Assessment of water footprint for crop production: a case study in North China

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Abstract. In this study, green water footprint (GWF), blue water footprint (BWF) and total water footprint (WF) of five crops (i.e., wheat, maize, cotton, groundnut and beans) for ten subareas in North China are calculated. The spatial distribution of GWF, BWF and WF are analysed and results that different crop in different subareas have different GWF, BWF and WF. Due to the uneven precipitation, the contribution of GWF to WF is lower than BWF in winter and higher than BWF in summer. Moreover, cotton has the highest average value of WF (5.3579 m\textsuperscript{3}/kg), then beans (1.4266 m\textsuperscript{3}/kg), groundnut (1.069 m\textsuperscript{3}/kg), wheat (0.7499 m\textsuperscript{3}/kg). Maize has the lowest average value of WF (0.5695 m\textsuperscript{3}/kg). It is suggested that the cultivated area of maize with the lowest WF should be expanded and the cultivated area of cotton with highest WF should be reduced. The results can help reduce water footprint of crops to ensure food security and alleviate water shortages.

1. Introduction

With water demand for municipal and industrial sectors increasing, the shortage of water for agriculture irrigation is regarded as one of the problems threatening food security. In order to ease water shortage and ensure food security, water footprint was proposed to obtained high crop yields with less water. In detail, water footprint for crops is defined as the volume of water used over the crop growing period. Water footprint consists of the green, blue and gray water footprint\textsuperscript{[1]}. The green water footprint is defined as the consumption of green water (i.e., precipitation seeps into soil and can be assimilated). The blue water footprint is defined as consumption of blue water resources (i.e., surface and ground water used for irrigation)\textsuperscript{[2]}. The gray water footprint refers to pollution, and it is defined as the volume of pollutants given natural background concentration and existing water quality standards\textsuperscript{[3]}.

Thus, in this study, the green water footprint and blue water footprint would be calculated to investigate how to produce high crop yields with less water so as to produce more food with less water. The spatial distribution of water footprint would be analysed and the cultivated area of crops should be expanded or reduced would be discussed. The efficiency of water resources management in different subareas would be reflected. Results can help make appropriate strategy to maintain the limited available water resources and food security.

2. Methodology

CROPWATER 8.0 model developed by the Food and Agriculture Organization and the Unit Nations was used to assess the water footprint of crops. In crop growing process, the water footprint (WF) for per unit of product, i.e., water volume per mass, is the sum of the green, blue and gray components\textsuperscript{[4]}:

\[
WF = GWF + BWF + GRWF
\]
Based on the green and blue components in crop water use ($BWU$ and $GWU$, m$^3$/ha), the green and blue components for water footprint of growing a crop ($BWF$ and $GWF$, m$^3$/ton) can be calculated through divided by the yield ($Y$, ton/ha) of different crop:

$$GWF = \frac{BWU}{Y}$$
$$BWF = \frac{GWU}{Y}$$

The green and blue components in crop water use are calculated by accumulation of daily green water evapotranspiration ($GET$, mm/day) and daily blue water evapotranspiration ($BET$, mm/day) over the growing processes of crops:

$$GWU = 10 \cdot \sum_{d=1}^{lgp} GET$$
$$BWU = 10 \cdot \sum_{d=1}^{lgp} BET$$

where, the constant 10 is used to convert water depths in millimetres into water volumes per land surface in m$^3$/ha. The summation is done from the first day of crop planted to the day of crop harvested. $lgp$ is the length of crop’s growing period in days. Since different growing period relates to different weather conditions, $lgp$ value would influence the calculated crop water footprint of growing a crop can be calculated based on the evapotranspiration:

$$GWF = \frac{10 \cdot \sum_{d=1}^{lgp} GET}{Y}$$
$$BWF = \frac{10 \cdot \sum_{d=1}^{lgp} BET}{Y}$$

Crop water requirement method is used to calculated daily evapotranspiration. If there is no water limitations to crop growth, i.e., under optimal conditions, the crop water requirement ($WR$) would be equal to crop evapotranspiration ($ET_c$). Based on the crop evapotranspiration coefficient ($K_c$) and the reference evapotranspiration ($ET_0$, mm/d), CWR can be estimated as follows:

$$ET_c = WR = \sum_{d=1}^{lgp} K_c \cdot ET_0$$

According to Penman-Monteith equation, $ET_0$ can be calculated based on meteorological data (e.g., temperature). Thus $ET_c$ can be formulated:

$$ET_c = \sum_{d=1}^{lgp} K_c \cdot \frac{0.408 \Delta (R_n - G) + 900 \gamma / (T + 273) \cdot U_2 \cdot (e_a - e_s)}{\Delta + \gamma (1 + 0.34 U_2)}$$

where $R_n$ is net radiation at the crop surface (MJ/(m$^2$·d)), $G$ is soil heat flux density (MJ/(m$^2$·d)), $T$ is air temperature at 2 m height ($°C$); $U_2$ is the wind speed at 2 m height m/s, $e_s$ is saturation vapor pressure (kPa), $e_a$ is actual vapor pressure (kPa), $\Delta$ is slope vapor pressure curve (kPa/°C), and $\gamma$ is constant (kPa/°C). In CROPWATER 8.0 model, effective precipitation ($P_{ef}$), defined as precipitation that reaches at the crop’s roots and the crop can benefits from, is calculated based on the follow equation:

$$P_{ef} = \begin{cases} P(4.17 - 0.02 P)/4.17, & P < 83 \\ 41.7 + 0.1P, & P \geq 83 \end{cases}$$

Then, the green and blue water evapotranspiration ($GET$ and $BET$) can be presented as follows:

$$GET = \min(ET_c, P_{ef})$$
$$BET = \max(0, ET_c - P_{ef})$$

3. Study area

Zhangweinan River Basin (112-118°E, 35-39°N), one of the main food and cotton producing regions in North China, has an average annual temperature of 14 °C and an average annual precipitation of 608.4 mm. Due to the uneven of precipitation (more precipitation occurs in summer than that in winter), there is a conflict between insufficient fresh water supply and increasing water demand for agricultural
development, especially from November to April\textsuperscript{9}\textsuperscript{10}. In recent years, with rapid economic development, water demand has raised to satisfy the increasing demand for municipal and industrial sectors. In order to meeting the large food demands with limited water resources, crop water productivity need to be improved to avoid environmental problems caused by unreasoned water utilization. Thus the problem under consideration is how to produce high crop yields with less water so that reduce the water footprint of each unit of the crops produced.

Based on the administrative division, ten subareas, including Anyang county (S1), Neihuang county (S2), Quzhou county (S3), Guangping county (S4), Chengan county (S5), Wei county (S6), Ci county (S7), Linzhang county (S8), Daming county (S9) and Feixiang county (S10) are taken into account to calculate the green and blue footprints of crops.

![Figure 1. Crop evapotranspiration coefficient of different crops](image)

Table 1. Crop yield and crop area of different crops

|            | Crop yield (ton) | Crop area (hm) |
|------------|-----------------|----------------|
|            | wheat | maize | cotton | groundnut | beans | wheat | maize | cotton | groundnut | beans |
| S1         | 173095 | 153028| 140    | 414       | 479   | 24331.8| 25487 | 88     | 101       | 114   |
| S2         | 374279 | 147312| 211    | 111447    | 313   | 61457  | 27737 | 127    | 22311.6   | 109   |
| S3         | 198119 | 223166| 6804   | 1900      | 442   | 28162  | 30365 | 6066   | 457       | 105   |
| S4         | 112344 | 124576| 947    | 2514      | 144   | 16160  | 16481 | 844    | 584       | 69    |
| S5         | 159581 | 145112| 10733  | 5149      | 640   | 21819  | 18932 | 8747   | 1088      | 231   |
| S6         | 297838 | 338845| 523    | 3792      | 439   | 42249  | 42479 | 640    | 1240      | 243   |
| S7         | 84699  | 111160| 32     | 588       | 679   | 14222  | 18099 | 26     | 165       | 193   |
| S8         | 286555 | 327890| 78     | 2003      | 435   | 38169  | 41195 | 78     | 612       | 95    |
| S9         | 397298 | 358796| 17     | 81178     | 99    | 57760  | 48782 | 20     | 19247     | 57    |
| S10        | 173322 | 177252| 4306   | 2381      | 745   | 24242  | 23322 | 3610   | 627       | 346   |
Figure 2. Evapotranspiration (a), effective precipitation (b) and irrigation requirement (c) of different crops in different subareas (unit: mm).

In the study area, wheat, maize, cotton, bean and groundnut are the main crops and consume the majority of fresh water. Wheat is seeded in middle of October and harvested in middle of June. The growing period of maize, groundnuts and beans are from middle of June to middle of October. Cotton has a special growing period from middle of May to late August. The data of crop yield and crop area in 2017 are acquired from Anyang statistical yearbook and Hand statistical yearbook (Table 1). The meteorological data, including average monthly maximum and minimum temperatures, relative humidity, wind speed, sunshine hours as well as the monthly precipitation are obtained from China Meteorological Data Service Centre. The crop coefficients of wheat, maize, cotton, bean and groundnut, shown in Figure 1, are obtained from Food and Agriculture Organization (FAO No.56).

4. Results
The evapotranspiration, effective precipitation and irrigation requirement of different crops through their growing processes are presented in Figure 2. The evapotranspiration of maize, cotton, groundnut and beans has similar geographical distribution in the ten subareas. For example, in S2, the evapotranspiration of maize (388.9 mm), cotton (595.1 mm), groundnut (412.7 mm) and beans (373.9 mm) is smaller than that in the other nine subareas. This is because that maize, cotton, groundnut and beans are summer crops growing in the same weather conditions. The geographical distribution of evapotranspiration for wheat (537.2 mm in S2, which is higher than that in the other subareas) is different from that of the other four crops due to the different weather condition in winter.

The effective precipitation, reflects the amount of precipitation crop can benefit from in different subareas and has little to do with crops. The highest values of irrigation requirement are 388.3 mm for wheat in S3, 143.9 mm for maize in S5, 255.1 mm for cotton in S3, 159.1 mm for groundnut in S5 and 130.6 mm for beans in S5. The average values of irrigation requirement are 379.79 mm for wheat, 133.33 mm for maize, 148.88 mm for cotton and 120.23 mm for beans. Although irrigation requirements of different crops in different subareas are different from each other, in the same
subarea, high irrigation requirement corresponds to low effective precipitation and low irrigation requirement corresponds to high effective precipitation.

The green and blue water footprints of different crops in different subareas are presented in Table 2. Results indicate that the contribution of GWF to WF is lower than BWF in winter and higher than BWF in summer. For instance, in S1, the WF for wheat is 0.725 m$^3$/kg, including 0.203 m$^3$/kg of GWF and 0.526 m$^3$/kg of BWF; the WF for maize is 0.663 m$^3$/kg, including 0.529 m$^3$/kg of GWF and 0.217 m$^3$/kg of BWF. This can be attributed to the uneven precipitation (more precipitation in summer than that in winter). Moreover, high GWF value indicates more water assimilated by crops and less water needed for irrigation (i.e., low BWF). Similarly, high BWF value reveals the low efficiency of water resources management in the subarea and measures should be taken to improve water use efficiency.

| Water footprint (m$^3$/kg) | S1    | S2    | S3    | S4    | S5    | S6    | S7    | S8    | S9    | S10   |
|---------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Wheat                     |       |       |       |       |       |       |       |       |       |       |
| WF                        | 0.725 | 0.882 | 0.730 | 0.733 | 0.702 | 0.726 | 0.852 | 0.689 | 0.742 | 0.718 |
| GWF                       | 0.203 | 0.268 | 0.181 | 0.200 | 0.178 | 0.205 | 0.216 | 0.181 | 0.203 | 0.185 |
| BWF                       | 0.656 | 0.630 | 0.551 | 0.560 | 0.528 | 0.548 | 0.552 | 0.640 | 0.512 | 0.536 |
| maize                     |       |       |       |       |       |       |       |       |       |       |
| WF                        | 0.663 | 0.732 | 0.543 | 0.528 | 0.520 | 0.499 | 0.647 | 0.495 | 0.542 | 0.526 |
| GWF                       | 0.529 | 0.669 | 0.392 | 0.401 | 0.388 | 0.389 | 0.499 | 0.394 | 0.411 | 0.395 |
| BWF                       | 0.217 | 0.234 | 0.187 | 0.182 | 0.188 | 0.164 | 0.208 | 0.159 | 0.181 | 0.188 |
| Cotton                    |       |       |       |       |       |       |       |       |       |       |
| WF                        | 3.798 | 3.582 | 5.399 | 5.389 | 4.933 | 7.386 | 4.983 | 5.996 | 7.119 | 5.084 |
| GWF                       | 2.440 | 2.514 | 3.137 | 3.328 | 2.977 | 4.694 | 3.021 | 3.834 | 4.393 | 3.056 |
| BWF                       | 1.408 | 1.417 | 2.274 | 2.074 | 1.972 | 2.736 | 1.883 | 2.211 | 2.745 | 2.064 |
| Groundnut                 |       |       |       |       |       |       |       |       |       |       |
| WF                        | 1.030 | 0.826 | 1.017 | 0.980 | 0.891 | 1.378 | 1.179 | 1.275 | 1.001 | 1.113 |
| GWF                       | 0.786 | 0.711 | 0.704 | 0.715 | 0.639 | 1.029 | 0.872 | 0.971 | 0.726 | 0.801 |
| BWF                       | 0.362 | 0.270 | 0.370 | 0.354 | 0.336 | 0.477 | 0.403 | 0.437 | 0.353 | 0.419 |
| beans                     |       |       |       |       |       |       |       |       |       |       |
| WF                        | 0.907 | 1.302 | 0.906 | 1.822 | 1.371 | 2.102 | 1.076 | 0.821 | 2.191 | 1.768 |
| GWF                       | 0.716 | 1.224 | 0.648 | 1.372 | 1.014 | 1.623 | 0.826 | 0.648 | 1.646 | 1.319 |
| BWF                       | 0.280 | 0.386 | 0.295 | 0.594 | 0.471 | 0.652 | 0.325 | 0.249 | 0.689 | 0.601 |

The highest values GWF are 0.268 m$^3$/kg for wheat in (S2), 0.669 m$^3$/kg for maize (S2), 4.694 m$^3$/kg for cotton (S6), 1.029 m$^3$/kg for groundnut (S6) and 1.646 m$^3$/kg for beans (S9). The highest BWF are 0.640 m$^3$/kg for wheat in (S7), 0.234 m$^3$/kg for maize (S2), 2.745 m$^3$/kg for cotton (S9), 0.477 m$^3$/kg for groundnut (S6) and 0.689 m$^3$/kg for beans (S9). Results revel that, because of soil conditions, irrigation and fertilization strategies, crop yields may be different in different subareas and low yields per hectare may lead to high GWF and BWF in the same subarea.

In Table 2, the values of WF range from 0.689 m$^3$/kg to 0.882 m$^3$/kg for wheat, from 0.495 m$^3$/kg to 0.732 m$^3$/kg for maize, from 3.582 m$^3$/kg to 7.386 m$^3$/kg for cotton, from 0.826 m$^3$/kg to 1.378 m$^3$/kg for groundnut and from 0.821 m$^3$/kg to 2.191 m$^3$/kg for beans. The crop consuming most water (i.e., highest WF) is cotton with average value of 5.3579 m$^3$/kg, then beans with average value of 1.4266 m$^3$/kg, groundnut with average value of 1.069 m$^3$/kg, wheat with average value of 0.7499 m$^3$/kg; the lowest WF is maize with average value of 0.5695 m$^3$/kg. Results indicate that, from the perspective of ensuring food security and alleviating water shortages, the cultivated area of maize with the lowest WF should be expanded and the cultivated area of cotton with highest WF should be reduced. Moveover, measures improving water conveyance efficiency and raising corp yields should be taken to reduce water footprint.

5. Conclusions
In this study, GWF, BWF and WF of wheat, maize, cotton, groundnut and beans are calculated for ten subareas in North China. Results indicate that the contribution of GWF to WF is lower than BWF in winter and higher than BWF in summer. In S1, the WF for wheat is 0.725 m$^3$/kg, including 0.203 m$^3$/kg
of GWF and 0.526 m$^3$/kg of BWF; the WF for maize is 0.663 m$^3$/kg, including 0.529 m$^3$/kg of GWF and 0.217 m$^3$/kg of BWF. Moreover, cotton has the highest average value of WF (5.3579 m$^3$/kg), then beans (1.4266 m$^3$/kg), groundnut (1.069 m$^3$/kg), wheat (0.7499 m$^3$/kg). Maize has the lowest average value of WF (0.5695 m$^3$/kg). From the perspective of ensuring food security and alleviating water shortages, the cultivated area of maize with the lowest WF should be expanded and the cultivated area of cotton with highest WF should be reduced.

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