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Water footprint analysis of bioethanol energy crops in Taiwan

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ABSTRACT

Due to Taiwan's subtropical location, this study investigates the water footprint of four energy crops (corn, sweet potatoes, sugarcane and sweet sorghum), and one food crop (rice), in order to establish the water footprint data of a subtropical region. Research results indicate that sweet potatoes have the smallest water footprint, followed by sugarcane and sweet sorghum, and corn has the largest water footprint of energy crops, though the water footprint of rice is much larger, which results are consistent with the average global water footprints for these crops. The green water component accounts for more than 50% of the overall water footprint for all energy crops except of corn, indicating that the cultivation processes of these energy crops relies more on rainwater, thus, fulfilling low input selection criteria. The water footprint of rice is about 13 times larger than that of sweet potatoes and 8.8–10.4 times that of sugarcane, indicating the relative resource inefficiency of cultivating rice as a food crop. Water footprint for Taiwan-grown sugarcane, corn, and sweet potatoes compare favourably to those in the top 3 producing countries (Brazil, United States and China), as the water footprint for Taiwan-cultivated corn is only 62% of that for corn planted in the United States. A comparison of energy crop water footprints in temperate, subtropical, and tropical climate zones indicates that sugarcane cultivation is relatively more efficient in tropical and subtropical regions, due to its heavy reliance on rainwater, while corn and sweet sorghum perform better in temperate and subtropical regions.

1. Introduction

The availability of water resources is a key factor in the development of bioenergy crops. Current research on environmental impacts and sustainability of energy crops mostly focuses on the benefits of greenhouse gas reduction, energy efficiency, and production cost economy, as well as assessments and selections of potential energy crops (Davis et al., 2009), while few studies focus on efficient water usage for energy crops. Most of these studies use Life Cycle Assessment (LCA) or water footprint methods to investigate water usage efficiency by energy crops. "Water Footprint Manual: State of the Art 2009" (Hoekstra et al., 2009) were the first scientific method for the analysis of water footprint (WF), thus, providing subsequent reports with a common basis for comparison of water usage. Hoekstra et al. (2009) defined WF as water consumption-based indicator based on the source of the water, including green, blue, and grey WFs. Jefferies et al. (2012) compared the difference between LCA and WF in water consumption assessment, and indicated that LCA calculates a single number from each impact category to describe the potential impact of an entire life cycle. Meanwhile, the WF approach emphasizes water consumption levels in the field, and allows for in-depth investigations of different water resource allocations and compositions.

WF of energy crops may be varied with different geographical cultivation regions. Gerbens-Leenes et al. (2009) averaged the international data of 12 kinds of energy crops used for the production of bioelectricity, bioethanol, and biodiesel, in order to compare green and blue WFs performances. However, the average values presented in their study only provided a comparison for the WFs of different energy crops, and did not consider the differences in cultivation at different latitudes. Hernandes et al. (2014) studied the green and blue WFs for the production of bioethanol and biodiesel using Brazilian sugarcane, and found that results varied among different regions. They ascribed this discrepancy to differences in climatic zones and agricultural irrigation systems.

Since Taiwan joined the WTO, the government has adjusted the production structure of rice by leaving the land fallow, which

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results in greatly increased fallow land. The government budgets USD 333 million annually to subsidize fallowing, which results in wasted land resources and stagnant development of rural economic activities. In recent years, Taiwan's government has been devoted to activating fallow lands. The self-sufficiency ratio of rice is over 90%, and farmers often consider rice as first priority when activating fallow lands. However, uneven precipitation periods and distribution are problems that threaten water resources in Taiwan. Comparing the precipitation in the dry season (from November to April) with the rainy season (from May to October), the rate of precipitation in the southern region, which is the main agriculture region of Taiwan, is 1:9 (Yang, 2010), meaning high risk to crop cultivation. In the global perspective, total WF of rice grain is 1325 m^3/ton and it has extra percolation of 1025 m^3/ton (Chapagain and Hoekstra, 2011). The total WF of rice is higher than sugarcane and corn, at 210 m^3/ton and 1222 m^3/ton, respectively (Mekonnen and Hoekstra, 2010). Therefore, in the water perspective, whether rice is a suitable crop for of the activating fallow lands requires further evaluation.

Most previous studies conducted global WF analysis of energy crops, but some researches had focused on regional WF recently; however, just a few of studies had complete calculation of total WF. The objectives of this research are to understand the water resource use efficiency of cultivating corn, sweet potatoes, sugarcane, and sweet sorghum energy crops, as well as the potential of cultivating energy crops in conditions of water deficiency, through analysis and discussion of the WF of energy crops. Moreover, this study compares the WF of energy crops with that of rice food crops within the same cultivation area, which provides policy suggestions for activating fallow lands in Taiwan, as seen from the water resource perspective. Furthermore, relevant literature shows that the WFs of energy crops and biofuel are impacted by regional climatic zones; however, most such research was conducted in temperate and tropical regions, with relatively few studies examining the WF of energy crops under subtropical climate zones. As Taiwan is located in a subtropical climate zone, the present study also compares the WF of energy crops grown in subtropical Taiwan with those grown in the top producing countries. Moreover, it establishes data resources of subtropical energy crops for comparison and analysis of the WF among temperate, subtropical, and tropical energy crops.

2. Materials and methodology

2.1. Materials

Research materials, and all data acquired for parameter construction, were established through field investigation. Where domestic data was unavailable, international literature was referenced. Field investigations for corn, sugarcane, and rice were collected from 2007 to 2011, while data for sweet potatoes and sweet sorghum were collected from 2007 to 2008. Data were collected from large machinery cropping service cooperatives and the Taiwan Sugar Corp. (TSC); and most field work was conducted in Yunlin, Tainan, and Chiayi counties in central and southern Taiwan. Survey items included the cultivation region and cultivation period of energy crops, fertilizer applications, and harvest yields (Table 1). To assess the impact of cultivation scale, data for sugarcane was collected from both TSC and small farmers. Ethanol was produced by fermentation of juice (sugarcane and sweet sorghum), grain (corn), and tubers (sweet potatoes). Ethanol conversion rates were based on previous experiments (Su et al., 2014).

The proper growing seasons are different for every crop (Table 1). In southern Taiwan, both corn and sweet potatoes are planted during the dry season in autumn. Sweet sorghum has a short growing period of less than four months, rendering it suitable for planting in spring and autumn. Newly planted sugarcane has a grow period of about 18 months. Once it's harvested, it leaves a small sprout that will continue to grow, and this ratooned sugarcane can be harvested after 12 months, thus, sugarcane can be harvested twice in 2.5 years. Therefore, this study calculates the WF of corn, sweet potatoes in fall cropping, and sweet sorghum using average data in spring and fall cropping for analysis. Rice can be planted twice a year in Taiwan; however, in order to allow for a comparison between energy and food crops, this study analyzed the WF data from the second crop.

Crop evapotranspiration (ET_0) and effective rainfall (P_{eff}) were calculated using local temperature, humidity, sunlight, and rainfall data from 2007 to 2011 from the Central Weather Bureau; while actual irrigation was analyzed by period average data (see Table 2). Crop coefficient (Kc) is an indicator of water consumption during the entire growth period for every crop, and can be measured using lysimeters or greenhouse cultivation observation. This indicator varies with crop variety, growth period and climate. In this study, the crop coefficient was set based on previous local studies (Shih et al., 1982; Shih and Chang, 1993; Shih and Hwang, 1994) (Table 3).

Table 2
Cultivation region and actual amount of irrigation water for corn, sweet potato, sugarcane, sweet sorghum, and rice in Taiwan. Amount of actual irrigation water is accounted for the whole planting period of each crop.

Crop	Cultivation region	Actual irrigation (mm/growth period)	Data source period
Corn	Tainan	60.6	2009–2011
	Chiayi	69.2	2011
Sweet potato	Tainan	90	2007
	Yunlin	90	2008
Sugarcane (TSC)	Tainan	162	2007–2011
	Yunlin	154	2007–2011
	Chiayi	186	2007–2011
Sugarcane (farmers)	Tainan	–	–
	Yunlin	–	–
	Chiayi	–	–
Sweet sorghum	Tainan	405	2007–2008
Rice	Yunlin	1029	2007–2010
	Chiayi and Tainan	2875	2007–2010

Table 1
Cultivation schedules, nitrogen fertilizer, crop yields, and ethanol conversion rates for crops in Taiwan. The nitrogen fertilizer and yield of all crops are based on the data collected from each crop growth period. The growth period of new planting sugarcane is 18 months, ratooned sugarcane is 12 months, and other crops are about 4–5 months.

Crop	Cultivation schedule	Growth period	Nitrogen fertilizer (kg/ha)	Period yield (ton/ha)	Ethanol conversion rate ($L_{ethanol}$/ton_{crop})
Corn	Autumn: October–February	5 months	160–171	4.5–8.7	370
Sweet potato	Autumn: August–December	5 months	80–88	14.5–41.0	122
Sugarcane (New planting)	July–December (of the following year)	18 months	40–44	82.0–106.2	70
Sugarcane (Ratoon)	January–December	12 months	100–256	57.6–80.4	70
Sweet sorghum	Spring: June–October	5 months	88	40.0–55.5	55
	Autumn: October–January	4 months	80	40.0	55
Rice	Autumn: July–October	4 months	105	3.7–7.5	–