} - EX_{c,i,t}} \tag{10}$$

$$\omega_{c,a,i,t} = \frac{ST_{a,i,t} \times \alpha_{c,a}}{\sum_a (S_{a,i,t} \times \alpha_{c,a})} \tag{11}$$

where, $f_{c,i,t}$ refers to the proportion of the consumption of forage crop c as feed ($F_{c,i,t}$) to the total consumption of forage crop c in country i in year t (FAO, 2018). The main factors that the different consumptions of forage crops in the animals are the diet structure and number of the animals. According to $\alpha_{c,a}$ (the proportion of forage crop c animal product a eats in its all forage crops) (Mekonnen & Hoekstra, 2010) and $S_{a,i,t}$, we calculated $\omega_{c,a,i,t}$. In addition, the LFs of derivative products are calculated in the same way as the WFs of derivative products, according to the product ratio and value ratio (Mekonnen & Hoekstra, 2010) (assuming that the land area of processing is 0).

2.4 Virtual water and land trades quantifications

The *VWT* and *VLT* of agricultural product p ($VWT_{p,i,j,t}$, m^3 and $VLT_{p,i,j,t}$, m^2) from country i to country j in year t are the volume of product trade from country i to country j in year t ($T_{p,i,j,t}$, t) times the virtual water content and virtual land content per unit product of origin country i in year t ($VWC_{p,i,t}$, m^3 t^{-1} and $VLC_{p,i,t}$, m^2 t^{-1}), respectively:

$$VWT_{p,i,j,t} = T_{p,i,j,t} \times VWC_{p,i,t} \tag{12}$$

$$VLT_{p,i,j,t} = T_{p,i,j,t} \times VLC_{p,i,t} \tag{13}$$

2.5 Water and land saving quantifications

Water saving can be used to evaluate the sustainability of *VWT*, that is, whether the direction of *VWT* from areas with high water use efficiency to areas with low water use efficiency, which is equal to the *VWT* when the *VWC* of product imported from foreign sources was equal to that of import country minus the actual *VWT* (Chapagain et al., 2006). Land saving is calculated in the same way:

$$WS_{p,i,j,t} = (VWC_{p,j,t} - VWC_{p,i,t}) \times T_{p,i,j,t} \tag{14}$$

$$LS_{p,i,j,t} = \left(VLC_{p,j,t} - VLC_{p,i,t}\right) \times T_{p,i,j,t} \tag{15}$$

where $WS_{p,i,j,t}$ and $LS_{p,i,j,t}$ are water saving and land saving between country *i* and country *j* in year *t*, m^3 and m^2, respectively.

2.6 Scarce blue water and land saving quantifications

The traditional water and land saving calculations do not account for the differences of water and land resource pressures in various regions. Inspired by the introduction of stress-weighted WFs by Ridoutt and Pfister (2010), we made *WSI* (Pfister & Bayer, 2014) and *LSI* as the pressure index of water and crop land resources, respectively, multiplied by the *VWC* and *VLC* of each product to calculate the scarce blue water saving (Zhao et al., 2018) and land saving, as follows:

$$SWS_{p,i,j,t} = \left(WSI_j \times VWC_{p,j,t} - WSI_i \times VWC_{p,i,t}\right) \times T_{p,i,j,t} \quad (16)$$

$$SLS_{p,i,j,t} = \left(LSI_{j,t} \times VLC_{p,j,t} - LSI_{i,t} \times VLC_{p,i,t}\right) \times T_{p,i,j,t} \quad (17)$$

where $SWS_{p,i,j,t}$ and $SLS_{p,i,j,t}$ are the scarce blue water and land saving of product *p* between country *i* and *j* in year *t*, m^3 and m^2, respectively. WSI and LSI are the water and crop land resource pressure indexes, respectively. Values on WSI per country are obtain from Pfister and Bayer (2014). The annual LSI per country is calculated by the following equations (Y. Cai et al., 2002)：

$$LSI_{i,t} = \frac{SM_{i,t}}{SA_{i,t}} = \frac{\beta_{i,t} \times G_{i,t}/(Y_{f,i,t} \times Q_{i,t} \times k_{i,t})}{SA_{i,t}} \quad (18)$$

$$\beta_{i,t} = \frac{P_{f,i,t}}{D_{i,t}} \times 100\% = \frac{P_{f,i,t}}{(P_{f,i,t} + I_{f,i,t} - E_{f,i,t})} \times 100\% \quad (19)$$

$$k_{i,t} = \frac{AS_{i,t}}{AC_{i,t}} \times 100\% \quad (20)$$

where *i*, *t* and *f* represent country, year and food, respectively. SM and SA refers to the cultivated land area minimum requirement and actual per capita, in units of ha, respectively. β is the food self-sufficiency rate and G is the food demand per capita, in units of kg cap^{-1}. Y is the yield of food, in units of kg ha^{-1}; Q is a ratio of the area food crops planted to the area of agricultural crops cultivated; and k is the multiple cropping index. P, I and E are the amount of food production, import and export, in units of t, respectively. D is the total demand of food, in units of *t*. AS and AC are areas agricultural crops sown and cultivated, in units of ha, respectively.

2.7 Scenario analysis

In order to explore the potential for food production improvements with lower WFs and LFs after Chinese agricultural investment in CANs, this study set up two scenarios based on data from 2014, and made the following rough assumptions: In S1, we assumed that, after the introduction of agricultural technology, the yield of all considered crop products in CANs and China increase to 125% of the highest yield level among the six countries in 2014, maintaining the crop and animal productions constant in each country. We then analysed the change in the WF and LF in agricultural production and the sustainability of relative VWT and VLT among the six countries. S2 aimed to increase the production so that the water consumption of each agricultural product is consistent with that of 2014 under the premise of S1 for evaluating the potential of agricultural production and food self-sufficiency rate. At the same time, we estimated the number of people who could be fed with the additional agricultural production (except tea and cotton products) in a year based on the data of the energy that agricultural products can provide (USDA, 2019) and the average global daily energy demand per capita (FAO, 2015).

3 Data

The annual average WFs, product ratios, and value ratios of agricultural products in this study came from Mekonnen and Hoekstra (2010; 2011, 2012). The data of agricultural production and trade, the population at country level, and global average daily energy demand per capita were from FAO (2003, 2015, 2018). The data of water resource pressure index were from Pfister and Bayer (2014) and the data of energy content in food were from the United States Department of Agriculture (USDA) (2019).

4 Results

4.1 Water and land footprints in agricultural production

During the study period of 2000-2014, the magnitudes of consumptive (green plus blue) WFs, blue WFs, and LFs per unit mass of the agricultural products considered in CANs were considerably higher than those in China (see Figure 1 for the level of year 2014). Blue WFs accounted for an extremely high proportion up to 90% in CANs. The largest disparity in terms of blue WF and LF per unit product was observed between Tajikistan and China in raising chickens. The blue WF (~9,027 m^3 t^{-1}) and LF (~7,932,076 m^2 t^{-1}) of Tajik chickens were 61- and 17-times China's, respectively. Regarding crops, Turkmen seed cotton had the highest WF (~9,469 m^3 t^{-1}) and blue WF (~7,830 m^3 t^{-1}); these were 8- and 42-times the Chinese level, respectively. The ratio of blue WFs for raising pigs in Turkmenistan (70%) and Uzbekistan (69%) were both 10 times the Chinese level.

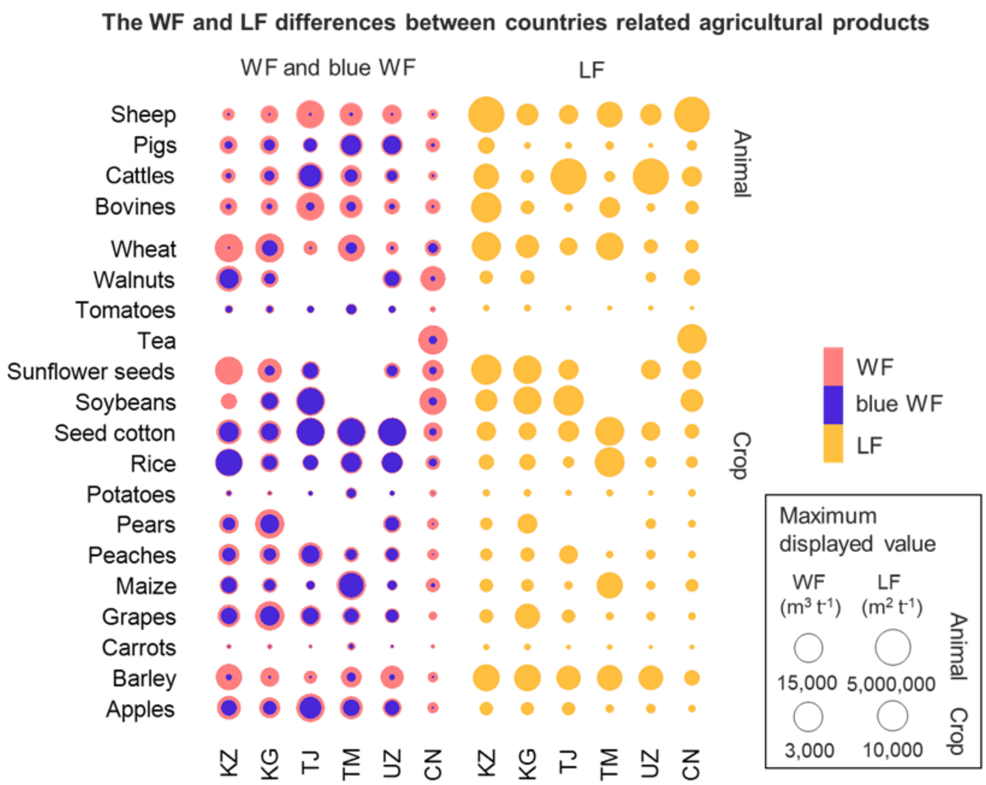
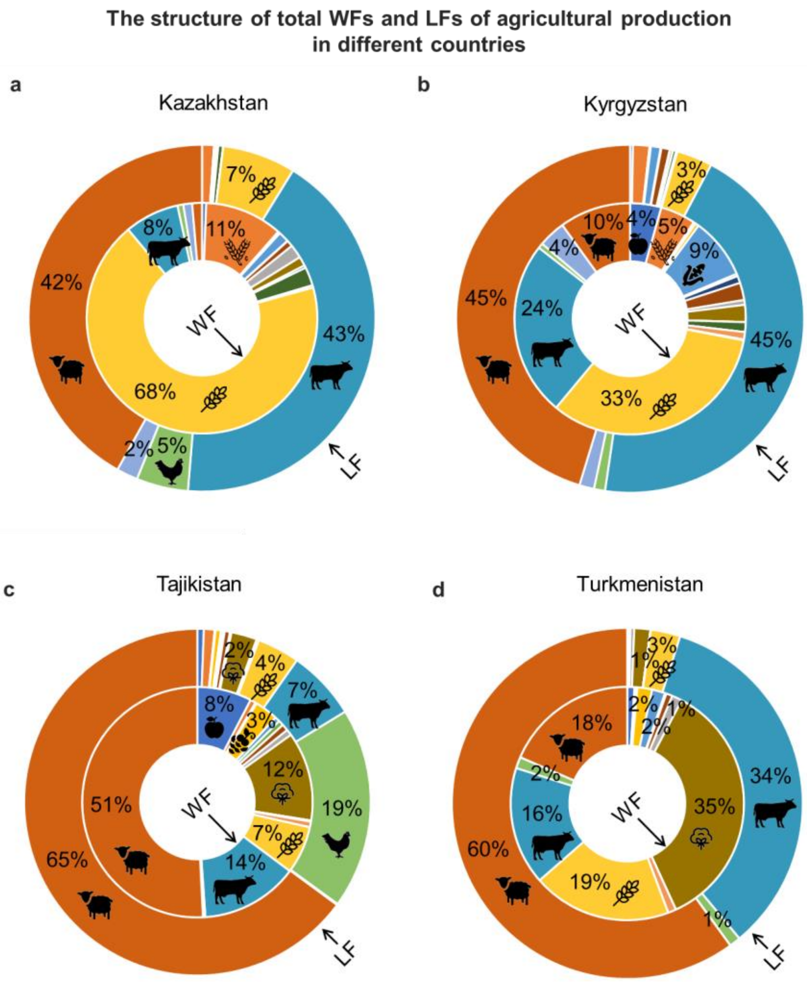


Figure 1. Water (WFs) and land footprints (LFs) per unit mass of agricultural products in Central Asian nations (CANs) and China. Circle size indicates the WFs (red), blue WFs (blue) and LFs (yellow) per unit of agricultural products in Kazakhstan (KZ), Kyrgyzstan (KG), Tajikistan (TJ), Turkmenistan (TM), Uzbekistan (UZ) and China (CN) in 2014. The larger the circle size, the higher footprints of agricultural production. Precise estimated values are reported in supporting information Table S1-7.

Clear disparities were observed between the WF and LF of some agricultural products for the CANs. For instance, the WF per unit of sunflower seed in Kazakhstan of 2,729 m^3 t^{-1} in 2014 was similar to that of the other countries, while the corresponding LF per unit was 14,993 m^2 t^{-1}， as high as 3 times the average level of the other 5 countries. The WF per unit of rice grown in Turkmenistan was 1,728 m^3 t^{-1}, at a level similar to the other countries, while the corresponding LF of 9,711 m^2 t^{-1} was 4 times the average of the other countries. Tajik WF of raising sheep was 39,150 m^3 t^{-1}, which was 19 times the minimum level in China, while the corresponding LF was 421,168 m^2 t^{-1} which was only 15% the maximum level in Kazakhstan.

There was an increase in the total WFs and LFs related to agricultural products in CANs and China except for Kyrgyzstan over the study period 2000-2014 (see supporting information Figure S1). Tajikistan experienced the highest increase in WFs (by 47%) and LFs (by 73%) compared with the other countries due to its dramatic increase in crops and animal production (126% and 157%, respectively). In Kyrgyzstan, the total WF and LF decreased by 3% and 28%, respectively. This difference can be attributed to the change in the types of crops produced; the total production of potatoes and maize increased by 36% while wheat production decreased by 45%.

Among CANs, Kazakhstan had the largest annual total WF (~54 billion m^3 y^{-1}) and LF (~1.7 million km^2 y^{-1}), in 2014. Kyrgyzstan had the smallest WF of 5.1billion m^3 y^{-1} while Tajikistan had the smallest LF of 74 000 km^2 y^{-1}. Interestingly, contributors to the WF and LF in a single country were not always consistent (Figure 2 and table S8). Meanwhile, the CANs and China had very different key contributors. Wheat production was the greatest contributor to the national agricultural WFs of Kazakhstan (~68%) and Kyrgyzstan (~33%). Cotton contributed more than other products to the total WFs in Turkmenistan (~35%) and Uzbekistan (~36%). The largest WF contributor for Tajikistan was sheep husbandry (51%), and for China was raising pigs (31%). In terms of national LFs, sheep husbandry appropriated the greatest area of land in Turkmenistan (60%), Tajikistan (52%), Kyrgyzstan (45%), and Uzbekistan (34%), while raising cattle accounted for most of the LF in Tajikistan (52%). Raising pigs contributed the most to the total agricultural LF of China (29%).



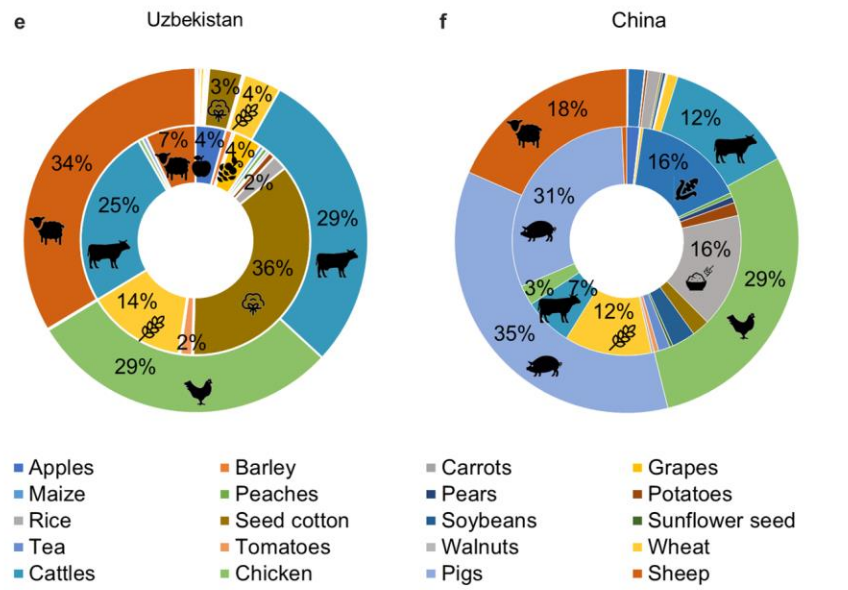


Figure 2. The structure of total water (WFs) and land footprints (LFs) of agricultural production in the study countries. The total agricultural production WFs (internal ring) and LFs (external ring) pattern in Central Asian countries (a, b, c, d, e) and China (f) at 2014. See supporting information Table S8 for all proportion values per agricultural products in the study countries.

4.2 Embedded scarce water and land in agricultural trade

As seen in the inter-annual variations in net VW and VL imports per country over the study period (Figure 3), the annual VLT patterns among the six countries were more consistent than the corresponding VWT patterns. Kazakhstan was the main net VW and VL exporter, whereas China was their biggest importer. As the volumes of its wheat exported to China increased, Kazakhstani net VW and VL exports grew by 93% and 104%, respectively. Wheat, cotton lint, and cattle hide products were the major agricultural products in both virtual water and land resources redistribution among CANs and China. They accounted for 69%, 12%, and 2% of the total VWT, while 76%, 0.5%, and 5% of the total VLT, respectively.

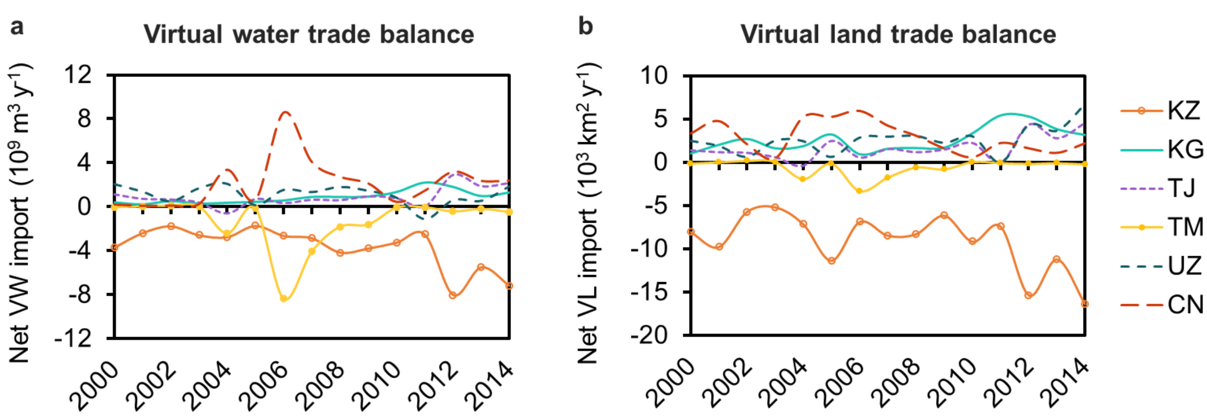


Figure 3. Virtual water (VW) and virtual land (VL) trade balances on national scale. The trade of agricultural products between six the countries including Kazakhstan (KZ), Kyrgyzstan (KG),

Tajikistan (TJ), Turkmenistan (TM), Uzbekistan (UZ) and China (CN) generated virtual water trade (a) and virtual land trade (b) from 2000 to 2014.

When tracking the VW and VL flow directions, we find that the VLT was mainly from countries under higher land scarcity levels to those with lower land scarcity levels (Figure 4). Simultaneously, CANs exported blue VW of 1.6 billion m^3 to China, accounting for 80% of the total blue VW flows; of these, Uzbekistan exported 1.1 billion m^3 of blue VW to China (98% from cotton) by 2014. However, both Kazakhstan and Turkmenistan had non-synchronous VWT and VLT variation. Agriculture has been very unsustainable and harmful to ecosystems and the environment in large parts of Central Asia ever since 1960s, particularly its arid parts, which is most clearly manifested by drying up of most of the Aral Sea (UNESCO, 1998). The increasing trend of food exported from those areas that were already facing water and land scarcity made the situation even more unsustainable.

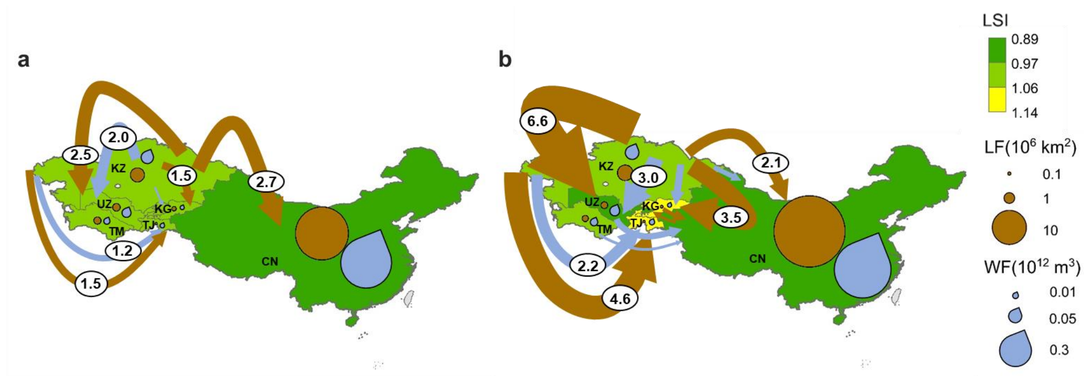


Figure 4. Virtual water and virtual land trade on national scale. a for year 2000), b for year 2014. The two maps illustrate the VWTs (blue arrows) and VLTs (brown arrows) in Kazakhstan (KZ), Kyrgyzstan (KG), Tajikistan (TJ), Turkmenistan (TM), Uzbekistan (UZ) and China (CN) and the size of arrows means the volume of VW (10^9 m^3) and VL (10^9 m^2). The size of circle and water drop respectively represent the total water (WF) and land footprint (LF) of agricultural production in each country. LSI refers to the land stress indicators.

Following the concept of "global water or land savings" referring to the agricultural products exported to countries with less water or land productivity (i.e., low WF and LF per unit product) than the countries of origin (Chapagain et al., 2006), we calculate the annual global water and land savings from trade among the six countries. The current case shows that the agricultural trade among the six countries had both "global water and land losses". In 2014, the net water loss was 5.2 billion m^3 and the net land loss was 5870 km^2 y^{-1} (Figure 5a and b). Wheat trade was the main reason, contributing to 81% and 84% of the total water and land waste, respectively. Cotton lint trade wasted 693 million m^3 of water while saving 823 km^2 of land (Figure 5a and b).

In order to measure the impacts of VWT and VLT on water and land scarcity in exporting regions, we weigh blue WF and LF by water stress indicators (WSI) (Pfister & Bayer, 2014) and land stress indicators (LSI) (Y. Cai et al., 2002), respectively (Ridoutt & Pfister, 2010). The resulted water and land equivalent volumes are called as "scarce blue water" (i.e., water in a place where blue water withdrawal exceeds blue water availability) (Pfister & Bayer, 2014) and "scarce land" (i.e., the land where the actual arable land area is smaller than required minimum) (Y. Cai et al., 2002). The losses of scarce blue water and scarce land through trade were displayed in Figure 5c and 5d, respectively. In 2014, cotton lint export from Uzbekistan was the main contributor to the waste of scarce blue water, accounting for 68% of the total. Wheat exports from Kazakhstan were the main contributor to the loss of scarce land, accounting for 83% of the total.

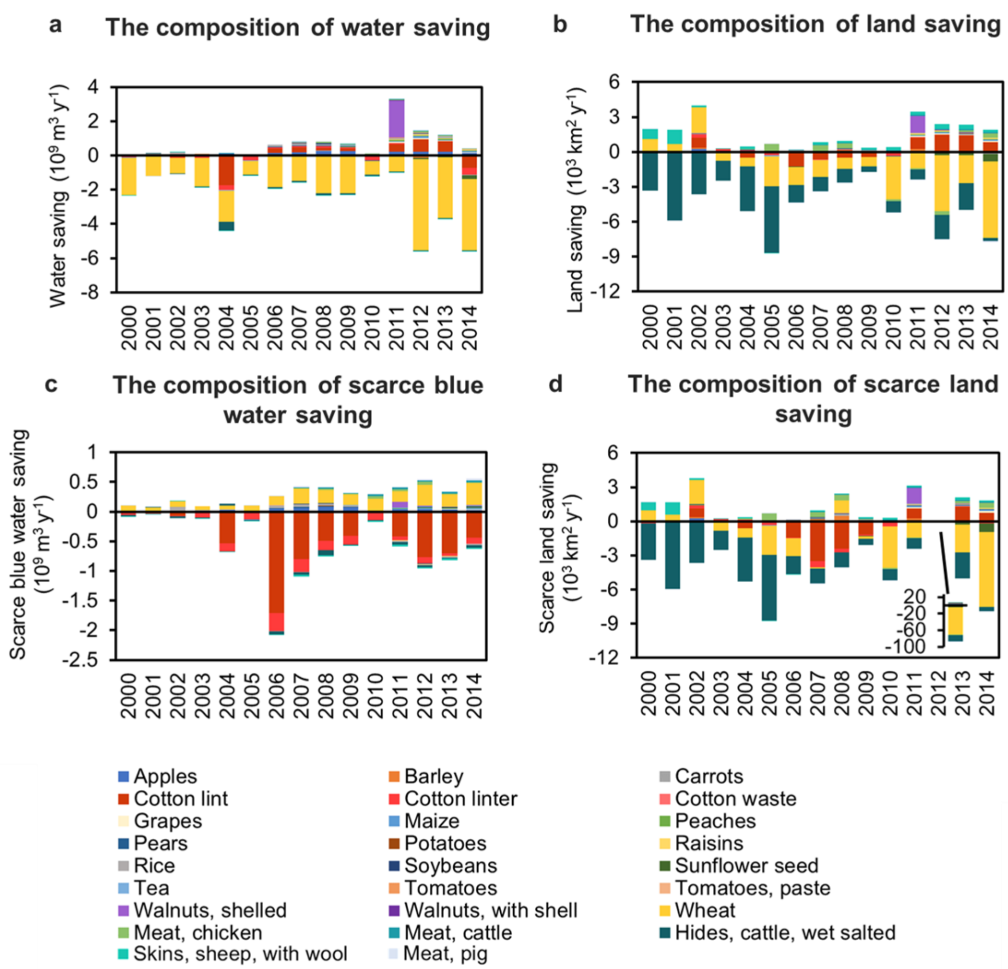


Figure 5. Savings and losses of global water, global land, scarce blue water and scarce land in agricultural trade among Central Asia countries and China. After the quantification of global water (a and land (b) savings of trade among six countries, the scarce blue water (c) and scarce land saving (d) from the VWTs and VLTs were weighted by water stress indicators (WSI) (Pfister & Bayer, 2014) and land stress indicators (LSI) (Y. Cai et al., 2002), respectively.

4.3 High potential for improving water and land efficiency

The above analyses clearly show that, in CANs, the relatively low production level per unit of used water and land is the leading reason for their unsustainable overuse of water and land for agricultural purposes. The existing yield gap assessment (Mueller et al., 2012), which refers to the differences between the actual and attainable crop yield under certain soil and climate conditions, shows that the actual crop productivity level in the CANs mostly are below half of the corresponding attainable levels. According to Mueller et al.(2012), in terms of the main exporting crops wheat and cotton in CANs, the yield of wheat and cotton in Tajikistan just reached 30% and 49% of its 95% attainable yield; whereas with similar level of attainable yield as for CANs, in China the actual yield of wheat and cotton is at 79% and 80% of its 95% attainable yield.

Apparently, for CANs, enhancing local crop water and land productivities, instead of trading more from a higher resource-efficient region, deserves the top priority in ensuring sustainable agricultural production and trade. Therefore, we set up scenarios S1 and S2 based on increasing the crop yield levels in CANs with different limitations, to test the potential for food supply improvements with lower WFs and LFs. The crop yield and agricultural trade pattern in 2014 was taken as reference for the current situation. Given the similarity in attainable yield levels between CANs and China for main crops (Mueller et al., 2012), we assume that the yields of all crop products in CANs and China increase to 125% of the highest yield among the six countries in 2014 in both scenarios. In S1, the crop and animal productions per country is held constant at the 2014 levels. In S2, the total WF per country is held constant at the 2014 levels.

In S1, the total WF and LF in agricultural production of each country were significantly reduced and the sustainability of relative VWT and VLT were greatly improved among the six countries compared with the 2014 levels (Figure 6a and b). There was a 56% reduction in total WF and 11% reduction in total LF for agricultural production in the CANs. The reduction in blue and green WFs in a country represent potential improvements in irrigation and rainwater productivity, respectively, in croplands. The decrease in the blue WFs were greater than those of green WFs except for Kazakhstan and China (Figure 6a). Tajik blue and green WFs decreased by 58% and 18%, respectively. Both Kazakhstani green WF and Turkmen blue WF for agricultural production fell by more than 70%. The LFs were much less sensitive than WFs to increases in crop yield. Kazakhstan had the largest reduction in LF at 14%. The relative VWT and VLT in S1 generated green water savings (198 million m^3 y^{-1}) and land savings (1.0 km^2 y^{-1}) while blue water loss was less than the reference level (Figure 6b). The corresponding scarce blue water waste decreased by 29%, while scarce land savings increased 13.8 times.

In S2, the total crop production in the six countries almost doubled. This was due to increases in crop yield and constant total WF in agricultural production, with significantly higher crop production, food self-sufficiency, and a 10% increase in total animal production due to smaller WF in feed crops (Figure 6c and d). Kazakhstan had the most significant growth in crop production and food self-sufficiency rates that were 3.7 and 6.9 times the reference levels, respectively. However, Uzbekistan had the least room for improvement of the other CANs, with an increase in crop production of 82% and a two-fold increase in food self-sufficiency rate compared to 2014. Similar responses were seen in China.

Based on a rough division of the total dietary energy that the total agricultural production in these six countries can provide (USDA, 2019) in S2 (~4.1×10^{14} kcal) by the global average daily dietary energy demand per capita (~2,903 kcal per capita per day) (FAO, 2015), the increased food production (excluding tea and cotton) in the six countries would be enough to feed 387 million people for a year. This is 5.7 times the total population of the five CANs and is close to half the population of people starving globally (FAO/IFAD/UNICEF/WFP/WHO, 2019). This encouraging estimate suggests more possibilities for achieving the United Nations Sustainable Development Goal 2 of “zero hunger” by 2030 (UN, 2015). In addition, the agricultural investment could create new economic opportunities for CANs and ease water related tensions among them.

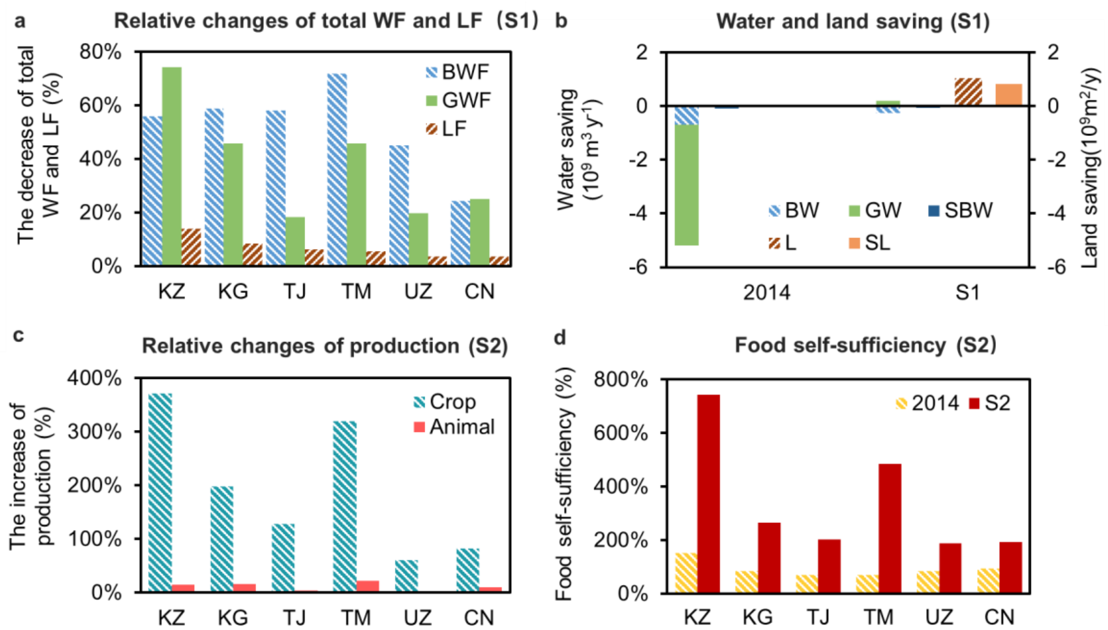


Figure 6. Responses in water footprints, land footprints, agricultural production and food self-efficiency in scenarios 1 (a, b) and 2 (c, d). With yield increases to the 125% of the current highest level, the total WF and LF are reduced (a). Agricultural trade generates land savings (b). For keeping the total WF per country invariant, the agricultural production (c) increases so that food self-sufficiency rate grows differently in six countries (d).

5 Conclusions

In CANs, over half of river runoff is used by humans. Such a level of overconsumption makes the region to belong to the top 10% of the world's most water stressed areas (Qin et al., 2019). Among many side-effects is the far-reaching collapse of the ecosystems in the Aral Sea and deltas, coasts, grasslands, and fertile river valleys (Qadir et al., 2009; Varis, 2014). The associated problems of soil salinization and desertification are striking and may hamper local urbanisation, social stability and securities. This analysis shows a vulnerable and degraded natural resources endowments in CANs with huge net water loss (5.2 billion m^3 y^{-1}) and net land loss (5870 km^2 y^{-1}) due to exporting agricultural products (Figure 5a and b); however, there is a lot of potential to increase food supply while lowering the environmental and ecological costs. We acknowledge that increasing food self-sufficiency and encouraging environmentally sustainable trade are equally important to ensure the adequate resilience of food supply to constrains from natural disasters, policy restrictions (Swinnen et al., 2017) , and public health event like the ongoing global COVID-19 outbreak (Qu et al., 2020). This can be accomplished through productivity and resource efficiency enhancements based on technological investments, governance improvements or establishing favourable trade patterns with indirect water and land savings.

Agricultural expansion to new lands could therefore be paused by narrowing the gaps in crop yield from poor land, improving seeding efficiency via investments in agricultural production and processing, and improving the irrigation water utilisation coefficient by improvements in maintaining irrigation facilities. This could lower the impacts on water and land, and benefit CANs while solving the current economically and ecologically unsustainable condition of the agricultural system; this has also been echoed by Rosa et al. (2020), Foley et al. (2011) and de Fraiture et al. (2007). The current analysis proves that CANs could take advantage of their geographic locations to increase agricultural trade with other countries, adjusting the structure therewith on the premise of efficient water and land resource use combined with proportional economic returns (Holden et al., 2018). For example, importing wheat from China could offset the unsustainable water and land resource requirements of this crop. It is important to emphasise that CANs should not neglect the rational land usage management, such as reducing the area of land used to plant cotton in the desert. When adjusting the planting structure and making trade policies, countries need to realise that there may be trade-offs between water and land resources relative to agricultural production and trade. Simple reductions in production or trade of either water- or land-intensive products cannot relieve pressure on water and land resources simultaneously. Therefore, the relationship between the two should be weighed. Additionally, it is not recommended to directly lease or purchase land with a high investment risk. The protection of the local interests should be taken seriously (D'Odorico & Rulli, 2013; Qiu et al., 2013). Kazakhstan and Turkmenistan show considerably higher crop production and food self-sufficiency in S2 (Figure 6c and d), as the two countries have the largest investment potential; they should actively introduce technologies and other approaches to continuously improve the efficiency of their water and land resource utilisation.

There are three main limitations in this analysis. Firstly, in estimating the temporal variations in crop WFs, the effects of climate variations are neglected. Although the uncertainties of the Fast Track approach has been tested and acceptable for both the globe (with standard deviation in errors around 0.1) (Tuninetti et al., 2017) and regional scales (with errors within ±20%) (Gao et al., 2020), if we want to apply it further to the local area at intra-national level, we should carry out a more rigorous and detailed quantification. Secondly, regarding estimation of scarce water and land losses through trade, the pressure index of water resources only considers the pressure on blue water resources, the pressure index of land does not consider the land availability (e.g. saline-alkali land), and only the pressures on cultivated land is considered. Further explorations on the effects of agricultural activities on other water and land use sectors are necessary as well. Thirdly, the current study is from quantity perspective of water and land resources sustainability in agricultural production and consumption, without consideration of resource quality issues which are also intense in CA. How to manage the limited water and land resources towards quantity-quality sustainable win-win situation is of crucial to guarantee adequate food and feeding for growing population and intensive market.

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