Water Footprint Analysis of Paddy Rice and the Nexus of Water-Land-Rice in Taiwan: *2005-2014*

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Abstract. This paper explores the water footprint (WF) of paddy rice and the nexus of water-land–food (rice) in Taiwan. The research results indicate that the average annual rice WF for the years 2005-2014 was about 7,580 m^3/ton, of which 80% was blue, 17% was green, and 3% was grey. This average annual footprint was about 5.7 times larger than the 2000-2004 average annual WF of rice for countries around the globe of 1325 m^3/ton, of which 48% was green, 44% was blue, and 8% was grey. The blue WF is the most important source of water for rice production in Taiwan. The water consumption of the second crop is higher than that of the first crop. The water use efficiency in the southern region of Taiwan is the best, while the northern part of Taiwan exhibits relatively high inefficiency. The rates of change in cultivated land and rice production in Taiwan are decreasing in a stable manner. However, the annual rate of change in the rice WF is unstable. The nexus of land, water, and food should be taken into consideration to protect water availability, maintain agricultural production, and avoid land degradation. The results could offer useful information for agriculture policy and water resource management.

1. Introduction

Rice is one of the major crops in Taiwan. In order to increase food security and the self-sufficiency ratio of rice, large irrigation projects are often constructed to meet the water demands for rice production [1], thereby allowing large populations to achieve food security. As a result, rice is among the crops that consume the largest amounts of water. Recently, concerns regarding the water-food nexus have significantly increased due to population growth, which has itself increased the demands for water and food. As water is becoming scarcer and scarcer, mitigation strategies and the conscious use of water resources are key concerns [2].

The concept of a water footprint (WF) was previously proposed as an indicator to evaluate the utilization of water resources relative to human consumption [3]. From the perspective of water consumption and pollution, WF evaluation has become one of the priorities for water sustainability and provides decision-making support for water resources management [4].

The WF of a product is defined as the volume of freshwater consumed and polluted in order to produce the product. The WF accounts not only for the direct water use of a consumer or producer but also for indirect water use [5]. A given total WF usually consists of a green WF (rainwater that does not run-off or recharge the groundwater), blue WF (irrigation water withdrawn from the ground or surface water), and grey WF (the volume of freshwater that is required to assimilate the load of pollutants) [1], [6].

The first study to analyse crop cultivation in terms of WFs was conducted by [7], who calculated WFs of cotton consumption. A similar study concerning rice was subsequently conducted by [8] when they investigated freshwater consumption for the 13 most important rice producing countries. According to the results of [8], the average annual rice WF for the investigated countries was 1325 m^3/ton (48% green, 44% blue, and 8% grey). In 2013, Yoo et al. calculated an annual rice WF for Korea equal to 844.5 m^3/ton [9], which was a slightly different result from 829 m^3/ton reported by [8]. Given the similar assumptions of the two studies, the differing results were probably influenced by climate in the different temporal contexts. Besides, [10] calculated the annual rice WF of Argentina and found a similar result of 845 m^3/ton (43.5% green and 56.3% blue) in the northern regions of the country and 987 m^3/ton (36.5% green and 63.5% blue) in the southern regions. Given the climate differences, the biggest variability was shown to be in blue water use. [2]

Recently, the development of WF research has proceeded rapidly. In previous studies, the WF methodology has been applied to many different fields related to the uses of water. Applications of the methodology to explore regarding agricultural products have been popular, with various studies having considered different products and countries. Such as, Chapagain and Hoekstra (2007) assessed the WF of coffee and tea consumption in the Netherlands [11]. The WF methodology has also been applied to other products consumed by people, such as the cotton consumed for clothes production [4], and tomato [12]. Likewise, the WF methodology has also been applied to account for the WFs of different diets [13], [14]. Similarly, the WFs of different regions and countries have also been evaluated [15], [16]. WFs have also been used to assess the production of hydropower energy [17] and biofuels [18], [19], amongst other applications [20]-[23].

For the most part, previous studies of this sort conducted global WF analyses of crop production, but a few recent studies focused, instead, on regional WFs, with only a few of studies having provided complete calculations of total WFs. A 2016 study by Lovarelli et al. reviewed the literature published from 2000-2015 regarding the WFs associated with the production of various crops [2]. According to that review, in early studies the main goal was to assess the water trade of products on a global scale, whereas in subsequent years, the goal was the rigorous quantification of the three components for specific crops in specific geographical areas. In the most recent assessments, similarities in the methodology and the tools employed emerged. Out of 96 scientific articles using WFs as indicators of agricultural production, 78% of the studies aimed to quantify WFs, while the remaining 22% analysed methodology, uncertainty, future trends, and comparisons using other footprints. It emerged that the largest percentage of studies that quantified WFs concerned cereals (33%), among which maize and wheat were the most investigated crops. In 46% of studies, all three components of the total WFs were assessed, while in 18%, no indication of any subdivisions was given; in the remaining 37%, only the blue component or the green and blue components were quantified [2].

Furthermore, land and water resources are central to agriculture and rural development, and are intrinsically linked to the global challenges of food insecurity, poverty, and climate change adaptation and mitigation, as well as to the degradation and depletion of natural resources that affect the livelihoods of millions of rural people around the world [24]. Current projections indicate that the world population will increase from 6.9 billion people today to 9.1 billion in 2050. In addition, economic progress, notably in the emerging countries, consistently translates into increased demand for food and diversified diets. The worldwide demand for food will thus surge as a result, and it is projected that food production will increase by 70% around the world and by 100% in developing countries. At the same time, both land and water resources, the basis of our food production, are finite and already under heavy stress, and future agricultural production will thus need to be more productive and more sustainable at the same time [24].

This paper estimated the blue, green, and grey WFs of rice production in Taiwan from 2005-2014 in order to explore the differences in the use of cultivated water resources in different regions of Taiwan, as well as to analyse its historical changes and composition characteristics. This paper is divided into four parts. In Section 2, the data and methodology, including the WF approach and the definition of its components, are introduced. In Section 3, the results are presented, analysed, and discussed. Finally, in Section 4, the conclusions are drawn.

2. Data and methodology

2.1. Data

The research data acquired for parameter construction were collected from 2005 to 2014. Survey items included the cultivation region and cultivation period of rice, fertilizer applications, and harvest yields. Rice can be planted twice a year in Taiwan. The growing seasons of rice are divided into two periods, the first season crop period (2/1~6/30) and second season crop period (7/1~11/30).

Crop evapotranspiration (ET_0) and effective rainfall (P_{eff}) values were calculated using local temperature, humidity, sunlight, and rainfall data from 2005 to 2014 from the Central Weather Bureau, while actual irrigation was analysed using period average data. The crop coefficient (K_c) is an indicator of water consumption during the entire growth period. In this study, the crop coefficient was set based on previous local studies [25]-[28].

2.2. Methodology

The WF of a product is the result of the quantification of three water volume components: (i) the green water component (WF_{green}, m^3), (ii) blue water component (WF_{blue}, m^3), and (iii) grey water component (WF_{grey}, m^3). Each of them represents an essential element of water use. [2]

Based on the “Water Footprint Manual” [29] and its update, “The Water Footprint Assessment Manual” [5], WF was calculated as follows:

$$WF = WF_{green} + WF_{blue} + WF_{grey} \quad (1)$$

First, the green WF is defined as the consumption of water from precipitation that is stored in the soil and does not run off or recharge the groundwater and, thus, is available for the evapotranspiration of plants.

CROPWAT 8.0 software was applied to calculate crop evapotranspiration and effective rainfall values, which were then used to establish the green and blue WFs of rice. Given that the water contained in the crop accounts for only 0.1%-1% of the total evapotranspiration, it was disregarded, and WF_{green} was set equal to the sum of green water evaporation alone [29] and was calculated as follows:

$$WF_{green} = \frac{10 * min(ET_{c,\ tot},\ P_{eff,\ tot}) \times A}{Y} \quad (2)$$

where WF_{green} is defined as the green WF (m^3/ton), $ET_{c,tot}$ is total evaporation (mm/period), $P_{eff,tot}$ is the effective total precipitation (mm/period), A is the planting area (ha), and Y is the crop yield (tons).

Secondly, the blue WF is an indicator of the surface water or groundwater consumption, which includes the evaporated water, water incorporated into the product, and lost return flow. WF_{blue} calculates the agricultural irrigation. Equation (3) was used to directly calculate WF_{blue}:

$$WF_{blue}(m^3/ton) = \frac{IR}{Y} \quad (3)$$

where IR is the amount of irrigation water per crop period (m^3).

Thirdly, the grey WF of a process step indicates the degree of freshwater pollution that can be associated with the process step. The grey WF is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards [5]. WF_{grey} calculates the use of water to dilute pollution, which mainly results from the use of nitrogen fertilizer [28]. WF_{grey} (m^3/yr) was calculated as follows:

$$WF_{grey} = \frac{1000 \times \alpha \times AR \times A}{Y(C_{max} - C_{nat})} \quad (4)$$

where AR is the area of nitrogen fertilizer usage (kg/ha); α is the leaching factor (%), which is set at 10% [1]; C_{max} is the maximum concentration of nitrogen for a given water body (mg/L), which is set at 10 based on Taiwan EPA groundwater pollution control standards [30]; and C_{nat} is the natural background concentration of nitrogen (mg/L), which is set at 0.

3. Results and discussion

3.1. Comparison of WFs for rice in different growth periods

The research results indicate that the average annual rice WF from 2004-2015 was about 7,580 m^3/ton (Figure 1), of which 80% was blue,17% was green, and 3% was grey. This average annual WF was about 5.7 times larger than the 2000-2004 average annual WF of rice for countries around the globe of 1325 m^3/ton, of which 48% was green, 44% was blue, and 8% was grey [1]. As indicated by the above results, the blue WF is the most important source of water for rice production in Taiwan. The WF from 2005-2008 increased by about 5%. The fallow area was increased by 5%, the cultivated acreage was reduced by 6%, and the production was reduced by 0.7%. However, the amount of irrigation water consumed was not reduced.

Figures 2-4 show the differences in the composition of WFs between the first crop and second crop for each year from 2004-2015 in Taiwan. The average WF of rice production for the first crop was 5,212 m^3/ton, while the average WF of rice production for second crop was 10,588 m^3/ton. In other words,

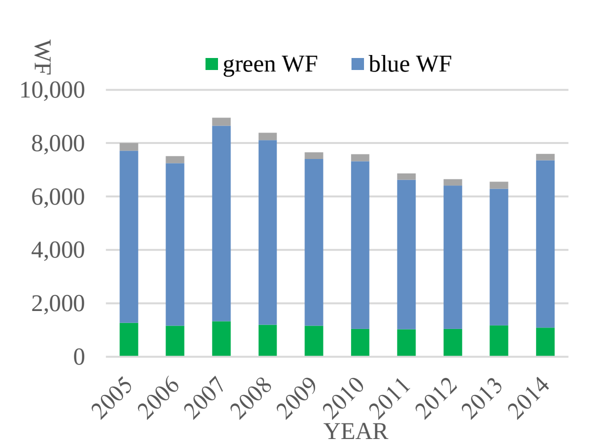

Figure 1. WFs from 2005 to 2014

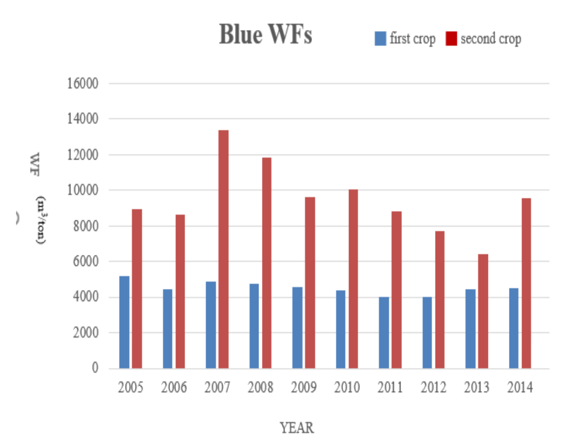

Figure 2. Blue WFs in different growth periods

Figure 3. Green WFs in different growth periods

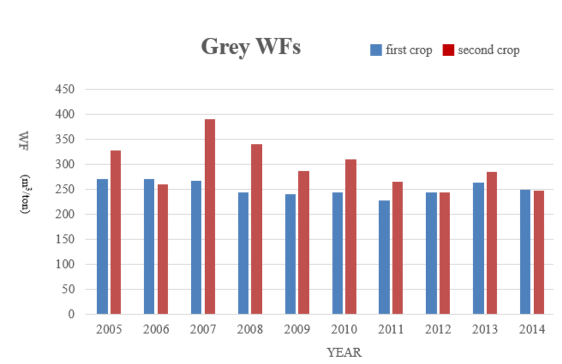

Figure 4. Grey WFs in different growth periods

the amount of water consumed for the second crop was higher than the amount consumed for the first crop. One reason for this difference is that the second crop is raised from July to November. During this period, the average annual amount of evapotranspiration for the years in question was 317 mm, and the effective rainfall was 8853 mm. Both of those values were higher than the corresponding values for the first crop season, which were 238 mm and 6620 mm, respectively. At the same time, the second crop is often affected by typhoons, heavy rain, cold damage, and other weather events, such that the amount of rice produced by the second crop is less than that produced by the first crop, even as the amount of irrigation water used for the second crop is not reduced.

The results of this study indicating the changes in the composition of green, blue, and grey water in Taiwan's first and second season crops are shown in the following figures. As can be seen from the figures, the main source of water resources for rice production in Taiwan is blue water, accounting for 80% of the total, a finding which demonstrates the importance of irrigation water. During the 2005~2008 period, the proportion of blue water in the overall WF was higher than the proportions of green and grey water for both the first and second crops. From 2005 to 2008, the blue WFs increased by 32%. Then, in 2009, the government activated the fallow farmland, causing the blue WFs to decrease. The green WF consistently accounted for a low proportion of the overall first crop and second crop WFs, and the proportion accounted for by the green WF should be affected by the climate and fallow system.

3.2. Comparison of WFs for rice in different regions

Figures 5-7 show the consumption of water resources in the northern region, central region, southern region, and eastern region of Taiwan during the 2005~2014 period. The average WF for the northern region, 35,415 m^3 /ton, was the highest. The average WF for the eastern region was 19,786 m^3/ton. The average WF for the central region, 14,112 m^3/ton, was smaller than that for the eastern region, while that for the southern region, 8,311 m^3/ton, was the lowest of all. Therefore, the water use efficiency of the southern region was the best, while the water use for the northern region was the most inefficient, especially in terms of blue WFs.

3.3. Water-land-rice nexus: land, rice yield, and WF

Rice requires both water and land resources. The annual rates of change for land usage, rice production, and WFs during the 2005-2014 period are shown in Figure 8. The rates of change in cultivated land and rice production in Taiwan during the period decreased in a stable manner. However, the annual rates of change in the WFs for rice production during the period were unstable. Until 2009, when the active fallow land policy was implemented, the rice acreage and yield gradually increased. The annual rates of change in the WFs for rice production in 2010 ~ 2011 were reduced.

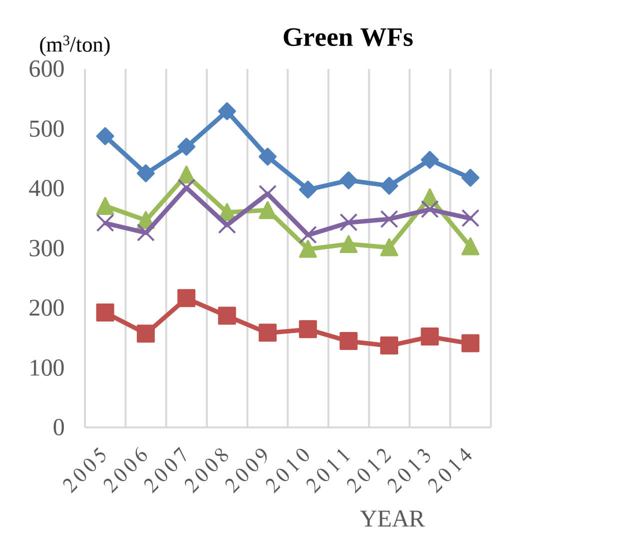

Figure 5. Green WFs in different regions

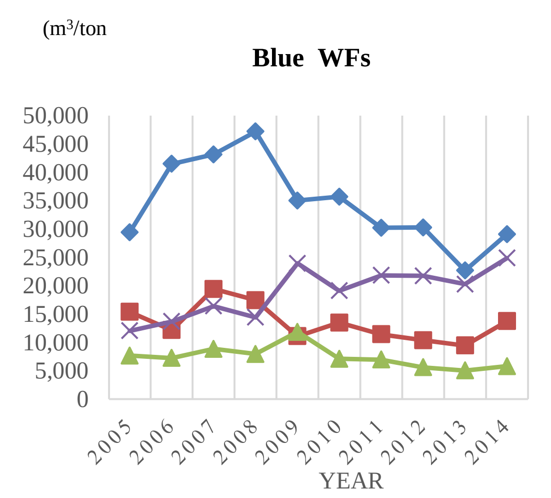

Figure 6. Blue WFs in different regions

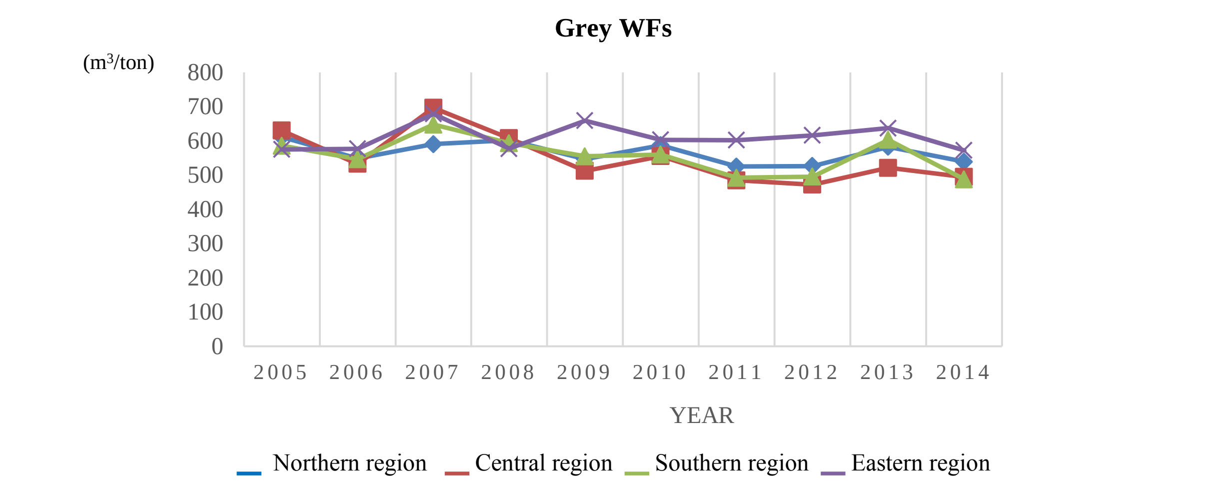

Figure 7. Grey WFs in different regions

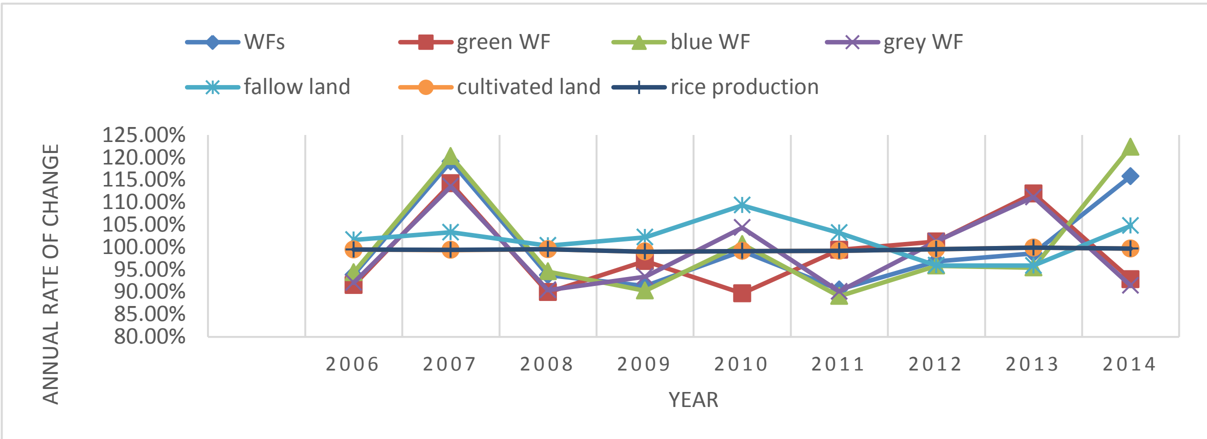

Figure 8. Annual rates of change for land, rice production, and WFs

4. Conclusion

Taiwan is listed as a country that suffers from water scarcity [28]. The results of this study showed that the average annual rice WF for the years 2005-2014 was about 7,580 m^3/ton, of which 80% was blue, 17% was green, and 3% was grey. This average annual footprint was about 5.7 times larger than the 1325 m^3/ton 2000-2004 average annual WF of rice for countries around the globe reported by [3], of which 48% was green, 44% was blue, and 8% was grey. The blue WF is the most important source of water for rice production in Taiwan. The water consumption of the second crop is higher than that of the first crop. The water use efficiency in the southern region is the best, while that of the northern region is the worst. The rates of change in cultivated land and rice production in Taiwan during the 2005-2014 period decreased in a stable manner. However, the annual rate of change in the rice WF was unstable. Until 2009, when the active fallow land policy was implemented, the rice acreage and yield gradually increased. Furthermore, land and water resources are central to agricultural development, and are intrinsically linked to challenges of food insecurity and poverty.

This research suggests that climate change will bring greater variation in weather events, including more frequent weather extremes. We will also face growing water scarcity, which will impact rural and urban livelihoods, food security, and economic activities. More specifically, water shortages will result in increasing competition, which will constrain agricultural production and affect the incomes and livelihood opportunities of many residents in both rural and urban areas. With increasing competition over water for agricultural purposes and in other sectors, governments will need to effectively communicate water scarcity conditions and use water wisely, thereby ensuring that water is allocated equitably and efficiently. However, in Taiwan, land and water institutions have not kept pace with the growing intensity of agricultural development and the increasing degree of interdependence and competition over land and water resources. As such, much more adaptable and collaborative institutions are needed to respond effectively to natural resource scarcity, particularly with regard to water and agriculture. Improvements will thus have to come from sustainable intensification that ensures the effective use of land and water resources, in addition to ensuring that such resources are not harmed [24]. Furthermore, the nexus of land, water, and food needs to be taken into consideration in order to protect water availability, maintain agricultural production, and avoid land degradation.

5. References

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