Analysis of spatial distribution characteristics of virtual water content of maize in China

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Abstract. Research on virtual water content of crops can provide the basis for agricultural water resources management; help to improve the efficiency of agricultural water use. Maize is one of the most important food crop in China and also one of the largest water consumers, so it is important to study the virtual water content (VWC) of maize and the spatial distribution characteristics of the VWC of maize in China. In this paper, we assessed the VWC of maize in China including green, blue, grey water and analyze the spatial distribution characteristics of the VWC of maize of 30 regions of China. The percentages of green, blue, and grey water in the total VWC of maize were 47.5%, 18.9%, and 33.6%. The total VWC of maize generally showed a three-tiered distribution, and decreased from southeast to northwest. For the country as a whole the green water is the most important contributor. The percentage of grey water of maize was much larger than blue water. Blue water occupied the smallest component of the total virtual water content of maize.

1. Introduction

The concept of virtual water provides a perspective for water resources management [1]. Virtual water content (VWC) on the one hand is an indicator of water use, that looks at both water consumption and pollution, on another hand it can also broaden water resources evaluation systems and provide water utilization information for decision-making [2].

China is one of the world's 13 most water-poor countries. Agriculture is the largest water user in China, accounting for more than 60% of total water withdrawals. The studies on VWC of crops of China are insufficient. Liu et al. estimated crop water productivity (CWP) on winter wheat of China. In this study, relatively higher CWP values were found in the high-yielding rain-fed winter wheat belt[3]. That means the VWC of wheat in these regions were relatively lower. Sun et al. used the crop water requirement to calculate the China average VWC of wheat, maize and rice, and found the proportions of green and blue water are 50.98% and 49.02%, 76.27% and 23.73%, 61.90% and 38.10%, respectively. For maize the low values were located in the eastern part of Northeast China, Huang-huai-hai region, the western part of the Middle–Lower Reaches of the Yangtze River and Southwest China; the high values of VWC for maize mainly located in Northwest China, the western part of Inner Mongolia and most parts of Southeast China [4]. Sun et al. estimated VWC of crops was 3.91 m³ kg⁻¹ in Hetao irrigation district of China by actual irrigation water consumption. The proportion of the blue water was relatively high (90.91%), while the share of green water was small (9.09%) [5]. However, these calculation frameworks on VWC all ignore the grey water. There is no research on the total VWC of maize and spatial distribution characteristics of the VWC of maize in China at provincial scale by the actual total water use.
China is the biggest maize-producing country in the world. The snow area of maize is about 29 million hectares which larger than rice and wheat and makes up 34 percent of the total planting area of grain crops; the maize production is around 186 million t and accounts for 33 percent of the total grain production in China in 2007. In this paper, we calculated the total VWC of maize for 30 Chinese provinces, autonomous regions, and municipalities in 2007, including green, blue, and grey water, using the actual total water use and analyze the spatial distribution characteristics of the VWC of maize of China. Because of the lack of data, Tibet is not taken into account.

2. Methodology and data

2.1. Methodology

According to the virtual water theory, the virtual water content of a crop is determined by the crop water consumption and affected by pollution during crop production process and crop yield per unit area [1]. The green water use is the lower of the potential crop evapotranspiration and the effective precipitation. The effective precipitation is defined as the amount of precipitation that enters the soil and will be available in the soil for crop growth [1]. The blue water of virtual water of crop is calculated according to the actual irrigation water consumption [5]. The grey water is calculated by multiplying the fraction of nitrogen that leaches or runs off by the nitrogen application rate and dividing this by the difference between the maximum acceptable concentration of nitrogen and the natural concentration of nitrogen in the receiving water boggy and by the actual crop yield [6].

2.2. Data

The climate data of 30 regions in 2007, including monthly average maximum temperature, monthly average minimum temperature, relative humidity, wind speed, precipitation and sunshine hours, is taken from the National Climatic Centre (NCC) of China Meteorological Administration (CMA). The agricultural data, including crop yield and sown area is taken from the China Agricultural Yearbook [7]. The average amount of fertilization of crops per unit area is taken from Li et al. [8]. The irrigation water consumption and irrigation water supply are taken from Water Resources Bulletin 2007 of 30 regions.

3. Results and Discussion

3.1. Green water of maize

Owing to the differences in climatic condition and crop yields, the regional differences of $VWC_{\text{green}}$ for maize of China were significant. The $VWC_{\text{green}}$ of maize of 30 regions in China in 2007 was 0.11 m$^3$ kg$^{-1}$ to 1.31 m$^3$ kg$^{-1}$. The average $VWC_{\text{green}}$ of maize was 0.75 m$^3$ kg$^{-1}$ in China. $VWC_{\text{green}}$ of maize was increased gradually from northern to southern regions (figure 1). The regional variability of green water proportions in VWC was in accordance with the distribution of precipitation in China. The regions with abundant precipitation usually have a high proportion of green water in crop VWC. Precipitation in southern regions of China is far greater than that in northern regions of China. According to the China Water Resources Bulletin 2007, the precipitation in southern regions of China only accounted for 66.6% of total precipitation of the whole country. Consequently, the $VWC_{\text{green}}$ of maize in southern regions would be higher than that in northern regions.

The regions with higher $VWC_{\text{green}}$ of maize were mainly concentrated in Southeast China, Southwest China and middle-lower reaches of the Yangtze River. The high $VWC_{\text{green}}$ is mainly due to the high ratio values of the effective precipitation and maize yields. The regions in Southeast China and Southwest China usually had relatively low maize yield (less than the average maize yield of China) and relatively high effective precipitation (more than the average effective precipitation of China). For example, the $VWC_{\text{green}}$ of maize was relatively high in Hainan (Southeast China), Guangxi (Southwest China) and Yunnan (Southwest China) being more than 1.10 m$^3$ kg$^{-1}$. It was mainly because the maize yield in these regions (3980 t ha$^{-1}$, 4162 t ha$^{-1}$ and 3889 t ha$^{-1}$) were relatively low
which much lower than the national average maize yield (5011 t ha$^{-1}$) and the effective precipitation over the growing period of maize in these regions were all relatively high more than 480 mm. In these regions, Hunan was the exception. Because the maize yield of Hunan was higher than other regions, which was 5282 t ha$^{-1}$ higher than the average maize yield of China and far above the average maize yield of the regions with high $VWC_{green}$ (4255 t ha$^{-1}$). The $VWC_{green}$ of maize in Hunan was lower than the regions with high $VWC_{green}$ in Southeast China, Southwest China and middle-lower reaches of the Yangtze River.

The $VWC_{green}$ of maize of the regions in Northwest China, Inner Mongolia and Tianjin were relatively low. High yield and low effective precipitation led to the lower $VWC_{green}$ in these regions. Especially for Xinjiang, the $VWC_{green}$ is the lowest (0.11 m$^3$ kg$^{-1}$). The reasons are as follows the maize yield in Xinjiang were 1.48 times higher than the national average maize yield and the effective precipitation over the growing period of maize in Xinjiang was small, less than 85 mm.

Figure 1. The spatial distribution of green water of maize of China (m$^3$ kg$^{-1}$)

### 3.2. Blue water of $VWC$ of maize

The differences in blue water requirement, actual irrigation water consumption and maize yields resulted the significant different of $VWC_{blue}$ for maize between regions. The $VWC_{blue}$ of maize was 0 m$^3$ kg$^{-1}$ to 1.26 m$^3$ kg$^{-1}$ in China. The average $VWC_{blue}$ for maize was 0.29 m$^3$ kg$^{-1}$ in China.

The regions with higher $VWC_{blue}$ of maize were mainly concentrated in Beijing, Tianjin and the southeast coastal regions of China. The $VWC_{blue}$ of maize was relatively higher in Beijing, Tianjin, Shanghai, Fujian and Zhejiang, being more than 0.55 m$^3$ kg$^{-1}$ which far above the average $VWC_{blue}$ for maize of China (0.29 m$^3$ kg$^{-1}$). Especially in Beijing (0.97 m$^3$ kg$^{-1}$) and Tianjin (1.26 m$^3$ kg$^{-1}$) the $VWC_{blue}$ of maize was much higher (figure 2). We can found that actual irrigation water consumption in the five regions were larger than the crop blue water requirement. In other regions the actual irrigation water consumption all can’t meet the irrigation water requirement of maize. The excessive consumption of actually irrigation water consumption caused these higher regions of maize blue water. So the $VWC_{blue}$ of maize in these five regions were higher than other regions.

The $VWC_{blue}$ of maize of the regions in the center of China, Southwest China, Inner Mongolia and Jilin were relatively low. The $VWC_{blue}$ of maize of Chongqing, Guizhou, Sichuan and Yunnan in Southwest China was less than 0.05 m$^3$ kg$^{-1}$. That because of the abundant precipitation in the four regions, the effective precipitation can almost meet the water requirement of maize, maize in these regions needs a small amount of actual irrigation water consumption, so the $VWC_{blue}$ of maize in these
regions were relatively low. Especially for Chongqing and Yunnan, because the effective precipitation can meet the water requirement of maize, there was no irrigation water requirement in the growing period of maize. The $VWC_{\text{blue}}$ of maize was 0 m$^3$ kg$^{-1}$ in 2007 in the two regions. And for the other regions with lower $VWC_{\text{blue}}$ of maize, these regions were the water-stressed and major food plant regions. The maize production in these regions accounted for 52.3% of the total maize production and only 35.2% actual irrigation water consumption of China was used in these regions in 2007. The actual irrigation water consumption for maize in these regions was very limited. So $VWC_{\text{blue}}$ of maize in these regions were relatively lower.

![Figure 2. The spatial distribution of blue water of maize of China (m$^3$ kg$^{-1}$)](image)

3.3. Grey water of maize

The $VWC_{\text{grey}}$ of maize was 0.30 m$^3$ kg$^{-1}$ to 1.17 m$^3$ kg$^{-1}$ in China in 2007. The average $VWC_{\text{grey}}$ for maize was 0.51 m$^3$ kg$^{-1}$ in China. $VWC_{\text{grey}}$ mainly depends on the nitrogen uses and the maize yield. The nitrogen uses were relatively the same in most regions of China. The maize yield of regions in North China, Northeast China and Northwest China were relatively high. So we can find that the $VWC_{\text{grey}}$ of maize of regions in North China, Northeast China and Northwest China were relatively low. The nitrogen uses in Inner Mongolia (323.0 kg ha$^{-2}$) is higher than that in the regions in the north of China (222.4 kg ha$^{-2}$), the $VWC_{\text{grey}}$ of maize in Inner Mongolia was higher than that in the regions in the north of China. The maize yield of Heilongjiang (3731 t ha$^{-1}$) was much lower, so the $VWC_{\text{grey}}$ of maize in Heilongjiang was higher than that in the regions in the northeast of China (figure 3).

The highest $VWC_{\text{grey}}$ for maize was in Yunan and Guizhou. Because the nitrogen uses for maize in Shanxi and Guangxi in 2007 (454.6 kg ha$^{-2}$) was much higher than other regions (the average nitrogen uses was 239.2 kg ha$^{-2}$). The $VWC_{\text{grey}}$ for maize in Yunnan (1.17 m$^3$ kg$^{-1}$) and Guizhou (0.93 m$^3$ kg$^{-1}$) was much higher than other regions with the average $VWC_{\text{grey}}$ of maize 0.47 m$^3$ kg$^{-1}$.

We can also find that the $VWC_{\text{grey}}$ of maize was higher than the $VWC_{\text{blue}}$ of maize in 23 regions and even in Shanxi, Inner Mongolia, Qinghai and Ningxia the $VWC_{\text{grey}}$ of maize were the most important components of $VWC_{\text{total}}$ of maize. The $VWC_{\text{grey}}$ occupies a very important position in $VWC_{\text{total}}$ of maize, we can’t ignore the $VWC_{\text{grey}}$ of maize in China.
3.4. Total VWC of maize

According to the results of the $VWC_{\text{green}}$, the $VWC_{\text{blue}}$, and the $VWC_{\text{grey}}$ of maize, the $VWC_{\text{total}}$ of maize between regions in China are shown in figure 4. There were large differences of $VWC_{\text{total}}$ of maize between regions in China. The $VWC_{\text{total}}$ of maize was 0.78 m$^3$ kg$^{-1}$ to 2.77 m$^3$ kg$^{-1}$ in China in 2007. The average $VWC_{\text{total}}$ of maize was 1.55 m$^3$ kg$^{-1}$ of China. The $VWC_{\text{total}}$ of maize of China showed three-steps distribution characteristics, decreased gradually from southeast to northwest regions. The $VWC_{\text{total}}$ of maize of the regions in southeast coastal regions of China and Southeast China were relatively high. The regions with lower $VWC_{\text{total}}$ of maize were mainly concentrated in Northeast China and Norwest China (figure 4). Overall, the regions in China with the lower maize yield most had the higher $VWC_{\text{total}}$ of maize. On the contrary, the regions in China with the higher maize yield most had the lower $VWC_{\text{total}}$ of maize.

The result is large different to the result by Sun et al. [4]. Follow their calculation, the low values of VWC of maize were located in the eastern part of Northeast China, Huang-huai-hai region, the western part of the Middle–Lower Reaches of the Yangtze River and Southwest China; the high values of VWC for maize mainly located in Northwest China, the western part of Inner Mongolia and most parts of Southeast China. Their calculation framework only considered the crop water requirement. Our calculation framework considers the effective precipitation and crop evapotranspiration, actual irrigation water consumption and freshwater that is required to assimilate the load of pollutants. The large differences of the $VWC_{\text{blue}}$, and the $VWC_{\text{grey}}$ of maize caused the spatial distribution characteristics of actual $VWC_{\text{total}}$ of maize of China was large different to the spatial distribution characteristics of maize water requirement of China. Our result can be better to describe the spatial distribution characteristics of actual water use of maize of China.
3.5. The analysis of VWC structures of maize in China

The regional differences of $VWC_{total}$ for maize were significant and the regional differences of the structure of the $VWC$ of maize were significant too. The average $VWC_{total}$ of maize in China in 2007 was 1.55 m$^3$ kg$^{-1}$. The proportions of $VWC_{green}$, $VWC_{blue}$ and $VWC_{grey}$ were 47.5%, 18.9%, and 33.6% in the $VWC_{total}$ of maize in China, respectively.

Generally speaking, the regions in China mostly had the higher $VWC_{green}$ of maize and the lower $VWC_{blue}$ of maize, such as Hebei (the proportion of $VWC_{green}$ was 47.5% and the proportion of $VWC_{blue}$ was 19.3%), Liaoning (the proportion of $VWC_{green}$ was 51.4% and the proportion of $VWC_{blue}$ was 20.0%), Jiangsu (the proportion of $VWC_{green}$ was 56.7% and the proportion of $VWC_{blue}$ was 10.9%) and Guangdong (the proportion of $VWC_{green}$ was 63.0% and the proportion of $VWC_{blue}$ was 10.3%). Four regions are the exceptions which had the lower $VWC_{green}$ of maize and the higher $VWC_{blue}$ of maize. These regions were Beijing (the proportion of $VWC_{green}$ was 27.1% and the proportion of $VWC_{blue}$ was 54.1%), Tianjin (the proportion of $VWC_{green}$ was 19.3% and the proportion of $VWC_{blue}$ was 63.0%), Ningxia (the proportion of $VWC_{green}$ was 24.9% and the proportion of $VWC_{blue}$ was 36.1%) and Xinjiang (the proportion of $VWC_{green}$ was 14.2% and the proportion of $VWC_{blue}$ was 47.6%). There were two different reasons leading to the different situation for the four regions. The excessive consumption of irrigation water caused Beijing and Tianjin had the lower $VWC_{green}$ of maize and the higher $VWC_{blue}$ of maize. The limited precipitation caused Xinjiang and Ningxia had the lower $VWC_{green}$ of maize and the higher $VWC_{blue}$ of maize. For the country, the proportion of $VWC_{green}$ of maize (47.5%) was far above the blue water (18.9%). The maize growth was mainly dependent on the green water in China in 2007.

The regional differences of $VWC_{grey}$ for maize were not very significant. The proportion of $VWC_{grey}$ of maize was 17.8% to 58.5%. The average proportion of $VWC_{grey}$ of maize was 33.6% in China. For the country as a whole, the percentage of grey water of maize was even far above that of blue water. This shows that the grey water in all regions occupied a very important position on $VWC_{total}$. Agricultural pollution was the important issue which can't be ignored in every region of China. Due to the grey water estimate only consider water quality pollution by chemical fertilizer, not consider the effect of pesticides and herbicides pesticides on water quality, therefore, the result of grey water use is a conservative estimate. The grey water will be even more import for the $VWC_{total}$ of maize in China.
4. Conclusions
In our calculation framework of VWC, the total VWC of crops is divided into green, blue and grey water. We calculate the total VWC of maize for 30 Chinese provinces, autonomous regions, and municipalities in 2007 using the actual total water use and analyze the spatial distribution characteristics of the VWC of maize in China in 2007. The following conclusions were reached.

1) The total VWC of maize for 30 regions of China in 2007 ranged from 0.78 m³ kg⁻¹ to 2.77 m³ kg⁻¹. The average total VWC of maize of China in 2007 was 1.55 m³ kg⁻¹. The percentages of green, blue, and grey water were 47.5%, 18.9%, and 33.6% in the total VWC of maize in China, respectively. The results showed that the total VWC of maize in China decreased gradually from southeast to northwest in 2007.

2) The green water of maize for 30 regions of China in 2007 ranged from 0.11 m³ kg⁻¹ to 1.31 m³ kg⁻¹, with an average of 0.75 m³ kg⁻¹. The regions with higher green water were mainly concentrated in Southeast China and Southwest China. The green water of maize for Northwest China and Inner Mongolia was relatively low.

3) The blue water of maize for 30 regions of China in 2007 ranged from 0 m³ kg⁻¹ to 1.26 m³ kg⁻¹, with an average of 0.29 m³ kg⁻¹. The regions with higher blue water of maize were mainly concentrated in Beijing, Tianjin and the southeast coastal regions of China. The blue water of maize of center of China and Southwest China was relatively low.

4) The grey water of maize for 30 regions of China in 2007 ranged from 0.30 m³ kg⁻¹ to 1.17 m³ kg⁻¹, with an average of 0.67 m³ kg⁻¹. The highest grey water for maize was in Yunan and Guizhou. The grey water of maize in North China, Northeast China and Northwest China was relatively low. The grey water of maize was higher than the blue water of maize in 23 regions and even in Shanxi, Inner Mongolia, Qinghai and Ningxia the grey water of maize were the most important components of total virtual water content of maize. In all regions, grey water occupies a very important position in total virtual water content of maize.

5) For the country as a whole, the percentage of green water of maize was far above that of blue water. Therefore, maize growth is mainly dependent on green water in China. The percentage of grey water of maize was much larger than blue water. Blue water occupied the smallest component of total virtual water content of maize.

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