รายงานวิจัยฉบับสมบูรณ์

โครงการ "การประเมินผลกระทบที่เชื่อมต่อกันของที่ดิน-น้ำ-อาหาร-เชื้อเพลิง-ภูมิอากาศ เพื่อความยั่งยืนด้านสิ่งแวดล้อมของการผลิตข้าวและอ้อยในประเทศไทย"

(Land-Water-Food-Fuel-Climate Nexus Assessment for Environmental Sustainability of rice and Sugarcane Production in Thailand)

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พฤษภาคม 2562

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Land-Water-Food-Fuel-Climate Nexus Assessment for Environmental Sustainability of rice and Sugarcane Production in Thailand

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สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัย (สกว.)
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กิตติกรรมประกาศ

โครงการการวิจัย “การประเมินผลกระทบที่เชื่อมต่อกันของที่ดิน-น้ำ-อาหาร-เชื้อเพลิง-ภูมิอากาศ เพื่อความยั่งยืนด้านสิ่งแวดล้อมของการผลิตข้าวและอ้อยในประเทศไทย” สามารถสำเร็จลุล่วงได้ด้วยการช่วยเหลือและสนับสนุนจากหลายฝ่าย อันดับแรกนักวิจัยต้องขอขอบคุณเป็นอย่างสูงสำหรับการให้คำปรึกษาและคำแนะนำอย่างดียิ่งตลอดเวลาของ ศ.ดร.แชบเบียร์ กีวาลา หัวหน้ากลุ่มวิจัย Life Cycle Sustainability Assessment Lab (LCSAL) บัณฑิตวิทยาลัยร่วมด้านพลังงานและสิ่งแวดล้อม มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรีในฐานะนักวิจัยที่ปรึกษา อันดับที่สองนักวิจัยต้องขอขอบคุณสำนักงานกองทุนสนับสนุนการวิจัย (สกว.) และมหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี สำหรับการสนับสนุนเงินทุนวิจัยตลอดการดำเนินงาน ภายใต้ทุนวิจัยเพื่อส่งเสริมนักวิจัยรุ่นใหม่ ตามสัญญาเลขที่ TRG5980018 รวมถึงนักวิจัยต้องขอบคุณโครงการ “ฟุตพริ้นท์น้ำของพืชอาหาร อาหารสัตว์ พลังงาน และเส้นใย เพื่อจัดการทรัพยากรน้ำอย่างมีประสิทธิภาพ (ระยะที่ 2)” ของบัณฑิตวิทยาลัยร่วมด้านพลังงานและสิ่งแวดล้อม ม.เทคโนโลยีพระจอมเกล้าธนบุรี ม.เกษตรศาสตร์ ภายใต้การอุดหนุนงบประมาณของสำนักงานกองทุนสนับสนุนการวิจัย (สกว.) สัญญาเลขที่ RDG5620052 ที่ได้จัดทำข้อมูลและผลการศึกษาตัวชี้วัดความตึงเครียดด้านน้ำซึ่งเป็นประโยชน์อย่างมากกับการใช้งานในการวิจัยนี้ และสุดท้ายนี้นักวิจัยต้องขอขอบคุณทีมงานสนับสนุนทุกท่านที่ร่วมดำเนินการเก็บและวิเคราะห์ข้อมูลจนทำให้การวิจัยสามารถสำเร็จลุล่วงได้

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ขยายเวลา 1 ปี (1 มิถุนายน 2561 – 31 พฤษภาคม 2562)

ประเด็นด้านที่ดิน น้ำ เชื้อเพลิง และอาหาร มีความสัมพันธ์กันอย่างแยกออกไม่ได้ ซึ่งปัจจุบันภาคการเกษตรในกลุ่มประเทศกำลังพัฒนากำลังเผชิญกับความท้าทายอันเนื่องมาจากการแสวงหาประโยชน์จากทรัพยากรที่ดินและน้ำอย่างมากเกินควบคุมเพื่อให้สามารถผลิตพืชวัตถุดิบได้เพียงพอกับการผลิตอาหารและการผลิตเชื้อเพลิงชีวภาพ ได้เพียง โดยเฉพาะสำหรับประเทศไทยการปลูกข้าวและอ้อยเพื่อจำหน่ายเป็นสินค้าถูกจัดเป็นสองภาคเศรษฐกิจการเกษตรที่สำคัญต่อความอยู่ดีมีสุขของคน การศึกษานี้จึงได้ศึกษาและประเมินผลกระทบที่เชื่อมต่อกัน (Nexus) ของที่ดิน-น้ำ-อาหาร-เชื้อเพลิง-ภูมิอากาศ ของระบบการผลิตข้าวและอ้อยในประเทศไทยโดยอาศัยตัวชี้วัดด้านฟุตพริ้นท์ประกอบด้วย วอเตอร์ฟุตพริ้นท์ คาร์บอนฟุตพริ้นท์ และอีโคโลจิคอลฟุตพริ้นท์ การศึกษาผลกระทบที่เชื่อมต่อกันด้านที่ดิน-น้ำ-พลังงาน ของระบบการผลิตอ้อยในลุ่มน้ำเจ้าพระยาและลุ่มน้ำชีของประเทศไทยทั้งระบบที่มีชลประทานและไม่มีชลประทาน พบว่า ทรัพยากรน้ำมีความสำคัญต่อการเพิ่มขึ้นของผลผลิตอ้อย โดยระบบชลประทานช่วยเพิ่มผลผลิตอ้อยได้ประมาณร้อยละ 23 – 54 เมื่อเทียบกับระบบที่ไม่มีชลประทาน ซึ่งผลต่อเนื่องทำให้ค่าคาร์บอนและอีโอโลจิคอลฟุตพริ้นท์ของผลิตภัณฑ์อ้อยมีความลดลงประมาณร้อยละ 11-36 และ 15-35 ตามลำดับ อย่างไรก็ตาม มีความเสี่ยงต่อการตึงเครียดน้ำที่สูงขึ้นซึ่งเทคโนโลยีชลประทานที่มีประสิทธิภาพเช่นระบบน้ำหยดจะเป็นปัจจัยสำคัญที่จะช่วยผลักดันให้เกิดการผลิตอ้อยที่ยั่งยืนมากขึ้นในอนาคต

การศึกษายังได้ประเมินถึงปริมาณการใช้น้ำและฟุตพริ้นท์การขาดแคลนน้ำของระบบการปลูกข้าวนาปีและข้าวนาปรังในพื้นที่ลุ่มน้ำเจ้าพระยา ท่าจีน มูล และชี ของประเทศไทย โดยผลการศึกษาชี้ให้เห็นถึงการใช้น้ำที่แตกต่างกันมากตั้งแต่ 0.9–3.0 ลบ.ม./กิโลกรัมข้าวนาปี และ 0.9–2.3 ลบ.ม./กิโลกรัมข้าวนาปรัง โดยที่การใช้น้ำในปริมาณมากจะพบในพื้นที่ภาคตะวันออกเฉียงเหนือ เช่น ลุ่มน้ำมูล และชี แต่อย่างไรก็ตามหากพิจารณาถึงค่าฟุตพริ้นท์การขาดแคลนน้ำ ผลการศึกษาชี้ให้เห็นว่าการปลูกข้าวนาปรัง เช่น ในพื้นที่ลุ่มน้ำเจ้าพระยาและท่าจีนจะมีค่าที่สูงและจำเป็นต้องมีการส่งเสริมเพื่อให้เกิดประสิทธิภาพชลประทานและการใช้น้ำเพื่อป้องกันความเสี่ยงด้านการขาดแคลนน้ำในอนาคต นอกจากนี้การศึกษาพบว่าระบบการปลูกข้าวแบบเปียกสลับแห้งสามารถเป็นแนวทางหนึ่ง

ที่นำมาใช้เพื่อทดแทนการปลูกข้าวแบบปกติ เพื่อส่งเสริมให้เกิดการใช้น้ำอย่างมีประสิทธิภาพในการปลูกข้าวนาปรังในพื้นที่ภาคกลาง การศึกษาได้มีการจัดทำข้อเสนอแนะสำหรับการจัดการผลกระทบที่ต่อเนื่องกันด้านที่ดิน-น้ำ-พลังงาน เพื่อให้เกิดการผลิตข้าวและอ้อยได้อย่างยั่งยืนในอนาคต ซึ่งรวมไปถึงการเสนอแนะให้ใช้แนวทางฟุตพริ้นท์และตัวชี้วัดความตึงเครียดด้านน้ำเป็นเครื่องมือหนึ่งสำหรับการประเมินผลกระทบที่ต่อเนื่องกันอันเนื่องมาจากนโยบายด้านการโซนนิ่งทางการเกษตร

คำหลัก: ผลกระทบที่เชื่อมต่อกัน; ที่ดิน-น้ำ-อาหาร-เชื้อเพลิง-ภูมิอากาศ; ฟุตพริ้นท์; ข้าว; อ้อย; นโยบายด้านเกษตร; การประเมินวัฏจักรชีวิต

Abstract

Project Code: TRG5980018

Project Title: Land-Water-Food-Fuel-Climate Nexus Assessment for Environmental Sustainability of rice and Sugarcane Production in Thailand

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Project Period: 2 Years (1 June 2016 – 31 May 2018)

Extension 1 Year (1 June 2018 – 31 May 2019)

Land, water, fuel and food are inextricably linked. The agricultural sector in developing countries is confronting challenges on the overexploitation of land and water resources for food and biofuels crop production. Rice and sugarcane cultivation are the two vital economic sectors of Thailand, which the well-being of people relying significantly on selling those two commodities. In the study, the land-water–food–fuel–climate nexus of rice and sugarcane production systems in Thailand was analysed through the set of footprint indicators including water, carbon and ecological footprints. The results of land-water-energy nexus of irrigated and non-irrigated sugarcane production systems in the Chao Phraya and Chi watersheds of Thailand indicate that freshwater resource is essential to sugarcane productivity improvement. Irrigation helps increase the sugarcane yields around 23-54% as compared to the non-irrigated system; the carbon and ecological footprint of sugarcane products are also consequently decreased by around 11-36% and 15-35%, respectively. Nevertheless, water scarcity potential would be increased. Hence, efficient irrigation technology like drip irrigation is an important factor to drive sustainable sugarcane production in the future.

The study also assessed the volumetric freshwater use and water scarcity footprint of the major and second rice cultivation systems in the Chao Phraya, Tha Chin, Mun, and Chi watersheds of Thailand. The results revealed that a wide range of freshwater use, i.e., 0.9–3.0m^3/kg of major rice and 0.9–2.3m^3/kg of second rice, and high water use of rice was found among the watersheds in the northeastern region, like the Mun and Chi watersheds. However, the water scarcity footprint results showed that the second rice cultivation in watersheds, like in Chao Phraya and Tha Chin, need to be focused for improving the irrigation water use efficiency. The alternate wetting and drying (AWD) method was found to be a promising approach for substituting the pre-germinated seed broadcasting system to enhance the water use efficiency of second rice cultivation in the central region. Land-water-energy nexus management measures for improving the sustainability of rice and sugarcane productions are also recommended. Recommendations vis-à-vis the use of the water stress index as a tool for agricultural zoning policy were also discussed.

Keywords: Nexus; Land-Water–Food–Fuel–Climate; Footprint; Rice; Sugarcane; Agricultural policy; Life cycle assessment

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Chapter 1 Introduction

Land, water, fuel and food are inextricably linked. Arable land is required for food and fuel crops plantation. Water is an input for producing agricultural goods in the fields and along the entire agro-food supply chain. Energy is required to produce and distribute water and food: to pump water from groundwater or surface water sources, to power tractors and irrigation machinery, and to process and transport agricultural goods. Use of land, water, and energy can cause greenhouse gases emissions which is a significant driver of climate change. Since arable land, freshwater and energy are the finite resources which can limit agriculture development, understanding the nexus and increasing use efficiency of these resources are therefore the challenges to protect against food insecurity and rural poverty for an agro-industrial based country like Thailand. For Thailand, the agricultural sector shares about 12% of the Gross Domestic Product (GDP) and accounts for almost 40% of the total employment in the country (BOT, 2011). Thailand is ranked as one of the world's leading countries for paddy (rice) production and export, the world's largest cassava producer and exporter contributing about 70% of the world market share; and the second leading sugar exporter (OAE, 2017). Apart from food crops production for local consumption and export, the Thai government has also promoted the use of indigenous feedstocks for bioenergy and biofuel production in order to enhance the country's energy security. Nevertheless, the increasing demand for food and biofuels nowadays and in the years to come driven by the growing population and economy has led to the debate on food-versus-fuel due to competition for limited resources such as arable land and freshwater which can be unsustainable in the long-term.

Agriculture is currently the largest user of freshwater at the global level, accounting for about 70% of total withdrawal although irrigated agriculture constitutes only 20% of the total cultivated land (Gondon et al., 2010; WWDR, 2012; WWAP, 2014). Over the last decades, pressure on freshwater resources is intensifying rapidly due to the growing of agriculture, industrialisation, households and energy consumption, especially biofuels which require a huge amount of water for feedstocks cultivation. Especially for water, concerns on water scarcity have become an essential issue, especially the threat to water availability at both global and regional level (ADE, 2013). Water scarcity is predicted to increase drastically in many parts of the world. An assessment of water management in agriculture revealed that a fifth of the world's population or around 1.2 billion people live in areas of physical water scarcity and a further 500 million people are approaching this situation (IWMI, 2007). The 2030 Water Resources Group stated that, assuming that if the total annual sustainable freshwater supply remaining static at 4,200 billion m3 and the present trends of water demand continue, the annual deficit for 2030 is forecasted to be 2,765 billion m3, or 40% of unconstrained demand (2030 Water Resources Group, 2009). Additionally, the degree of uncertainty in the frequency and intensity of flood and drought-affected areas are likely to increase as the result of climate change. These effects are already being felt in Thailand.

There are several linkages and trade-offs between land, water, energy use and food production. For instance, using water to irrigate crops might increase food production, but it can also reduce river flows which in turn would affect ecosystems and the hydropower potential. Growing biofuel crops under irrigation uses arable land and increases overall water withdrawals which in turn would affect food security. Using high efficiency pressurized irrigation may help save water but also can result in higher fuel use for pumping. Recognizing these synergies and balancing these trade-offs are therefore essential to ensure the land, water, fuel and food security. The nexus assessment of land-water-energy resources for existing food and biofuel fuel crops production systems in Thailand is therefore important and needs to be conducted to ensure that all the impacts, benefits and trade-offs are considered and the appropriate measures for food and biofuel production promotion are initiated.

1.1 Objectives

The project's objectives are as follows:

1) To assess the land-water-food-fuel-climate nexus of paddy (rice) and sugarcane production systems in different regions of Thailand
2) To identify the environmental hotspots and recommendations for mitigating the impacts on water consumption, land use and GHG emissions of rice and sugarcane production in Thailand
3) To analyse the policy implications for the case of land conversion from paddy field to sugarcane

1.2 Scope of research

Rice and sugarcane are selected as the studied food and fuel crops because these two crops are the key economic crops of the country and currently the Thai government has a policy on expanding sugarcane planted areas to support the increased demand of sugarcane for sugar and bioethanol production. Low productivity paddy field is one of the focused areas of the government to convert to sugarcane.

Figure 1.1 shows the scope of land-water–food–fuel–climate nexus assessment in the study which will be evaluated and measured by the key three footprint indicators including land, water and carbon footprints. The food and fuel crop production systems can be divided into two levels, i.e. direct production system and indirect production system, which will result in the direct and indirect footprints, respectively. Direct production system means the operations of farmers since land preparation, planting, fertilization and weed control, harvesting and post-harvest on agricultural residues. For example, the paddy rice system will consist of various steps including seedling, rice cultivation, water management, fertilisation and weed control, harvesting, and rice straw management. The assessment will also take into account the production of materials, chemicals and energy used in the system boundary as the indirect production systems.

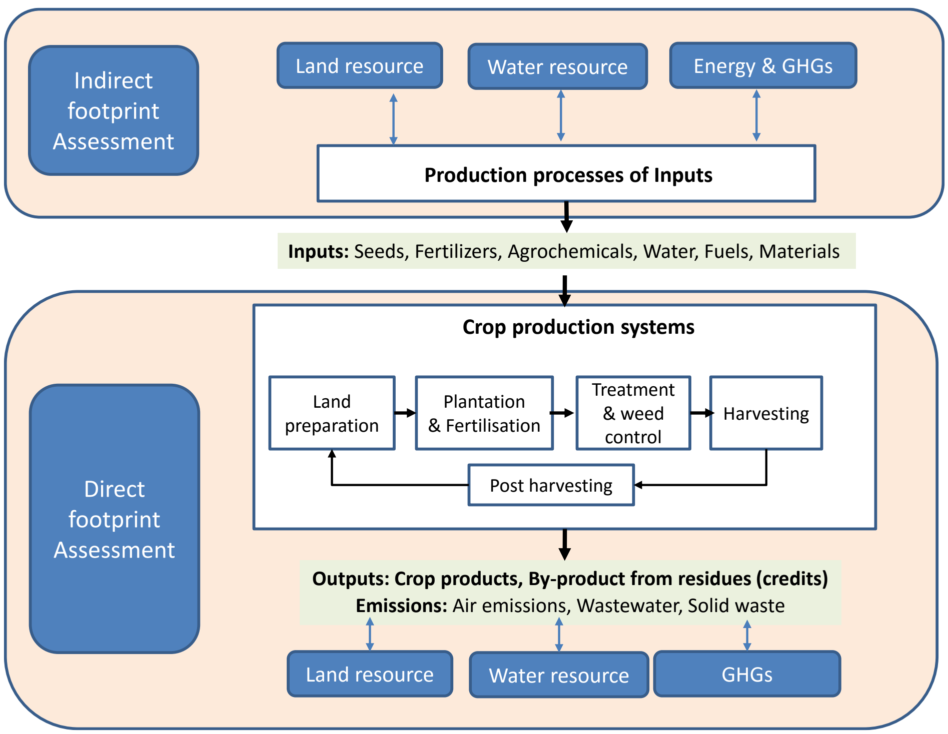


Figure 1.1 Scope of Land-Water–Food–Fuel–Climate Nexus Assessment

Table 1.1 shows the scope of studied areas, seasonal factors considered and the potential paddy rice and sugarcane production system in Thailand.

Table 1.1 Studied areas and crop production systems

Studied regions	Seasonal factors	Food and Fuel Crop Production Systems	
		Paddy (rice)	Sugarcane
Central Northeastern	Wet season Dry season	• Irrigated/ Rainfed • AWD cultivation	• Plant cane/ Ratoon cane • Irrigated/ Rainfed plantation • Manual/ Mechanised farming

1.3 Research methodology

The land-water–food–fuel–climate nexus of different rice and sugarcane production systems in different regions of Thailand will be analysed through the set of footprint indicators including land, water and carbon footprints. Footprint is the terms that has generally used for the indicators that account the total direct and indirect effects of a product. The footprint assessment will help quantification of the environmental burdens including greenhouse gas emissions, biologically productive land and water area required and freshwater consumption caused by different rice and sugarcane production systems in Thailand. Land footprint is measured in terms of hectares of land with biological productivity (ha-yr), water consumption is measured as the green and blue water (m^3) and weighted blue water footprint (m^3H_2Oeq), and GHG emission is measured in terms of kg CO_2eq. The different footprints will be evaluated and presented per tonne of crop at farm gate. This combination use of the land, carbon and water footprints can give a comprehensive picture of the environmental impacts of resource consumption patterns due to the different crop production systems which in turn will help in identification of policy solutions, trade-offs and synergies aiming at a resource efficient and sustainable use of natural resources.

The step-by-step methodology of this study is:

(1) Literature review on global and regional WF, CF and Land footprint assessment

(2) Modeling potential paddy (rice) and sugarcane production systems in Thailand

  a. Paddy (rice) production systems

  b. Sugarcane production systems

(3) Field survey for collecting life cycle inventory data for those studied systems

(4) Nexus assessment and interpretation

    a. Water footprint assessment

    b. Land footprint assessment

    c. Carbon footprint assessment

(5) Identification of hotspots and recommendations for mitigating the impacts on water consumption, land use and GHG emissions of rice and sugarcane production

(6) Nexus assessment and policy analysis on land conversion from paddy field to sugarcane

(7) Conclusions and publications

1.4 Research plan

Activities	Months																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1. Literature review on global and regional WF, CF and Land footprint assessment																								
2. Modeling paddy (rice) and sugarcane production systems																								
2.1 Paddy (rice) production systems																								
2.2 Sugarcane production systems																								
3. Field survey for collecting LCI data																								
4. Nexus assessment and interpretation																								
4.1 Water footprint assessment																								
4.2 Land footprint assessment																								
4.3 Carbon footprint assessment																								
5. Identification of hotspots and recommendations for mitigating the environmental impacts of rice and sugarcane production in Thailand																								

Activities	**Months**																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
6. Policy analysis on land use conversion from rice to sugarcane																		▬	▬	▬	▬	▬	▬	▬
7. Conclusion and publications											▬	▬											▬	▬
Reports																								
Progress report I						●																		
Progress report II												●												
Progress report III																		●						
Final report																								●

Chapter 2 Literature Review

2.1 What about Land-Water-Food-Fuel-Climate Nexus?

Agriculture is known as the key economic sector for developing countries vis-a-vis their socio-economic development; human well-being and economic prosperity of people rely heavily on the development of agro-industry supply chains. The rapid development nowadays raises the demands for food, feed and fuels, and brings about increased concerns on the competition between land, water and energy resources as well as consequences on greenhouse gases (GHG) emissions. The demands for freshwater, land, and energy for food have been projected to increase significantly in the next decades due to population growth, urbanization and economic development (Hoff, 2011).Water crises have become one of the top five key global risks over the past five years (2011-2016) as reported by the World Economic Forum (WEF, 2017).

Meanwhile, agriculture is the most freshwater consumptive sector accounting for around 85% of global freshwater consumption (Hoekstra and Chapagain, 2007). To meet the global demands for food in 2050, food production needs to be increased by about 60% (FAO, 2011). This has raised concerns on water scarcity caused by the overexploitation of water for food and biofuels along with climate change effects (Zhang et al., 2013; Gheewala et al., 2014, 2017). In view of the impact from climate change, food production accounted for 19-29% of the global anthropogenic GHG emissions, 80% of which was from agriculture (Vermeulen et al., 2012). The promotion of biofuels to substitute fossil fuels will induce more requirements for land and water resources which in turn will compete with food production systems (Popp et al., 2014). In addition, increasing crop production either by intensification of agriculture or by expansion of land can lead to increase in GHG emissions (Tilman et al., 2002; Searchinger, 2010). The volatility of water and food prices are also anticipated due to the increased production of bioenergy (World Bank, 2008; Peri et al., 2017). All these issues indicate that the interrelationships of land, water, energy and crop production systems need to be understood by the decision makers to formulate appropriate policy measures for enhancing the efficient use of these resources (Flammini et al., 2014; Rasul and Sharma, 2016). However, to formulate the appropriate policy measures especially for agriculture, it is necessary to investigate specifically for each region by considering the local context such as geographical and climate conditions, irrigation infrastructure, local freshwater resource availability as well as farming practices.

Scientists and policy makers worldwide are well aware of food, energy and water challenges, but so far those challenges were individually assessed and addressed. Over the past decade, studies on life cycle GHG emissions assessment or carbon footprint of food and biofuels have been extensively conducted worldwide including in Thailand (Ngyen et al., 2007; Sillalertruksa and Gheewala, 2009; 2012), water footprint studies being considered more recently. Nowadays, there are several international standards for carbon footprinting (BSI, 2011; ISO, 2012). For Thailand, the Thailand Greenhouse Gas Management Organization (TGO) has also published a national guideline on carbon footprinting of products for using in the certification of "carbon footprint labeling" schemes.

Recently, since the water scarcity become the global challenge, the water footprint is increasingly concerned worldwide. Water footprint (WF) has been introduced as a method to indicate the water use and impacts of the production system on water resources measured as an indicator of the total volume of freshwater used to produce products (ISO, 2014). ISO has defined the water footprint assessment is the compilation and evaluation of the inputs, outputs and the potential environmental impacts related to water of a product, process or organization. According to criteria on water footprint assessment of ISO 14046, it has pointed that the old concept of water footprint which divides the water use into three components i.e. green, blue and grey water of Water Footprint Network (WFN) will not meet the criteria of full water footprint assessment. The green water footprint refers to the volume of rainwater consumed during the production process of product. For agricultural and forestry products, it generally refers to the total rainwater evapotranspiration. Blue water footprint refers to the volume of surface and groundwater consumed into the production of a product. This old concept green and blue WF assessment has been widely applied in many studies concerning water use, especially for food and agricultural products (Chapagain and Hoekstra, 2004; Mekonnen and Hoekstra, 2011; Gerbens-Leenes and Hoekstra, 2012). However, it must be noted that the water footprint studies which considering only the green and blue water consumption according to the WFN concept can be just called as the "water scarcity footprint" not the full water footprint according to ISO14046. This is because focusing only the volumetric WF does not directly provide information on the actual impacts of water use. This is because it is not very meaningful to compare impacts of water use in regions of water abundance to those where scarcity exists without somehow accounting for the abundance of water or lack of it. ISO14046 therefore defined that the WF impact assessment must be conducted for completing the full water footprint assessment.

Nowadays, the methodologies combining WF and hydrological water availability e.g. water stress index (Pfister et al., 2009) and some other water use impact assessment methodologies have been proposed in the life cycle assessment (LCA) community (Bayart and Grimaud, 2011). For

Thailand, the studies on WF and the impact assessment of water use by combining WF and the water stress index are in the preliminary stage. There have been some studies in the recent past evaluating the volumetric water consumption of field crops (Nilsalab et al., 2012; Kaenchan and Gheewala, 2012; Kongboon and Sampattagu, 2012). However, those studies lack consideration of the impacts of water use due to the different water scarcity situation in each region. Anyway, recently there has been the development of WSI for Thailand and this has been applied for evaluating the water footprint impact assessment of bioethanol policy in Thailand (Gheewala et al., 2013; 2014). The full WF analysis, according to the ISO14046, can help a better understanding of the impacts of water of agricultural products and can help the identification of "hotspots" linking the water use and source of water.

2.2 Nexus assessment approaches

Nowadays, there is an increasing concern about the Land-Water-Energy Nexus because these resources are in a close relationship and essential to economic and social development. The nexus approach has been proposed to enhance efficiency and balance between the different uses of ecosystems resources like water, land and energy by various stakeholders in a particular region (Flammini et al., 2014; Azapagic, 2015; Sanders and Masri, 2016; Smajgl et al., 2016). **Figure 2.1** shows the simplified linkage and trade-offs between land, water and energy in agriculture as well as food and bioenergy production (Silalertruksa and Gheewala, 2018). According to the figure, the "energy" can be represented as either energy for economic activities such as fuels, electricity or energy for human i.e. food. Hence, the increase in the production of energy carriers like biofuels will require the land for biomass feedstock cultivation and water for crop's irrigation. In the meantime, energy is used to distribute the water for agriculture and other uses. Also, energy is used for agricultural machinery since the land preparation, crop plantation until harvesting.

The land-water-energy trade-off is such that the use of irrigated water might be able to increase crop yield which leads to improved land productivity; however, this has to trade-off with the more energy required for irrigation and more potential water competition with other water users in the region. Recognizing these synergies and balancing these trade-offs are therefore essential to ensure the land, water, fuel and food security. Thus, it is gaining attraction as the key issue that needs to be understood in biofuel policy making to move the implementation of policy towards sustainable biofuel production.

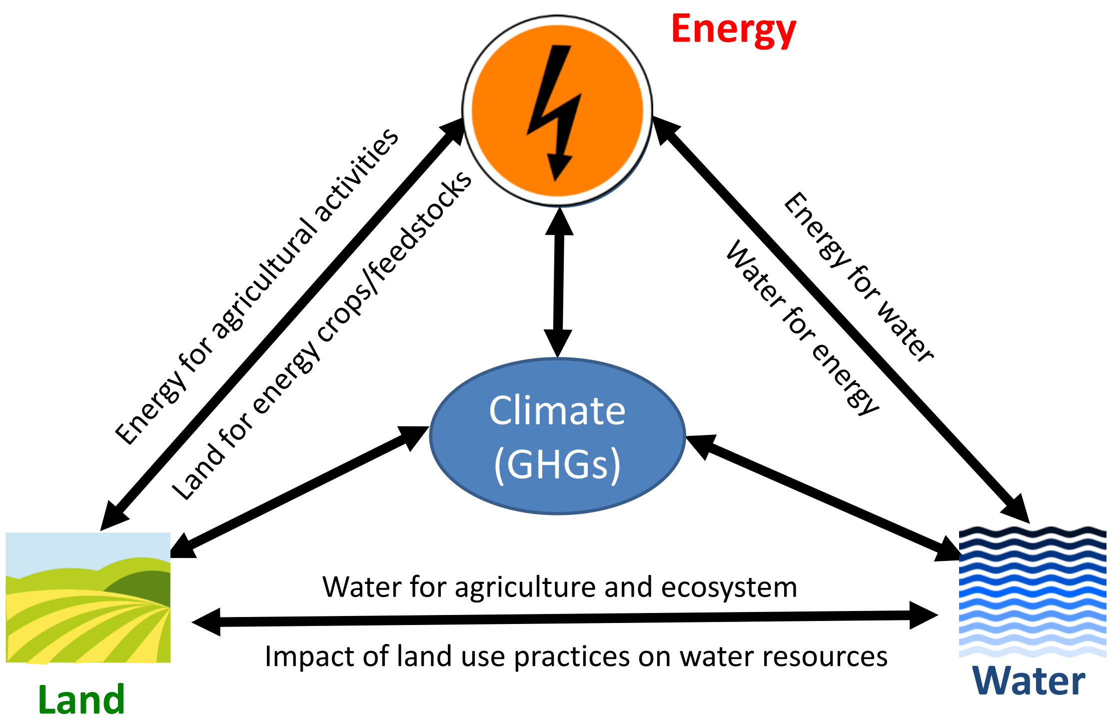


Figure 2.1 Land-water-energy-climate nexus in agriculture

2.3 Relationships of the footprints and Land-Water-Energy nexus of biofuels

To assess the nexus on land, water, energy and GHGs that occurs from biofuels production and use, it is necessary to understand the scope of each footprint because each footprint indicator generally has its own focus and way of interpretation. **Table 2.1** shows the overlapping of the three footprint indicators on impact assessment of land, water and energy resources used for biofuels production systems. Ecological footprint overlaps with the carbon footprint i.e. the impact of CO_2 emission will be taken into account in terms of land equivalent for capturing it. It can be seen that there is no one footprint indicator that can capture and explain the whole land-water-energy nexus of biofuel production. Carbon footprint is the indicator that can reveal the whole GHG emissions associated with the use of land, water and energy for biofuel production but the results can not reveal the impact in view of resource use and scarcity which is a key issue of the nexus assessment. Thus, there is still a gap for future improvement of the footprint indicators for capturing the land-water-energy nexus impact.

Table 2.1 Relationships of the Footprints and Land-Water-Energy Nexus

	Ecological footprint (Land occupation)	**Water scarcity footprint (Water use and scarcity)**	**Carbon footprint (GHGs)**
Land 	Land occupation for biofuel crop cultivation	-	GHGs emission from land use/land-use change for biofuel crop cultivation
Water 	-	Impact of irrigation water use in view of water deprivation potential	GHG emission from water treatment, irrigation water use, water distribution
Energy 	Land occupation for energy production	Impact of water use for energy production and use in view of water deprivation potential	GHG emissions from energy production and use in processes
GHGs 	Land occupation for capturing CO_2 emissions	-	Total GHG emissions of biofuel

2.3.1 Water footprint assessment

Water footprint assessment is a tool for compilation and evaluation of the environmental impacts related to water. Nowadays, it has been standardized by the International Organization for Standardization (ISO) as ISO14046 (ISO, 2014). **Figure 2.2** shows the water footprint assessment framework which consists of four main stages including (1) definition of the goal and scope of the study; (2) water footprint inventory analysis identification and quantification of environmental loads involved; e.g. the energy and raw materials consumed, the air emissions, water effluents, and wastes generated (inventory analysis); (3) evaluation of the potential environmental impacts related to water based on the water use and degradation (water footprint impact assessment) and (4) assessment of available options for reducing the impacts related to water (water footprint interpretation).

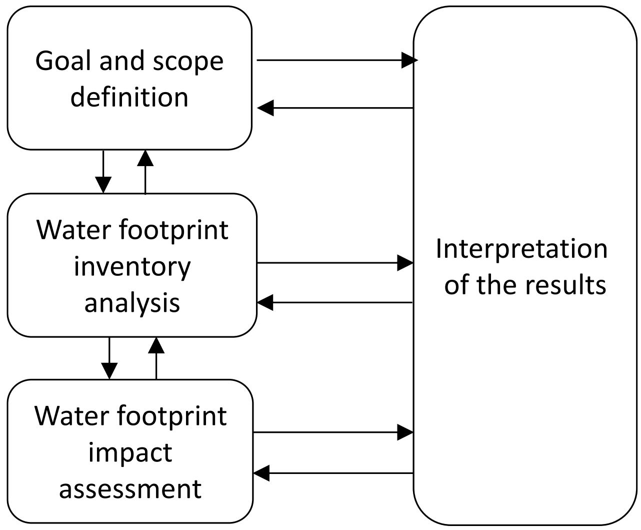


Figure 2.2 Water footprint assessment framework of ISO14046

(1) Water footprint inventory

In the study, the WF of crops implies to the amount of consumptive water use of those crops classified by each province and respective cropping calendars. The total water footprint of the cultivation process (WF_{crop}) is adapted from the general formula of (Hoekstra et al., 2011):

$$WF_{crop} = WF_{crop,green} + WF_{crop,blue} \quad [m^3/ton] \qquad \text{(Eq.2.1)}$$

Where $WF_{crop,green}$ refers to the green water used for growing a crop (total rainwater evaporated from the field during the growing period) [m^3/ha], $WF_{crop,blue}$ refers to the consumption of blue water resources, i.e., surface and ground water (or the total irrigation water evaporated from the field during the growing period) [m^3/ha]. The grey water is not taken into consideration because it is not a physical quantity of water use but associated with water pollution. To determine $WF_{crop,green}$ and $WF_{crop,blue}$ of crops, the "Crop evapotranspiration (ET)" is calculated from the crop coefficient (K_c) and the reference crop evapotranspiration (ET_o) by the Eqs. (2.2) and (2.3):

$$ET_c = K_c \times ET_0 \qquad \text{(Eq. 2.2)}$$

$$WU_c = 10 \times \sum_{d=1}^{lgp} ET_c \ (m^3/ha) \qquad \text{(Eq. 2.3)}$$

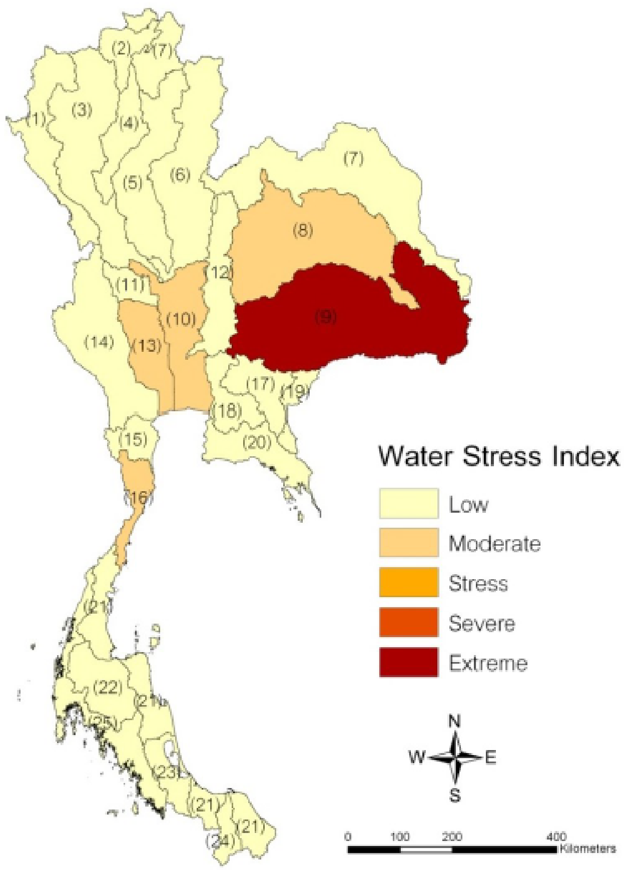
ET_{crop} represents crop evapotranspiration [mm/day], K_c represents crop coefficient [dimensionless], and ET_o represents the reference Penman-Monteith crop evapotranspiration [mm/day] which will be varied by the location of the plantation area. The factor 10 is used to convert water depth in millimeters into water volume per land surface in m^3/ha. The summation will be done over the period from the day of planting (day 1) to the day of harvest (lgp stands for length of growing period in days).

(2) Water Stress Index (WSI) and Water Use Impact Assessment

A unit of water consumed for growing crops in a region where water stress exists would have more impacts than the same amount of water used in a region of water abundance. Hence, to evaluate the impact of water use for crops grown in the different regions and watersheds of Thailand, the "water stress index (WSI)" will be used as the tool to indicate the extent of water scarcity for crop growing in the various watersheds. In the study, the WSI for the 25 watersheds of Thailand (Gheewala et al., 2014) will be applied to evaluate and compare the impact of water use for crop cultivation in different regions by quantifying the "WSI-weighted water volume consumed" or so-called "water deprivation" (Pfister et al., 2009). It can be calculated by multiplying the blue WF of crops with the water stress index (WSI) in the specific location i as shown in the Eq (2.4).

$$\text{Water Scarcity Footprint}_{\text{sugarcane,region } i} = \text{Irrigation water use}_{\text{sugarcane,region } i} \times \text{WSI}_{\text{region } i} \quad \text{(Eq. 2.4)}$$

This water deprivation quantifies the amount of water deficient to downstream human users and ecosystems. The WF results obtained will be expressed in the unit of **"m^3H_2Oeq"**. **Figure 2.3** shows the water stress index (WSI) for the 25 major river basins of Thailand. The WSIs were estimated using the Annual Water Withdrawal to Annual Water Availability ratio. The results indicated that currently the Chi watershed has more water stress than the Chao Phraya watershed as indicated by the WSI values of about 0.471 and 0.339, respectively (Gheewala et al., 2014).



Watersheds	WSI
(1) Salawin	0.017
(2) Kok	0.018
(3) Ping	0.023
(4) Wang	0.021
(5) Yom	0.044
(6) Nan	0.015
(7) Khong	0.014
(8) Chi	0.471
(9) Mun	0.927
(10) Chao Phraya	0.339
(11) Sakae Krang	0.031
(12) Pasak	0.050
(13) Tha Chin	0.287
(14) Mae Klong	0.018
(15) Phetchaburi	0.022
(16) West Coast Gulf	0.158
(17) PrachinBuri	0.016
(18) Bang Pakong	0.026
(19) Thole Sap	0.019
(20) East-Coast Gulf	0.015
(21) Peninsula-East coast	0.067
(22) Tapi	0.060
(23) Thale sap Songkhla	0.014
(24) Pattani	0.025
(25) Peninsula-West coast	0.012

Figure 2.3 Water stress index classified by 25 watersheds of Thailand (Gheewala et al., 2014)

2.3.2 Carbon footprint assessment

The carbon footprint is a measure of the environmental impact created from greenhouse gas emissions. The carbon footprint captures the full amount of greenhouse gas emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of products, which are consumed in a country. Nowadays, there are several international standards for carbon footprinting published, including the PAS 2050 standard (BSI, 2011) and the ISO 14067 (ISO, 2012). In the study, the carbon footprint or life cycle GHG emission calculation of crop products will be calculated as shown in Eq. (2.5) (ISCC, 2011). The GHG emissions sources associated with bioenergy crop production system are as follows:

- Land Use Change and Management (E_{LU})
- Manufacturing of fertilisers, agrochemicals, materials used (E_{ec})
- Emissions of N_2O resulted from fertilisers application (E_{field})

- Fossil fuel used in the field operation (E_{field})
- Transportation of materials (E_{td})
- GHG emissions credits from the improved agricultural practices (E_{crd})

$$E_{Total} = E_{LU} + E_{ec} + E_{field} + E_{td} - E_{crd} \qquad \text{(Eq. 2.5)}$$

Where:

- E_{Total} = Total GHG emissions of energy crop production (kg CO_2eq/ha-year)
- E_{LU} = Annualized GHG emissions from C-Stock changes caused by land-use change and management during land clearance before cultivation (kg CO_2eq/ha-year).
- E_{ec} = GHG emissions from production of input materials including fertilisers, agrochemicals, etc. (kg CO_2eq/ha-year)
- E_{field} = GHG emissions occurred during plantation activities e.g. direct and indirect N_2O emissions from the applied fertilisers, GHG emissions from combustion of fuels in agricultural machinery (kg CO_2eq/ha-year)
- E_{td} = GHG emissions caused by transportation of raw materials used (kg CO_2eq/ha-year)
- E_{crd} = GHG emissions credits from the improved agricultural practices (kg CO_2eq/ha-year)

To determine the life cycle GHG emissions of energy crop plantation in the unit of "a tonne of crop product, at farm exit gate", the total GHG emissions obtained using Eq. (5) will be divided by the agricultural productivity per hectare per year.

2.3.3 Land footprint assessment

Land footprint concept so far has been used for assessing the total domestic and foreign land required to satisfy the final consumption of goods and services of a country in terms of "virtual land" which can help policy makers especially who are going to implement the biofuel policy to see the whole picture of global competition over land (Giljum et al., 2013). Nevertheless, the land data so far were focused only the agricultural and forestry. In the study, land footprint will be considered in terms of a consumption-based indicator i.e. focusing on the land resources needed to create a final product when considering the whole life-cycle of the product system. It will be measured as the biologically productive land area that is directly and indirectly required (**unit: ha-year**). Nevertheless, it must be noted that this land footprint approach will differ from the calculations of the ecological footprint. The land footprint is a suitable indicator to assist the analysis of global land use related to consumption of a country or region and to monitor land use.

2.3.4 Ecological footprint

The ecological footprint (EF) is a measure of the area of biologically productive land and water that is required for an individual or an activity to produce all the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management practices (Wackernnagel and Rees, 1997). However, in the concept of LCA, the ecological footprint of a product is defined as the sum of time-integrated direct land occupation and indirect land occupation for capturing CO_2 emissions from fossil energy use and cement burning (Huijbregts et al., 2008). In this study, the ecological footprint of sugarcane cultivation is scoped as the sum of direct land occupation (EF_{direct}) and indirect land occupation (m^2a) related to CO_2 emissions from fossil energy use (EF_{CO2}) (Frischknecht et al., 2007) as shown in Equation (2.6).

$$EF = EF_{direct} + EF_{CO2} \qquad \text{(Eq. 2.6)}$$

For interpretation, the study classified the ecological footprint result into two categories i.e. direct ecological footprint which refers to the direct land occupation for sugarcane cultivation, and the indirect ecological footprint which refers to the indirect land occupation for the production of material used during sugarcane cultivation and indirect land occupation for capturing atmospheric CO_2 emissions from fossil fuel combustion.

2.4 Food-Feed-Fuel Production in Thailand

Thailand is located in the south eastern region of Asia, between 5°–20° N and 97°–105° E. The climate region is tropical where a variety of crops, fruits and plants grow well. Thailand is therefore known as one of the world’s leading countries in agricultural production and exports. Of the total country’s land area of about 51.3 million hectares, 46% is agricultural land, followed by forest land 32% and other lands 22% (OAE, 2016). Rice (paddy) fields occupy the highest at around 47% of the total agricultural land followed by perennial crops and fruit orchards, cropland, vegetable and flowers and others at about 23%, 21%, 1% and 8%, respectively. This has led Thailand to be the sixth-largest rice producer and the world’s leading country for rice export; being the world’s largest cassava producer and exporter contributing about 70% of the world market share; and recognized as the world's second-leading sugar exporter. Moreover, Thailand is also a key producer of other agricultural commodities such as palm oil, natural rubber, maize, beans, fruits and vegetables (OAE, 2016).

Figure 2.4 shows the maps of Thailand classified by geographical and hydrological boundaries. Based on geographical boundaries, the country can be divided into five regions i.e. North, Northeast, Central, East and South, covering all the 76 provinces. Based on hydrological boundaries, the country can be divided into 25 major watersheds.

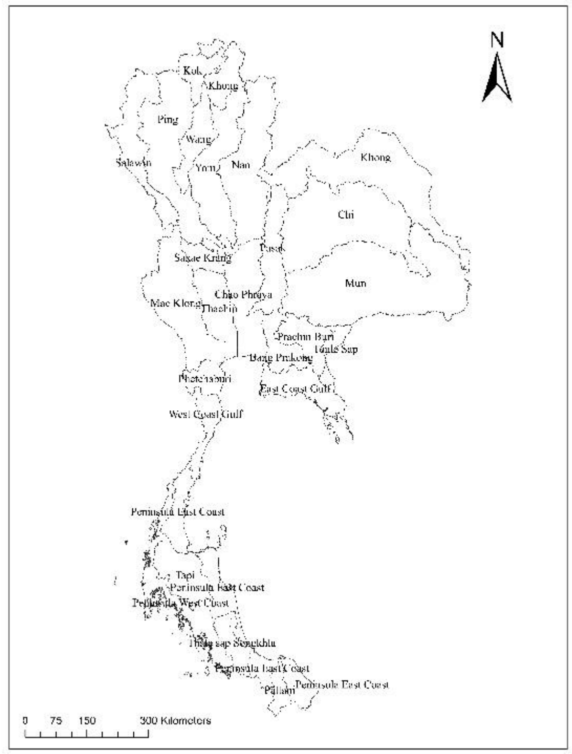


Figure 2.4 Maps of Thailand classified by geographical and hydrological boundaries

2.4.1 Rice (Paddy) production

Thailand is ranked as the 6th largest rice (paddy) producer and playing as one of the leading countries for rice exporter. Thailand produced around 30 Mt and exported around 10 Mt rice (OAE, 2016). Rice is grown nationwide but the capacity of rice cultivation in each region is different depending on the availability of water supply. In general, rice cultivation in Thailand can be classified into two crops depending on the period of plantation. The first crop, or "major rice", is grown in the rainy season (between May and October); while the second crop, or "second rice", is grown in the dry season (between November and April) using water from irrigation. The main region of paddy plantation in Thailand is the northeast contributing around 51% of the total planted areas (OAE, 2016). The northeastern region dominates in terms of the largest major rice production (rainfed paddy fields). However, the central region is outstanding in terms of the irrigated paddy fields and the ability to cultivate two crops a year. **Table 2.2** summarizes the rice planted areas, production, and yields in Thailand from a geographical perspective.

Table 2.2 Rice productions and yields in Thailand classified by regions (Year 2015)

Watershed	Plantation areas (ha)			Rice production (tonne)			Yields (t/ha)		
	Major rice	Second rice	Total	Major rice	Second rice	Total	Major rice	Second rice	Total
North	2,042,903	594,660	2,637,563	6,801,718	2,339,551	9,141,269	3.33	3.93	3.47
Northeast	5,790,946	188,870	5,979,815	12,230,973	606,677	12,837,650	2.11	3.21	2.15
Central	1,321,831	523,134	1,844,965	4,904,410	2,244,669	7,149,079	3.71	4.29	3.87
South	134,476	47,058	181,534	374,438	156,018	530,456	2.78	3.32	2.92
Total country	9,290,156	822,030	10,112,186	24,311,539	5,346,915	29,658,454	2.62	6.50	2.93

2.4.2 Sugarcane production

Sugarcane can be grown well nationwide due to the tropical climate with the average annual rainfall of about 1,200-1,600 mm. a year, except the southern region where the average rainfall is much higher i.e. around 4,500 mm a year which it is not suitable for sugarcane cultivation. With a total annual sugarcane production of about 94 million tonnes and the exportation of about 6.5 million tonnes of sugar in 2015/2016 (OAE, 2016), Thailand has become the fifth largest producer and second largest exporter of sugar in the world. The country's average sugarcane yield was about 57 tonnes/ha (OAE, 2017). In 2016, sugarcane plantations covered a total area of about 1.65 million ha. **Figure 2.5** shows the expansion of sugarcane plantations in the country over the past decade. It increased on average by about 3% per year over the period 2008/2010 to 2016/2017 (OAE, 2017). Nevertheless, the sugarcane cultivation in Thailand is mainly rainfed; the sugarcane production, therefore, could be slightly varied year by year due to the climate situation such as drought and floods. For example, in crop year 2016/17, the harvested area has decreased by 4% from the year 2015/2016 due to the drought impacts. This led to a decrease in sugarcane production from 94 million tonnes in 2015/2016 to 90 million tonnes in 2016/2017. The Northeastern region shared about

45% of the total sugarcane production, following by the Central 29% and the Northern 26%, respectively (OAE, 2016).

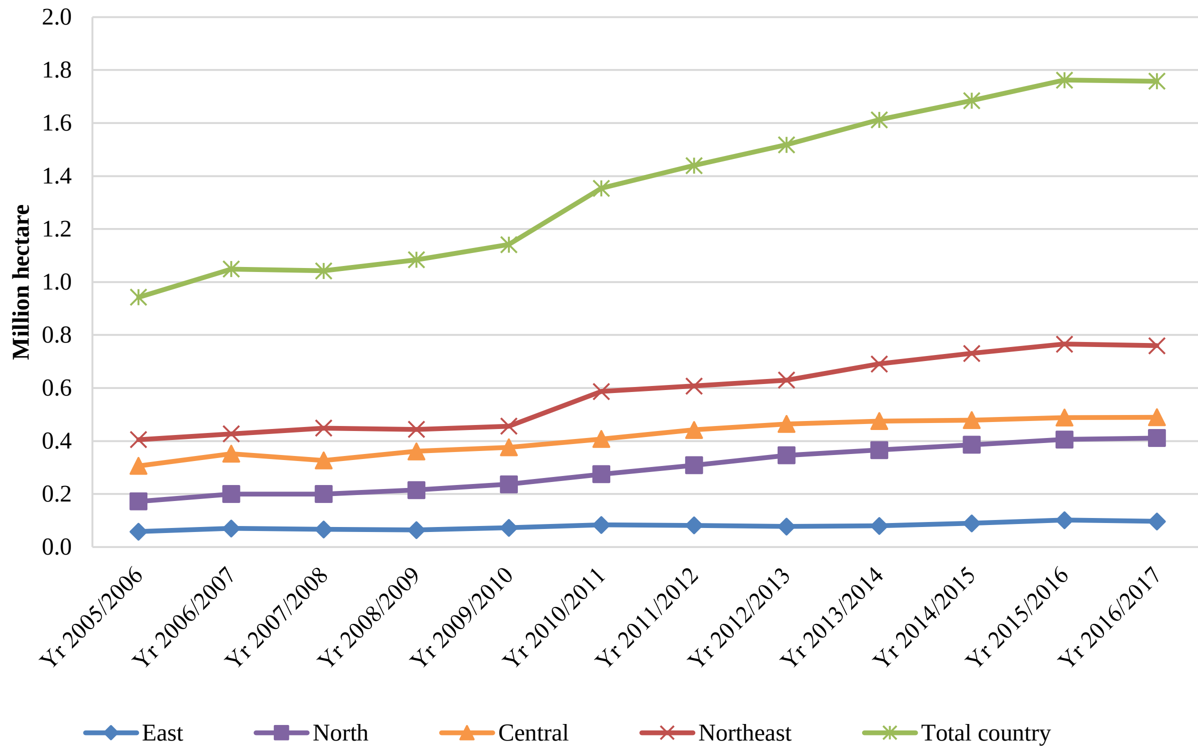


Figure 2.5 Sugarcane plantation areas in Thailand by regions from year 2005-2016

Chapter 3 Land-water-food-fuel-climate nexus of sugarcane production systems

3.1 Problem statement

Currently, bioethanol production in Thailand is about 3.2 ML/day with around 59% from sugarcane molasses along with 3% directly from sugarcane juice. However, the Alternative Energy Development Plan 2015 (AEDP) of the government has set the goal for bioethanol production in the country to be about 11.3 ML/day in the year 2036 (DEDE, 2015). This has brought about the requirement for boosting productivity of sugarcane cultivation in the country to fulfill the demands for sugarcane as biofuel feedstock.

The expansion of sugarcane plantation areas by substituting the low-productivity paddy fields has also been introduced as an option to increase farmers' income, reduce water consumption and to fulfill the excess capacity of the existing sugar mills. Nevertheless, from the nexus point of view as mentioned earlier, the expansion of sugarcane cultivation in different regions can bring about a difference in the scale of impacts on land, water and GHG emissions depending on factors such as soil condition, rainfall, water stress situation, agricultural practices and productivity. There have been several carbon and water footprint studies of sugarcane cultivation carried out in Thailand in the last few years (Pongpat et al., 2016; Gheewala et al., 2014; Yuttitham et al., 2011); however, most of the studies were single-issue based thus not capturing the trade-off among the impacts on land, water, energy and GHG emissions. Moreover, the scarcity situation of resources such as freshwater in the sugarcane cultivation areas was not taken into account in the studies so far. This study therefore aims to assess the land-water-energy nexus of different sugarcane production systems in two regions of Thailand where the expansion of sugarcane is being promoted. The local water scarcity index of different regions where the sugarcane is grown is specifically considered. The trade-off between the impacts on land, water use, and GHG emissions due to different farming practices are determined using a set of indicators including carbon footprint, ecological footprint, water consumption and water scarcity footprint in order to provide the recommendations for improving the sugarcane production system.

3.2 Sugarcane cultivation systems and studied areas

Thailand is located in the South Eastern region of Asia; the country's climate is mainly tropical i.e. exhibiting hot and humid conditions throughout the year, where sugarcane can be grown well.

The studied areas are the sugarcane cultivation systems in two provinces i.e. Nakhon Sawan and Chaiyaphum representing the Chao Phraya and Chi watersheds, respectively. The Chao Phraya watershed mainly covers the central and some parts in northern Thailand. The total area of the Chao Phraya watershed is 20,266 km^2 covering 11 provinces including Nakhon Sawan, Chai Nat, Sing Buri, Lop Buri, Ang Thong, Ayutthaya, Saraburi, Pathum Thani, Nonthaburi, Samut Prakan and Bangkok. The average annual rainfall of this watershed is approximately 1,140 mm with around 3,786 million m^3 accounted for as the average annual runoff. Around 60% of the cultivated area in the Chao Phraya watershed is irrigated. On the other hand, the Chi watershed is located in north eastern Thailand and is a part of the Mekong river basin. The total area of the Chi watershed is 49,130 km^2 covering 12 provinces including Khon Kaen, Chaiyaphum, Kalasin, Maha Sarakham, Roi Et, Yasothon, Ubon Ratchathani, Nakhon Ratchasima, Loei, Nong Bua Lam Phu, Udon Thani, and Si Sa Ket. The average annual rainfall in this watershed is approximately 1,208 mm with around 11,160 million m^3 accounted for as the average annual runoff. It was found that only 12% of the cultivated areas in Chi are under irrigation. Those two regions were selected as the studied areas for comparison because the infrastructure like irrigation systems, water resource availability, water stress situation, agricultural practices and socio-economic of farmers are different. **Figure 2.3** shows the water stress index (WSI) for the 25 major river basins of Thailand. The WSIs were estimated using the Annual Water Withdrawal to Annual Water Availability ratio. The results indicated that currently, the Chi watershed has more water stress than the Chao Phraya watershed as indicated by the WSI values of about 0.471 and 0.339, respectively (Gheewala et al., 2014).

3.3 System boundary of nexus assessment

Sugarcane is newly planted once and then harvested repeatedly after 12 months of growth for 3 to 4 years. **Figure 3.1** shows the system boundary of sugarcane cultivation systems which can be classified into four main stages i.e. land preparation, planting, treatment and irrigation, and harvesting. The reference unit for the footprint assessments of sugarcane is set as a tonne of sugarcane product. Land preparation includes the step of ploughing by riper, two or three times of disk ploughing and disk harrowing. For provinces like Nakhon Sawan in the Chao Phraya watershed, the land is generally prepared and the sugarcane planted in November to December and harvested in December to January of the following year. Water is normally required since the beginning of planting using irrigation system such as furrow irrigation. However, for the northeastern region, like in the Chi watershed, planting is in the rainy season for which land clearing starts in April and harvesting is around January to March of the following year.

Planting, nowadays mostly mechanized, is carried out by billet planters. Chemical fertilizers and agrochemicals such as herbicides and insecticides are used in varying amounts depending on farmers' practices. The most common irrigation system used is furrow irrigation. Harvesting begins 10-14 months after planting. However, mechanized harvesting is currently gaining attention by farmers as well as the sugar millers due to the lack of farm workers. Nevertheless, manual harvesting along with cane trash burning before harvesting is still the common practice sharing about 70% of total harvested sugarcane going into the mills.

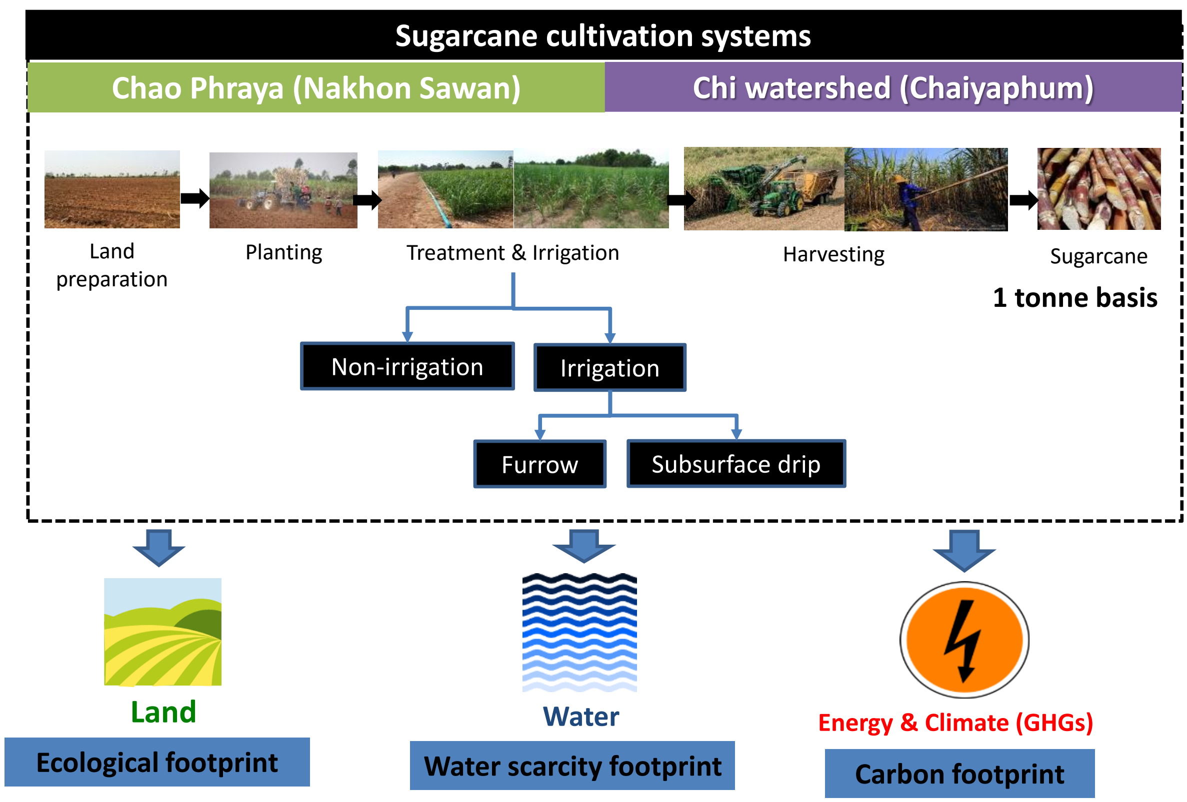


Figure 3.1 System boundary of nexus assessment

3.4 Data sources

Primary data for sugarcane cultivation in the irrigated and non-irrigated areas are collected from sugarcane growers located in the Nakhon Sawan (Chao Phraya watershed) and Chaiyaphum (Chi watershed) provinces. The reference unit of the assessment is a tonne of sugarcane at farm gate.

Primary data for sugarcane cultivation are collected from 30 sugarcane growers in two provinces i.e. Nakhon Sawan (covering planted areas around 350 hectares) and Chaiyaphum (covering planted areas around 140 hectares). There are two types of irrigation systems compared in the study i.e. furrow irrigation and subsurface drip irrigation. Fuel used for both irrigation systems is estimated based on 5.5 hp pump which is generally used by the sugarcane growers. The water pumping specification used in the assessment is about 1100 L/min and diesel consumption 2L/hour. **Table 3.1** shows the key input-output materials for the surveyed sugarcane plantations. The life cycle inventory (LCI) for the production of input fertilizers, agrochemicals, and fuels used are referred from the Thai national LCI database (MTEC, 2014) and the international life cycle inventory databases such as Ecoinvent (Ecoinvent, 2012).

Table 3.1 Weighted average of input-output of the studied sugarcane cultivation systems

	Inventory	Unit	Nakhon Sawan (Chao Phraya)		Chaiyaphum (Chi)	
			Irrigated	Non-irrigated	Irrigated	Non-irrigated
Sample sizes	Total planted areas	ha	163	184	48	90
Product	Sugarcane yields	t/ha	111	72	86	70
Land preparation	Diesel	L/ha	126	131	106	106
	Manure	kg/ha	-	23	315	1018
Planting	Diesel	L/ha	16	34	14	2
Treatment	N-fertilizer	kg/ha/y	58	102	104	57
	P-fertilizer	kg/ha/y	40	82	46	57
	K-fertilizer	kg/ha/y	26	60	85	56
	Urea	kg/ha/y	109	114	13	25
	Diesel (fertilizers & chemical applications including weed control)	L/ha/y	6 (manual & knapsack-type applicator)	3 (manual & knapsack-type applicator)	26 (mechanical application)	2 (manual & knapsack-type applicator)
	Diesel (irrigation)	L/ha/y	21 (furrow irrigation)	-	9 (Subsurface drip irrigation)	-
	Agrochemicals	kg/ha/y	18	27	25	9
Harvesting	Diesel	L/ha/y	30	29	28	8

Transport	Truck 20t	t.km	4440	2880	3440	2800

The difference in the data of non-irrigated system in Chao Phraya and Chi such as the amount of organic fertilizer used and fuel consumption is due to the different farming practices. Sugarcane growers in the Chi watershed (northeastern region of Thailand) generally have low household incomes; thus, manure is highly relied on as a fertilizer. Also, the farming practice is mainly manual for both planting and harvesting. On the other hand, sugarcane growers in the Chao Phraya watershed (central region) generally apply more chemical fertilizers as they have higher household incomes. In addition, there is more use of machinery for both sugarcane planting and harvesting due to lack of labor in the central region, unlike in the northeastern region.

3.5 Results and Discussion

3.5.1 Comparison of footprint indicators

Table 3.2 shows the water scarcity footprint, carbon footprint and ecological footprint results per tonne of sugarcane under irrigated and non-irrigated cultivation conditions in Nakhon Sawan (Chao Phraya watershed) and Chaiyaphum (Chi watershed). The results reveal that the irrigation system can help spur the yield of sugarcane as compared to the non-irrigated system by around 23% (Chaiyaphum) - 54% (Nakhon Sawan). One of the reasons that causes the irrigated sugarcane cultivation in Nakhon Sawan to have a higher yield improvement than Chaiyaphum is because the actual irrigation supplied by farmers in Nakhon Sawan is estimated to be about 17 m^3/t cane which is closer to the irrigation water requirement of sugarcane i.e. 34 m^3/t cane (which was calculated from the crop evapotranspiration (ET) of sugarcane and the rainfall data in the region). Meanwhile, the actual irrigation supplied by farmers in Chaiyaphum is found to be around 32 m^3/t which still far from the irrigation water required for sugarcane growing in Chaiyaphum which is around 67 m^3/t cane. The furrow irrigation system was commonly found in the field survey in both provinces. However, nowadays, there is an increasing use of the higher efficiency irrigation systems such as the subsurface drip irrigation and big gun sprinkler by sugarcane growers in Thailand. This would help improve the water use efficiency for sugarcane cultivation in the future because the furrow irrigation has an irrigation efficiency of just about 55% while the subsurface drip irrigation has an efficiency of about 97% (OCSB, 2015).

The use of irrigation will increase the consumption of energy i.e. diesel, which in turn also induces additional GHG emissions per hectare. However, accounting for the yields improvement due to irrigation, the carbon footprint and ecological footprint of sugarcane product are decreased by around 11-36% and 15-35%, respectively. Nevertheless, the increased freshwater resources used for irrigation bring about an increase in the water scarcity footprint of irrigated sugarcane as also revealed by **Table 3.2**. The direct water scarcity footprint results of irrigated sugarcane in Nakhon Sawan and Chaiyaphum are about 6 and 15 m^3 H_2Oeq/t cane, respectively.

Table 3.2 Ecological footprint, water scarcity footprint and carbon footprint of sugarcane production in different conditions

Aspects	Indicators	Nakhon Sawan (Chao Phraya)		Chaiyaphum (Chi)	
		Irrigated	Non-irrigated	Irrigated	Non-irrigated
Crop yield	Sugarcane (t cane/ha)	111	72	86	70
Water use	Rain water (m^3/t cane)	68	105	66	81
	Irrigation water requirement (m^3/t cane)	34	52	67	82
	Actual irrigation water used (m^3/t cane)	17	-	32	-
	Water scarcity footprint (Direct) (m^3 H_2O eq/t cane)	6	-	15	-
	Water scarcity footprint (Indirect) (m^3 H_2O eq/t cane)	5	5	6	5
	Total Water scarcity footprint (m^3 H_2O eq/t cane)	11	5	21	5
Climate change	Life-cycle GHG emissions (kg CO_2eq/t cane)	30	47	32	36
Land	Ecological footprint (m^2a/t cane)	242	377	301	353
	Direct land occupation (m^2a/t cane)	197	303	256	313
	Indirect land occupation from raw materials (m^2a/t cane)	1	2	1	1
	Carbon dioxide (m^2a/t cane)	44	72	44	39

3.5.2 Environmental hotspots of sugarcane cultivations in view of footprint indicators

Table 3.3 shows the key hotspots on biological productive land use, water scarcity, energy use and GHG consequences that can be identified from the different footprints using the case of irrigated sugarcane cultivation in Nakhon Sawan province. For water scarcity footprint, the results show that direct irrigation water use is the main contributor to the impact on water scarcity potential accounting for about 57% of the total water scarcity footprint, followed by the indirect water scarcity footprint from agrochemicals and urea production which contributed about 19% and 11%, respectively. For ecological footprint, the results reveal that the direct arable land use for sugarcane cultivation contributes about 82% of the total ecological footprint, followed by the indirect impact from diesel fuel and urea fertilizer production which shared about 7% and 4%, respectively. The energy use in agricultural machines such as diesel is one of the key hotspots on the GHG emissions i.e. sharing about 21% of the total carbon footprint. However, the highest GHG emissions for sugarcane cultivation are from cane trash burning during sugarcane harvesting which is still the common practice for the small sugarcane growers in Thailand i.e. around 70% of total cane production in Thailand was found to be the burnt cane (OCSB, 2015). The N_2O emissions caused by the N-fertilizer application to the soil is also accounted in the carbon footprint and is one of the key contributors to the carbon footprint of sugarcane.

Table 3.3 Environmental hotspots of irrigated sugarcane cultivation in Nakhon Sawan province classified by water scarcity footprint, ecological footprint, and carbon footprint

Process	Water scarcity footprint (m^3 H_2O eq./t cane)		Ecological footprint (m^2a/ t cane)				Carbon footprint (kg CO_2eq/ t cane)	
	Value	%*	Land occupation	CO_2	Total	%*	Value	%*
Direct agricultural land use	-	-	197	-	197	82%	-	-
Direct irrigation water use	6	57%	-	-	-	-	0.6	2%
Cane trash burning	-	-	-	-	-	-	10	33%
N_2O from N-fertilizer applied	-	-	-	-	-	-	3	11%
Diesel (excluding irrigation)	0.2	2%	0.0	16	16	7%	5.4	19%
Urea	1	11%	0.1	11	11	4%	4	14%

Process	Water scarcity footprint (m^3 H_2O eq./t cane)		Ecological footprint (m^2a/ t cane)				Carbon footprint (kg CO_2eq/ t cane)	
	Value	%*	Land occupation	CO_2	Total	%*	Value	%*
N fertilizer	0.5	5%	0.1	2	3	1%	1	3%
P fertilizer	0.5	4%	0.3	1	2	1%	0.6	2%
K fertilizer	0.1	1%	0.0	0.3	0.4	0%	0.1	0%
Agrochemicals	2	19%	0.1	5	5	2%	2	6%
Transport	-	-	-	8	8	3%	3	10%
Total footprint	**11**		**198**	**44**	**242**		**30**	

*% represents the contribution percentage of that process to the total footprint results

3.6 Land-Water-Energy Nexus management

The next step after the land-water-energy nexus assessment by footprint indicators is the nexus management which should be analyzed. As mentioned earlier, although there is a partial overlap between water scarcity footprint, ecological footprint and carbon footprint, none of these indicators alone can be used to explain the land-water-energy nexus of agriculture. The results revealed that the land-water-energy impacts directly come from the sugarcane cultivation stage i.e. land occupation and irrigation water use for sugarcane production. The indirect land-water-energy impacts caused by the materials and agrochemicals production as well as transportation are much lower than the sugarcane cultivation stage. To improve the efficiency of land use, water and energy during cultivation, treatment and harvesting of sugarcane should therefore be focused. The nexus management can be proposed as follows:

(1) The nexus assessment shows that the key linkage to the improvement on land, water, energy and GHG emissions performance of sugarcane cultivation is the promotion of an appropriate irrigation system. Freshwater resource is the vital factor for the crop's productivity improvement. However, in reality, the freshwater resource management for agriculture is a challenge for both the farmers and policy makers because the resource is limited to a certain area and period. The water management plan of the Royal Irrigation Department (RID) has reported that for agriculture in dry season, of the total sugarcane planted areas of about 68,670 hectares in Chaiyaphum and 96,896 hectares in Nakhon Sawan provinces, only 1%

and 4% are under irrigation (RID, 2014). Expanding irrigation infrastructure entails a high cost for the government meanwhile, installing irrigation technology in the farm is a high cost to the sugarcane growers. Additionally, the freshwater resource has to be shared by many stakeholders in the region; therefore, the water user groups need to be set up and engaged for making a water management plan. This is quite a contrast to the land which generally the farmers will have their rights to use and manage; as well as the energy that farmers have their purchasing power for potentially unlimited use. However, nowadays, there is an increase in contract farming which would be helpful in terms of soft loans from sugar millers to their contract farmers for investing in irrigation systems as well as the mechanized farming system.

(2) The water use is found to be the key factor in land-water-energy nexus management of sugarcane. This is because, firstly, water is one of the key factors to improve the yield of sugarcane. The ecological footprint in view of direct land occupation could be reduced significantly for the case of irrigated sugarcane due to the higher yields as compared to non-irrigated case. At the same time, the additional energy use for irrigation is found to not significantly increase GHG emissions i.e. only around 2% of total carbon footprint of sugarcane as presented in **Table 3.3**. The challenge is only the irrigation infrastructure development for supporting sugarcane growers as well as the management of the remaining water availability in that area.

(3) High efficiency water irrigation system such as drip irrigation which is known to be the most precise and efficient to deliver water and nutrients to crops should be encouraged for sugarcane farmers. This is especially for the sugarcane planted areas located in the high water stress areas like in Chao Phraya, Chi and Mun watersheds of Thailand. The furrow irrigation system which so far has been the common system used for irrigated sugarcane cultivation, has an irrigation efficiency of only about 55% (OCSB, 2015). Meanwhile, other irrigation systems like the big gun sprinkler, center pivot and subsurface drip irrigation have efficiencies of around 75%, 85% and 95%, respectively (OCSB, 2015). The irrigation water requirement for sugarcane cultivation in Nakhon Sawan and Chaiyaphum was estimated to be around 3,736 m^3/ha and 5,722 m^3/ha, respectively. To achieve the water requirement of sugarcane, using drip irrigation to substitute furrow irrigation will reduce the irrigation water use by about 2,860 m^3/ha for the case of Nakhon Sawan province and 4,380 m^3/ha for the case of Chaiyaphum province. Apart from the water use reduction, the diesel used for

irrigation would be decreased which in turn leads to the reduction in carbon footprint. For example, the water scarcity footprint and carbon footprint of sugarcane for the case of Nakhon Sawan would be decreased from 11 to 9 m^3 H_2O eq/t cane and 30 to 29 kg CO_2eq/t cane, respectively if subsurface drip irrigation were used to substitute furrow irrigation.

(4) For agricultural zoning policy, so far, the land suitability is used as well as the rainfall; these are considered as the key criteria for identifying crops appropriate to each agricultural zone. However, due to climate change as well as the increased concerns on freshwater resource availability, the water stress index derived from the ratio of water demand and water availability in each region should be further taken into account for identifying areas to promote sugarcane. This is because the irrigation water must be one of the key factors for modern farming of sugarcane in the future, considering only the rainfall availability but not considering the existing or future demands on water in the region will affect water competition in the long run.

Chapter 4 Land-water-food-fuel nexus of paddy (rice) production systems

4.1 Problem statement

The water footprint of rice has so far been conducted by focusing on the volumetric water consumption of rice cultivation in various countries as the virtual water footprint (Yano et al., 2015; Chapagain and Hoekstra, 2011; Shrestha et al., 2017; Marano et al., 2015). The results revealed that although the water footprint of rice in Asia is high, the contribution to water scarcity is relatively low because the rice is generally grown in the wet season (rainfed paddy field) and rainwater is the major water source. However, the environmental impact due to the irrigated water use in rice production should be specifically analysed based on the location and timing of the water use (Chapagain and Hoekstra, 2011). This is consistent with the concept of water scarcity footprint in which the potential environmental impact of water use is assessed considering the time and water stress situation of each location (Jeswani and Azapagic, 2011; Nunez et al., 2012). There is still a lack of assessing the potential impact of rice cultivation in term of water scarcity footprint especially for the case where rice cultivation systems are shifted due to limited water resources. This study aims to integrate water footprint based on LCA approach as a tool for providing recommendations to support the policy makers on promoting sustainable rice cultivation in view of water efficiency and water scarcity footprint reduction. The water footprint inventory as well as the water scarcity footprint of different rice cultivation systems of Thailand, have been investigated and assessed. The studied areas cover the four key watersheds of rice cultivation in Thailand including Mun, Chi, Chao Phraya and Tha Chin.

4.2 Rice cultivation systems and studied areas

4.2.1 Cultivation systems

Rice cultivation in Thailand is mainly the wet system i.e. rice fields are prepared and the soil is kept saturated. There are three major types of rice cultivation found in the studied areas i.e. (1) transplanting, (2) dry ungerminated seed broadcasting and (3) pre-germinated seed broadcasting. Transplanting is a traditional technique for growing rice by transplanting seedlings that are firstly grown in nurseries. This method requires less seeds and is easy for controlling weeds; but is labor intensive and the crop takes longer to mature (IRRI, 2017). Dry ungerminated seed broadcasting or so-called “Dry direct seeding” is a technique for rainfed ecosystems, where farmers will sow the ungerminated seeds onto the dry soil surface and then incorporate them either by ploughing or by harrowing. Pre-germinated seed broadcasting or so called “wet direct seeding” is a technique commonly used for irrigated areas i.e. seed is normally pre-germinated prior to broadcasting onto the recently drained, well-puddled seedbeds or into pre-standing water in the fields (IRRI, 2017). **Figure 4.1** shows the simplified rice cultivation system and water use covering soil preparation, sowing, cultivation and harvesting to get the rice grain product.

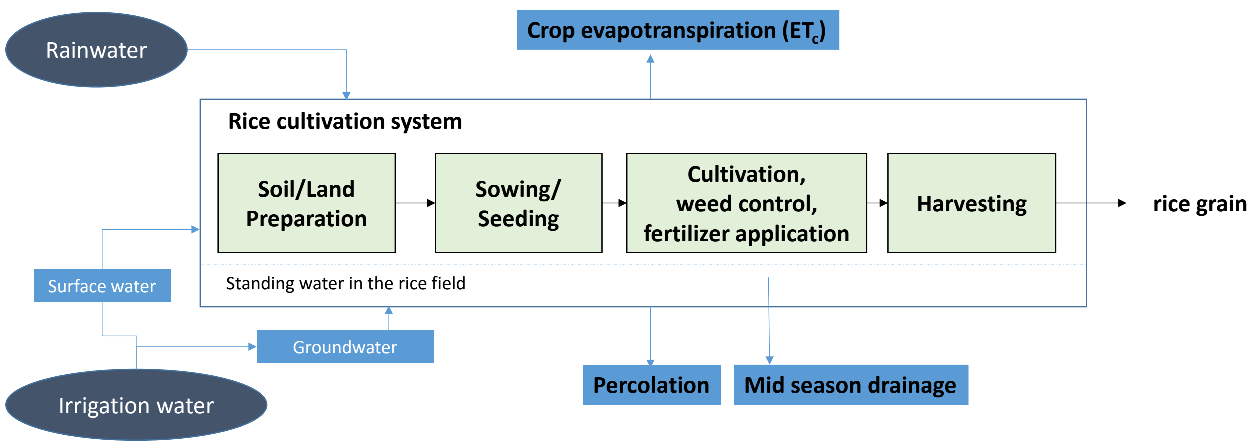


Figure 4.1 Rice cultivation system and water use

4.2.2 Studied areas

Thailand can be divided into 25 major watersheds as shown in **Figure 4.2**. The hydrological boundary is essential for policy makers to use for water resource management. The study highlights the four key watersheds i.e. Chao Phraya, Tha Chin, Mun and Chi in the water use and water scarcity footprint assessment of rice (paddy) production in Thailand. This is because the Chao Phraya and Tha Chin watersheds represent the central region with the irrigated cultivation system where both major and second rice can be grown. Meanwhile, Mun and Chi are located in the northeastern region where major rice is widely grown under the rainfed cultivation system.

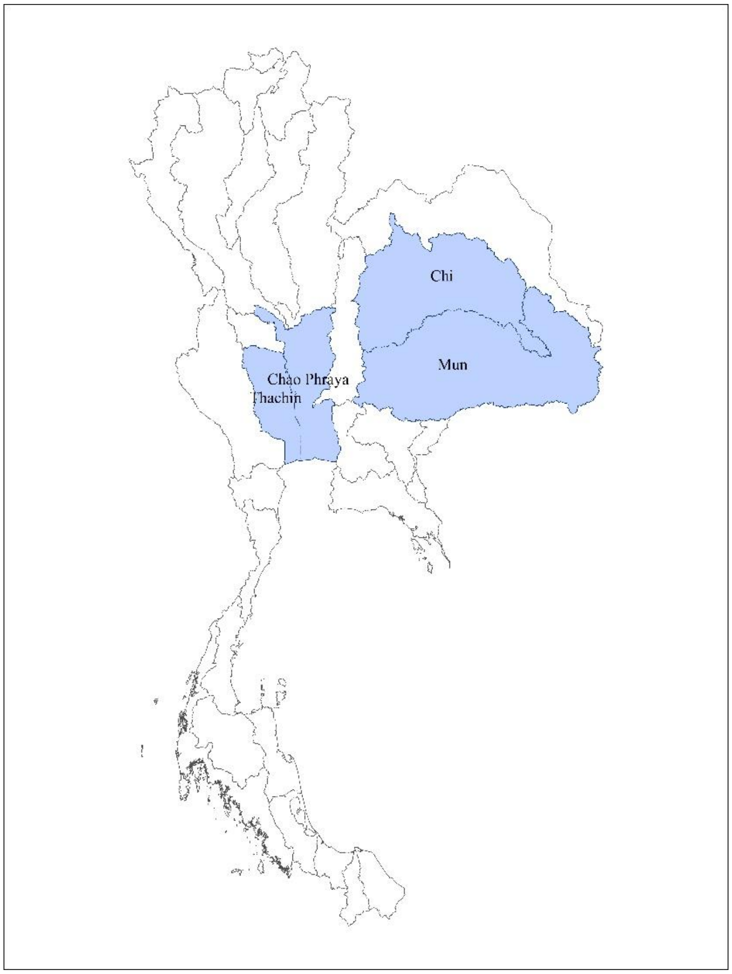
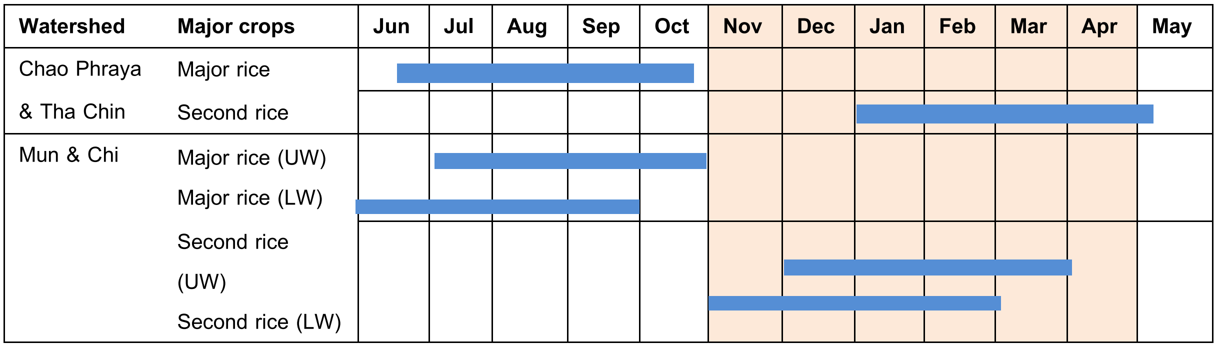


Figure 4.2 Mun, Chi, Chao Phraya and Tha Chin watersheds of Thailand

4.2.3 Cropping calendar

Figure 4.3 shows the cropping calendar of rice which is referred as the baseline for estimating crop water requirement. The dry season of Thailand runs from November through April (shaded in the figure). The geographical location of Chao Phraya and Tha Chin watersheds is in the central region where the rainfall starts since mid-May to mid-August due to the southwest monsoon and another with northwest monsoon in mid-October to end of November. Therefore more than one crop of rice is generally grown if than farmers have enough water supplement for land preparation. It was found that in the Ayuthaya, Nakhon Pathom, Pathum Thani provinces, the farmers are able to grow crop twice a year. However, in case of the northeastern region (i.e. Mun and Chi watersheds), the rainy season generally comes a bit later than the central so that farmers generally start to prepare their rice fields since mid-July and then sowing in mid-August in order to use the rainwater.

Nowadays, the non-irrigated rice fields have been promoted by the Department of Agriculture to cultivate mungbean or other beans in order to improve soil quality.



*UW : Upper watershed; LW: Lower watershed

Figure 4.3 Cropping calendar for rice cultivation

4.3 Data sources

Data on rice cultivation collected from farmers in 15 provinces are shown in **Table 4.1**. The samples are identified by the provincial agricultural officers to representing various practices of farmers in the studied provinces. The planted areas of rice in Tha Chin and Chao Phraya watersheds are generally the lowland paddy rice which farmers are able to cultivate with irrigation water. Meanwhile, the cultivated areas in the Mun and Chi watersheds mostly relied on rainwater. In Chao Phraya and Tha Chin, the cultivation system of the surveyed samples for both major and second rice is pre-germinated seed broadcasting. However, in the Mun watershed, the cultivation systems for major rice consist of dry ungerminated seed broadcasting (50%), pre-germinated seed broadcasting (30%) and transplanting method (20%); and the cultivation system for second rice is mainly dry ungerminated seed broadcasting. In the Chi watershed, the cultivation systems for major rice consist of dry ungerminated seed broadcasting (40%), pre-germinated seed broadcasting (27%) and transplanting method (33%); and the cultivation system for second rice is mainly the pre-germinated seed broadcasting.

Table 4.1 Data sources

Watershed	Provinces	Data collection area (hectare)	
		Major rice	Second rice
Chao Phraya	Pathum Thani, Ayutthaya, Nakhon Sawan, Chai Nat, Lop Buri	3443	2607

Watershed	Provinces	Data collection area (hectare)	
		Major rice	Second rice
Tha Chin	Suphan Buri, Kanchanaburi, Nakhon Pathom	322	297
Mun	Ubon Ratchathani ,Nakhon Ratchasima, Buri Ram	1020	362
Chi	Nakhon Ratchasima, Chaiyaphum, Kalasin, Khon Kaen	828	245

4.4 Water footprint assessment approach for land-water-food-fuel nexus

Water footprint is recognized as a tool for evaluating the relationship between agricultural production, water resources, and environmental impacts in order to enhance water use efficiency, sustainability of water use within the watersheds, mitigate impact of water use and improving water resource management (Mekonnen and Hoekstra, 2011; 2014; Pfister and Bayer, 2014; Lovarelli et al., 2016). The same term “water footprint” is used by two approaches i.e. water footprint network and life cycle assessment (LCA) although the definition of it is different (Hoekstra, 2016; Pfister et al., 2016). The two approaches can provide the different views of useful information to support the policy decision for enhancing water resource management as well as for water impacts mitigation to avoid the water risks (Gheewala et al., 2014; Hoekstra et al., 2016). The volumetric quantification of water use for agricultural product in water footprint assessment of the water footprint network approach provides useful information in terms of water use efficiency and water productivity by considering the freshwater consumption over the production chain of crops. Meanwhile, the water footprint assessment based on LCA approach will combine the volumetric freshwater consumption with the water stress index of the region, where the water is extracted, in order to determine the impact of freshwater consumption in view of water deprivation potential [(Pfister et al., 2009; Pfister and Bayer, 2013).

4.4.1 Crop water use assessment

Crop water use (CWU) refers to the volume of water lost via the evapotranspiration process including evaporative water from soil and crop surfaces and transpired water from crops to the atmosphere. CWU is denoted as crop evapotranspiration (ETc). The water use of rice is estimated based on the crop evapotranspiration calculation complemented with the rain fed and/or irrigated conditions of the planted areas as well as irrigation practices of farmers. Data on farming practices, irrigation techniques and efficiency are primarily collected, complied and aggregated from farmers.

The general formula (**Eq. 4.1**) used for estimating crop water use is expressed as follows (Allen et al., 1998; FAO, 2010).

$$ET_c = K_c \times ET_o \qquad \text{(Eq. 4.1)}$$

Where ET represents the crop evapotranspiration i.e. the amount of water evapotranspired by the crops in a specific climate regime and adequate soil water is maintained by rainfall and/or irrigation; K_C represents the crop coefficient of Penman-Monteith; and ET_O represents to the reference crop evapotranspiration of Penman-Monteith (Allen et al., 1998). Accordingly, CWU of rice (major and second) can be estimated. The reference crop evapotranspiration (ET_O), crop coefficients and monthly average rainfall data for different provinces of Thailand are referred from (RID, 2010; 2011; TMD, 2014). The crop evapotranspiration (ET_C) and the effective rainfall are calculated for the given set of data on ET_O, monthly rainfall, K_C and the crop calendar.

In general, rice cultivation begins with the land preparation by puddling. This is done by saturating the soil layer for one month before sowing. The volume of water that is necessary for saturated soil is about 200 mm (Brouwer and Heibloem, 1986). For the lowland rice growing, standing water is required for weed control. The wet system has a constant percolation and seepage loss during this period. Since the percolation loss is primarily a function of soil texture, the study refers the percolation loss factor based on Royal Irrigation Department (RID, 2011b) which is about 1 mm/day for the central region and 1.5 mm/day for the other regions of Thailand (RID, 2011b). A water layer is assumed to be established during transplanting or sowing and maintained throughout the growing season but the level of water layer can differ depending on the farmers' practices. This standing water is assumed to be used for the entire period of rice cultivation except for the last 15 days when the field will be dried out to facilitate harvesting. The total freshwater demand for rice cultivation is therefore calculated from the summation of ET_C, standing water, and percolation for each time step.

To classify the crop water use into rainwater and irrigation water, if rice is grown in non-irrigated areas, the water used for growing rice is supposed to be equal to the amount of effective rainfall. If CWU is higher than effective rainfall, water withdrawal for rice in non-irrigated areas is equivalent to the amount of effective rainfall. On the other hand, if effective rainfall is higher than CWU, water withdrawal for rice in non-irrigated areas is equivalent to the amount of CWU. Water required for growing crops cultivated in irrigated areas are expected to meet total amount of crop water requirement. Thus, a sum of effective rainfall and irrigation water is accounted as the total water withdrawal for crops cultivated in irrigated areas. This irrigation water is defined as the additional amount of water required to reach the total crop water requirement. In general, to calculate the amount of irrigation water requirement for irrigated agriculture, irrigation efficiency and water loss through percolation are taken into account as can be expressed in the Eq. 4.2 (RID, 2011b). Even though the irrigation efficiency at 0.65 is suggested by the specialist from RID using a rule of thumb approach, this factors depends not only on those three relative factors but also geographical conditions.

$$Irrigation\ water = \frac{(crop\ water\ use - effective\ rainfall) + water\ loss\ (percolation) \times 100}{Irrigation\ efficiency^{*}} \qquad \text{(Eq. 4.2)}$$

Remark: *Irrigation efficiency = 0.65 [derived from the efficiency of water conveyance (0.9) × efficiency of irrigation system (0.9) × efficiency of irrigation (0.8)]

4.4.2 Water scarcity footprint assessment

The environmental impact of water use depends on not only the amount of water consumed but also the water stress situation of the area where the water was extracted. The water deprivation potential or called as “water scarcity footprint” is therefore proposed as the proxy indicator to determine and compare the potential impact of water use in view of the amount of water deficiency to downstream human users and ecosystems (Pfister et al., 2009; Pfister and Bayer, 2013). A low water scarcity footprint indicates the lower impacts on water consumed. Equation (3) shows the general formula for water scarcity footprint assessment. The water scarcity footprint is calculated based on the “monthly water stress index (WSI)” of the 25 watersheds of Thailand (Gheewala et al., 2017). **Table 4.2** shows the monthly WSI of the Mun, Chi, Chao Phraya and Tha Chin watersheds.

$$\text{Water scarcity footprint}_{rice,i} = \text{Irrigation water use}_{rice,i} \times WSI_i \qquad \text{(Eq. 4.3)}$$

Where, irrigation water use$_{rice,i}$ represents the amount of irrigation water use for rice cultivation in the watershed i; WSI_i represent the water stress index of watershed (i). The water scarcity footprint is measured in terms of “m^3 H_2Oeq”. Actually, only the actual amount of irrigation water consumption for rice should be used for calculating the water scarcity footprint. The standing water in rice field that can percolate and recharge surface water and ground water will not be considered as a loss in will of catchment area (Bouman et al., 2007). However, the volumetric irrigation water used for rice cultivation is referred in the study because of its timing of use will contribute to the local water availability at the region. Policy makers have also considered the amount of standing water as well as water percolation loss in their irrigation water allocation plan for rice cultivations.

Table 4.2 Monthly WSI of the four selected watersheds (Gheewala et al., 2017)

	Monthly WSI											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Chao Phraya	1.00	1.00	0.99	0.08	0.04	0.52	0.90	0.86	0.28	0.05	0.35	0.98
Tha Chin	1.00	1.00	0.94	0.04	0.03	0.42	0.76	0.82	0.28	0.04	0.06	0.69
Mun	0.08	0.07	0.02	0.02	0.02	0.37	0.36	0.34	0.25	0.03	0.01	0.04
Chi	0.10	0.07	0.03	0.02	0.02	0.21	0.34	0.18	0.20	0.03	0.02	0.03

4.5 Results and Discussion

4.5.1 Water use for rice cultivation in different watersheds

Table 4.3 shows the comparison of freshwater use for major and second rice cultivation in the Chao Phraya, Tha Chin, Mun and Chi watersheds. For major rice, the results revealed that the total freshwater used per unit area for rice cultivation in those four watersheds are not different i.e. ranging between 6,800-7,500 m^3/ha. Rainwater is the main water source for major rice cultivation sharing around 75% of total freshwater used. Irrigation water is used only when the rainwater is not sufficient to meet the crop water requirement. However, per kilogram of rice product, the results showed the significant difference between major rice grown in the central region (Chao Phraya and Tha Chin) and the northeastern region (Mun and Chi) i.e. about 0.9-1.4 m^3/kg and 2.2-3.0 m^3/kg of rice, respectively. This is due to the differences in rice yields of each region. Rice yields depend on a number of factors such as the crop variety, soil quality, fertilization, and treatment practices; however, the Mun watershed has the famous Hom Mali rice (Thai jasmine rice) whose yield is generally lower than ordinary rice.

Contrary to the major rice, irrigation water is the major source contributing around 70-75% of total water used for second rice cultivation. The yields obtained from the second rice cultivation in Mun and Chi are increased as compared to major rice because only the irrigated rice fields can grow the second rice. Meanwhile, the major rice grown in those two regions are rainfed and might be cultivated in a deficit condition as compared to the crop water requirement if the rainfall if not enough. However, for the central region, the yields between major and second rice do not differ much because they are generally the irrigated and enough water will be supplied to the field as per the crop's requirement both for major rice and second rice cultivation. The total water used for second rice grown in Mun, Chao Phraya, Chi and Tha Chin are about 2.30, 1.53, 1.14 and 0.89 m^3/kg rice, respectively. The amount of water used can be divided into two main purposes i.e. (1) the water used for rice growing and (2) percolation loss and standing water. The water used for rice growing based on the crop evapotranspiration is estimated to be around 55% of the total water used; the remaining being the percolation loss. Considering the irrigation water used which the policy makers have to manage and allocate to the other users too, the results show that the lowest irrigation water used per kilogram of rice is for the second rice grown in Tha Chin, followed by Chi, Chao Phraya and Mun.

Table 4.3 Water use of rice production in different watersheds

	Parameter	Unit	Chao Phraya	Tha Chin	Mun	Chi
Major rice	Yield	kg/ha	5,088	5,769	2,669	2,994
			(5,019–5,156)	(5,519-6,631)	(2,569-2,769)	(2,919-3,069)
	Total water used	m^3/ha	7,275	5,596	7,499	6,796
			(7,026-7,528)	(5,077-7,493)	(6,653-8,389)	(6,421-7,181)
		m^3/kg	1.43	0.97	2.81	2.27
			(1.4 - 1.46)	(0.92 - 1.13)	(2.59 - 3.03)	(2.2 - 2.34)
	Rain water used	m^3/ha	5,495	4,096	5,204	6,317
			(5,270-5,723)	(3,698-5,637)	(4,470-5,981)	(5,983-6,659)
		m^3/kg	1.08	0.71	1.95	2.11
			(1.05 - 1.11)	(0.67 - 0.85)	(1.74 - 2.16)	(2.05 - 2.17)
	Irrigation water used	m^3/ha	1,781	1,500	2,268	449
			(1,656-1,908)	(1,214-2,586)	(1,772-,2796)	(359-552)
		m^3/kg	0.35	0.26	0.85	0.15
			(0.33 - 0.37)	(0.22 - 0.39)	(0.69 - 1.01)	(0.12 - 0.18)
Second rice	Yield	kg/ha	5,525	5,300	3,375	4,088
			(5,350-5,700)	(4,844-6,881)	(3,363-4,688)	(2,813-5,625)
	Total water used	m^3/ha	8,453	4,717	7,763	4,660

	Parameter	Unit	Chao Phraya	Tha Chin	Mun	Chi
			(7,918-9,006)	(3,875-8,258)	(5,178-11,156)	(2,813-8,438)
		m^3/kg	1.53	0.89	2.30	1.14
			(1.48 - 1.58)	(0.8 - 1.2)	(1.54-2.38)	(1.0-1.5)
	Rain water used	m^3/ha	2100	1325	2363	1390
			(1,926-2,280)	(872-3,303)	(673-3,609)	(844-2,250)
		m^3/kg	0.38	0.25	0.70	0.34
			(0.36 - 0.4)	(0.18 - 0.48)	(0.20-0.77)	(0.30-0.40)
	Irrigation water used	m^3/ha	6,354	3,392	5,400	3,270
			(5,939-6,783)	(2761-6,124)	(4,506-7,547)	(1,969-6,750)
		m^3/kg	1.15	0.64	1.60	0.80
			(1.11 - 1.19)	(0.57 - 0.89)	(1.34-1.61)	(0.7-1.2)

4.5.2 Water scarcity footprint of rice in different watersheds

To compare the potential impact from the freshwater used for rice cultivation in the different watersheds, the scarcity footprint is then assessed by combining the volume of irrigation water used for rice with the water stress index of each watershed and each period of time that water is used as shown in Eq. (3). The irrigation water is focused in the scacity assessment because it is the resource that will be competed with other water users. **Table 4.4** shows the water scarcity footprints of major and second rice cultivation in the four studied regions. The results show that although the total water used for rice grown in Mun is the highest i.e. 2.81 m^3/kg rice, the water scarcity footprint of major rice grown in Mun is almost equal to the Chao Phraya and Tha Chin watersheds i.e. ranging between 0.28-0.31 m^3 H_2Oeq/kg rice. This implies that the water deprivation potential impact from freshwater used for major rice cultivation does not different among the three studied watersheds. Only the rice grown in the Chi watershed has a much lower water scarcity footprint value indicating lower potential impacts on water consumed. The low water scarcity footprint of major rice cultivated in Mun and Chi is because of the lower water stress index from June to August of those two watersheds as compared to Chao Phraya and Tha Chin.

For second rice cultivation too, the Chi watershed has to lowest water deprivation potential, followed by the Mun, Tha Chin and Chao Phraya watersheds. The high water scarcity footprint of second rice cultivated in Chao Phraya and Tha Chin watersheds is because during January to March, the water stress index of both watersheds are indicated as severe. The irrigation water during those three months of dry season should therefore be considered as a scarce resource which needs to be used efficiently. In addition, the high irrigation water used for second rice cultivation in Chao Phraya watershed showed the low efficiency of water use and needed further improvement. The water scarcity footprint results imply that second rice grown in Chao Phraya and Tha Chin should be focused on by the policy makers to identify measures for improving efficiency of irrigation water use. Otherwise, there will be a high risk of irrigation water competition between farmers who want to grow second rice and the other water users in those two watersheds. The obtained results of water scarcity footprint directly match the real situation in the country where there has been an increasing risk of freshwater shortage over the past two years that made farmers especially in the central region like Chao Phraya and Tha Chin watersheds lose productions because of the lack of freshwater (LDD, 2015). In case of drought, the second rice cultivation which is recognized as water intensive will be abandoned or delayed by the government in order to save water resources for domestic (sanitation) uses and for ecosystem preservation.

Table 4.4 Water scarcity footprint of rice production in different watersheds

		Unit	Chao Phraya	Tha Chin	Mun	Chi
Major rice	Total water use	m^3/kg rice	1.43	0.97	2.81	2.27
	Water scarcity footprint	m^3 H_2Oeq/kg rice	0.31	0.28	0.29	0.04
Second rice	Total water use	m^3/kg rice	1.53	0.89	2.30	1.14
	Water scarcity footprint	m^3 H_2Oeq/kg rice	1.15	0.62	0.10	0.06

4.6 Recommendations for enhancing sustainable rice production

The results from water footprint assessment revealed that second rice cultivation in the central region of Thailand like in the Chao Phraya and Tha Chin watersheds would potentially face the challenge on water scarcity. To enhance sustainable rice production in those two watersheds, several measures should be encouraged or taken into account by the policy makers:

4.6.1 Improve water use efficiency of rice cultivation

The study has compared the freshwater use for different rice cultivation systems including the traditional practices like transplanting method, pre-germinated seed broadcasting and dry ungerminated seed broadcasting and the alternate wetting and drying (AWD). The “AWD system”, a water-saving technique for rice cultivation, is being encouraged to farmers in order to reduce irrigation water use in rice fields due to the increasing water scarcity situation, without decreasing yields. In AWD, irrigation water is applied a few days after the disappearance of the ponded water. Hence, the field is alternately flooded and non-flooded. The number of days of non-flooded soil between irrigation events can vary from 1 to more than 10 days depending on several factors such as soil type, weather and crop growth stage. To implement AWD, a "field water tube" is used to monitor the water depth on the field.

Figure 4.4 presents the estimated water use for second rice cultivation in the irrigated rice field in central region (Ayutthaya province, Chao Phraya watershed).The results revealed that the transplanting method brings about the highest water use at 1.34-1.48 m^3/kg rice, followed by pre-germinated seed broadcasting (1.25-1.37 m^3/kg), dry-ungerminated seed broadcasting (1.06-1.17 m^3/kg) and alternate wetting and drying (0.96-1.03 m^3/kg). The high water use for transplanting and pre-germinated broadcasting is due to the water requirement for land preparation and standing water as compared to the AWD method. Thus, the AWD method can be an option for farmers in the area as well as the year when the irrigation water is limited. The focus of AWD method should be for second rice cultivation because for major rice cultivation, the control of water level in the field must be difficult in practice as the water source relies on rainfall.

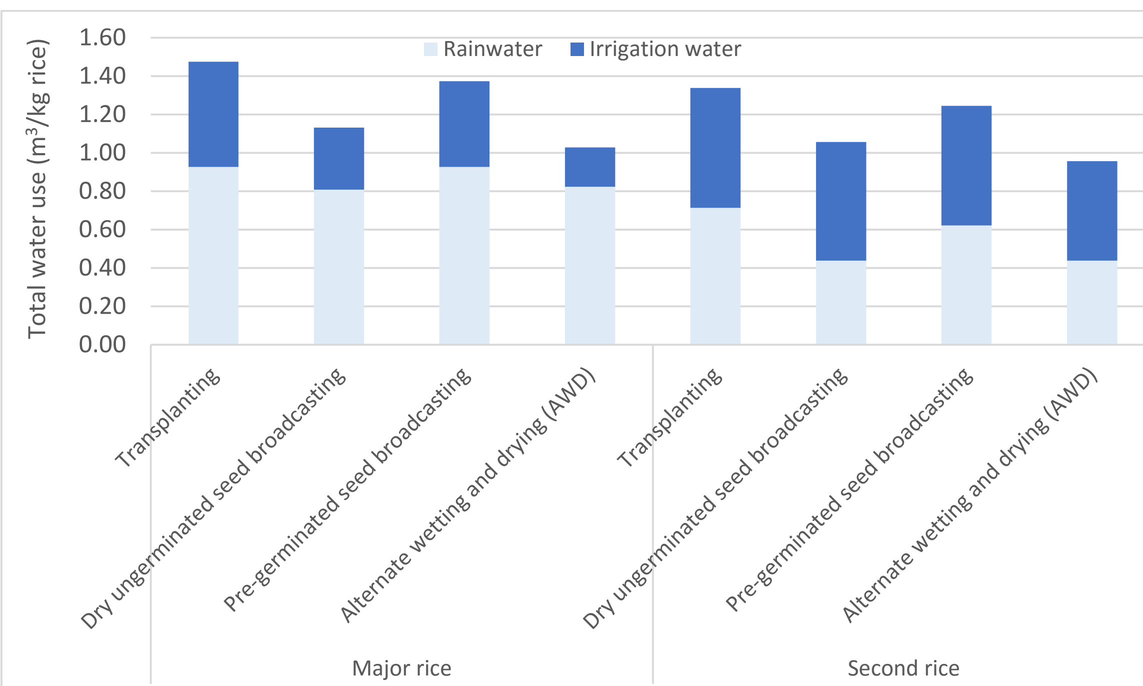


Figure 4.4 Water use for different rice cultivation methods in the central region of Thailand

The Office of Agricultural Statistics (OAE) revealed that about 92% of the second rice planted areas in the central region of Thailand followed the pre-germinated seed broadcasting system. Hence, it is estimated that if the AWD method is applied to replace the pre-germinated seed broadcasting method for second rice cultivation in the central region, the irrigation water requirement for rice would be reduced by around 570 m^3/hectare or around 17% irrigation reduction. This estimation is based on the conservative assumption that the yield would not be affected by the difference in water delivery method although several field experiments have indicated that the AWD would help increase the productivity of rice by around 10%. Of the total second rice planted areas in the central region of about 523,134 hectares, if 10% were changed to AWD method, the government would save around 298 million m^3 of irrigation water. However, the challenge is that the farmers must be able to control the water level in their fields appropriately as well as the manual weed control may be required because of less standing water in the field as compared to the traditional rice cultivation. Hence, more efforts of farmers for field management are required which might in turn lead to the increased cost and working time spent as compared to the traditional practice.

4.6.2 Expansion of irrigated areas

The assessment revealed that the irrigated rice fields bring about higher productivity than the rainfed ones. Thailand is an agro-industry based country; however, the irrigation area is nowadays just only 4.8 million hectares or about 20% of the total agricultural areas. This is one of the constraints to the development of productivity and competitiveness of the Thai agriculture industry because the production is very dependent on rainfall. This is also one of the reasons that rice yields have been lower than in other rice-producing countries. Apart from the expansion of irrigated areas, the irrigation efficiency should also be improved by reducing efficiency loss of water conveyance, setting the water distribution schedule appropriate to the crop growing, etc.

4.6.3 Agricultural zoning by integrating the water stress index

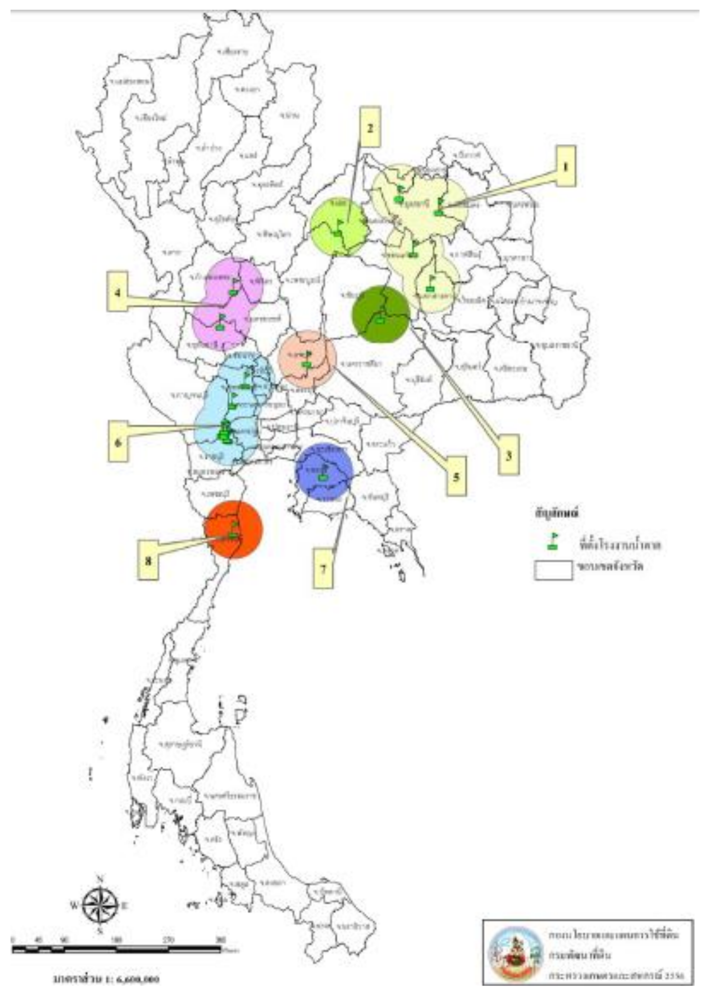
The agricultural zoning system is gaining attraction by the policy makers. The crop zoning policy is expected to mitigate the risks of farmers on low-productivity crop production; simultaneously, helping manage the supply of crops in the market to avoid the overproduction which in turn will bring about lower prices. The suitable agricultural zones are generally identified by using the agricultural land use data and matching it with the criteria such as (1) natural factors e.g. soil conditions, water (rainfall), sunlight, humidity data for a particular region like district and provinces and (2) crop requirement for those natural resources in order to create the land suitability level for each crop and to identify how much the current planted area of crops that are on the suitable and non-suitable land. This approach is well recognized for identification of the suitable agricultural zones for the crops for a particular region because all the natural factors essential for crop growing are accounted in the screening process. However, it does not consider the external challenges such as the actual available water in that particular region, both current situation (after accounting the water demands for other uses in the area) and future scenarios (if the land use for crops is changed according to the zoning policy as well as according to the demands for crops in the future). Water competition might occur in the future if zoning is set on areas that are currently facing water stress. The water stress index (WSI) should therefore be used as one of the criteria for further agricultural zoning. Also, the water scarcity footprint should be applied to identify the water use impact potential from rice cultivation in other regions.

Chapter 5 Land-use policy analysis for conversion of rice to sugarcane

5.1 Land-water nexus of land-use policy for agriculture

Sugarcane is nowadays a staple crop playing an important role in the Thai economy not only for sugar production but also for bioenergy production. Thailand is ranked as the 2^{nd} largest sugar exporter by exporting about 8 M.ton sugar/year. The demands for sugarcane for food (sugar) and energy (bioelectricity and bioethanol) are increasing continuously due to the increase of population as well as the policy on bioenergy promotion worldwide. The Thai Government has launched the 10-Year Alternative Energy Development Plan (AEDP) by setting a target that renewables will contribute 25% of the country's energy mix by 2021. Under the AEDP, different types of renewable energy sources are promoted, including bioenergy such as electricity from biomass and biofuels like bioethanol. Sugarcane is expected to play an important role as bioenergy feedstock for Thailand in the future because it has a high proportion of biomass especially in the form of readily fermentable sugars that can be used for biofuels.

The government currently has initiated the policy on converting upland paddy fields with low productivity to sugarcane plantation to fulfill the excess capacity of current sugar millers along with the expectation to increase farmers' income. The current target is set to about 2.1 M.rai that will be converted to sugarcane focusing on the Northeast and Central regions of Thailand. The Land Development Department (LDD) has developed the map of potential areas for substituting low productivity paddy field by sugarcane. The criteria for determining the substitution areas are as follows: (1) the current paddy field that located in the land classified as the low and non-suitable areas for rice; (2) the radius of about 50 km of 20 sugar factories that currently needs more sugarcane to fulfill their production capacity. The results found that, for short-termed target, the potential areas found are 2.3 million rais covering 3 provinces in the eastern region, 11 provinces in Northeastern region, 6 provinces in north and 13 provinces in central region as shown in **Figure 5.1**.



Province	Areas (rai)
North	**418,928**
Kamphaeng Phet	193,415
Nakhon Sawan	101,609
Phichit	70,277
Phitsanulok	312
Uthai Thani	21,622
Central	**260,287**
Kanchanaburi	73,569
Chai Nat	26,104
Nakhon Pathom	32,152
Prachuap Khiri Khan	14,608
Phra Nakhon Si Ayutthaya	276
Phetchaburi	4,663
Ratchaburi	18,411
Lop Buri	39,492
Samut Sakhon	345
Saraburi	1,042
Sing Buri	4,888
Suphan Buri	35,599
Ang Thong	9,132
Eastern	**15,629**
Chachoengsao	12,733
Chon Buri	2,794
Rayong	102
Northeastern	**1,633,526**
Kalasin	52,962
Khon Kaen	360,908
Chaiyaphum	228,117
Nakhon Ratchasima	146,329
Maha Sarakham	283,365
Roi Et	11,389
Loei	91,632
Sakon Nakhon	49,660
Nong Khai	26,418
Nong Bua Lam Phu	71,482
Udon Thani	312,264

Source: LDD (2014)

Figure 5.1 Potential areas of paddy field conversion to sugarcane

Based on the information of potential rice planted areas to convert to sugarcane as shown in Error! Reference source not found. and the amount of rainwater and irrigation water used for growing rice and sugarcane which would be different in each province, the impacts of land-use change policy on water resource availability can be evaluated. The potential impacts of LUC policy for rice field conversion to sugarcane is shown in **Table 5.1**. The assessment has been conducted into potential scenarios i.e. non-irrigated rice field conversion, irrigated land rice field conversion (with one crop basis), and irrigated land rice field conversion (with two crops basis). The results can be summarized as follows:

- If non-irrigated rice field is converted to sugarcane: there will have no affect to irrigation water resource because it doesn't used. However, the yield of major rice and sugarcane may not reach the baseline yield in calculation i.e. 814 kg rice/rai and 15 t cane/rai (due to water deficit)
- If irrigated rice field (one crop basis) is converted to sugarcane: LUC will require the additional irrigation water about 940 m^3/rai/yr (if irrigation efficiency is not improved) and 450 m^3/rai/yr (if sub surface dip is applied for sugarcane irrigation)
- If irrigated rice field (two crops basis) is converted to sugarcane: LUC will decrease the irrigation water used about 210 m^3/rai/yr (if irrigation efficiency is not improved) and 750 m^3/rai/yr (if sub surface dip is applied for sugarcane irrigation)

Table 5.1 Potential impacts of policy on land conversion from rice field to sugarcane on water resource availability

Land type	Cropping change scenarios	Theoretical CWR (m^3/rai/crop)		Total water used (m^3/rai/crop)		Effect of land on irrigation water resource
		RW	IRW	RW	IRW	
Non-irrigated area	Major rice → Sugarcane	Major rice = 1,080; Sugarcane = 1,100	Major rice = 80 Sugarcane = 590	Major rice = 1,080; Sugarcane = 1,100	Major rice = 0 Sugarcane = 0	• No affect to IRW resource because IRW is not used • Yield of major rice and sugarcane may not reach the baseline dataset i.e. 814 kg rice/rai and 15 t cane/rai (due to water deficit)
Irrigated area	Major rice → Sugarcane	Major rice = 1,080; Sugarcane = 1,100	Major rice = 80 Sugarcane = 590	Major rice = 1,080; Sugarcane = 1,100	Major rice = 160 Sugarcane = 1,100 (54% irrigation efficiency)	• LUC will require additional irrigation water 940 m^3/rai/yr (if irrigation efficiency is not improved) • LUC will require additional irrigation water 450 m^3/rai/yr (if irrigation efficiency of sugarcane is improved to

Land type	Cropping change scenarios	Theoretical CWR (m^3/rai/crop)		Total water used (m^3/rai/crop)		Effect of land on irrigation water resource
		RW	IRW	RW	IRW	
						97% by using sub surface dip)
	Major rice + Second rice →Sugarcane	Major rice = 1,080 Second rice = 380 <u>Total (rice)</u> = 1,460 Sugarcane = 1,100	Major rice = 80 Second rice = 660 <u>Total (rice)</u> = 740 Sugarcane = 590	Major rice = 1,080 Second rice = 380 <u>Total (rice)</u> = 1,460 Sugarcane = 1,100	Major rice = 160 Second rice = 1,150 <u>Total (rice)</u> = 1,310 Sugarcane = 1,100 (54% irrigation efficiency)	● LUC will decrease irrigation water use 210 m^3/rai/yr (if irrigation efficiency is not improved) ● Reduce irrigation water used 750 m^3/rai/yr (if irrigation efficiency is improved to 97% by using sub surface dip)

*Cropping cycle: rice (4 months); sugarcane (9-10 months)

Table 5.2 shows the implications of LUC policy of rice field conversion to the monthly water stress index of the relevant watersheds. The results reveal that the policy on converting 2.3 million rice planted areas to sugarcane potentially reduce the water withdrawal for agriculture which in turn will affect to the reduction of the water stress index of the relevant watersheds i.e. Mun, Chao Phraya, Bang Pakong, Tha Chin, Mae Klong, Sakae Krang, etc. The WSI of June – September would be reduced. The amounts of agricultural water required during June to September decreases around 62, 221, 144, and 122 million m^3, respectively. It can be concluded that the policy on converting 2.1 M.rai low-productivity rice field to sugarcane in the Northeast and Central regions of Thailand will help reduce the amount of water requirement for agriculture in those regions.

Although the changes of WSI results between two LUC scenarios is not significant in view of the whole watershed, for example, WSI of Chao Phraya watershed can be reduced just about 1% (during June – September); however, if looking at the volumetric water saving, it would totally be reduced around 549 million m3. This amount of water resource can be further used for the other crops, which in turn will increase economic benefits of other farmers. Hence, WSI can be used the reference indicator for policy decision making that the new policy on agricultural promotion in any particular region shall not exceed the critical WSI of each watershed. In principle, the recommended WSI baseline should not more than 0.5 which equivalent to WTA of about 0.4 of each particular region/watershed.

Table 5.2 WSI of June-September

Watershed	WSI				LUC policy			
	JUN	JUL	AUG	SEP	JUN	JUL	AUG	SEP
Ping	0.021	0.027	0.022	0.022	0.021	0.027	0.022	0.022
Yom	0.099	0.165	0.104	0.073	0.098	0.162	0.103	0.072
Nan	0.044	0.059	0.048	0.049	0.044	0.058	0.048	0.049
Khong	0.099	0.091	0.070	0.084	0.098	0.089	0.069	0.083
Chi	0.208	0.344	0.183	0.197	0.202	0.319	0.175	0.190
Mun	0.367	0.359	0.342	0.255	0.366	0.354	0.339	0.253
Chao Phraya	0.520	0.898	0.864	0.282	0.516	0.893	0.860	0.279
Sakae Krang	0.134	0.428	0.698	0.333	0.132	0.413	0.688	0.327
Pasak	0.063	0.210	0.144	0.129	0.063	0.207	0.143	0.128
Tha Chin	0.419	0.757	0.824	0.281	0.415	0.747	0.818	0.277
Mae Klong	0.022	0.024	0.026	0.023	0.022	0.024	0.025	0.023
Phetchaburi	0.042	0.075	0.096	0.031	0.042	0.074	0.095	0.031
West Coast Gulf	0.132	0.170	0.125	0.040	0.131	0.167	0.123	0.039
Prachin Buri	0.063	0.053	0.060	0.039	0.063	0.053	0.060	0.039
Bang Pakong	0.227	0.506	0.674	0.158	0.227	0.504	0.673	0.158
East-Coast Gulf	0.024	0.020	0.026	0.020	0.024	0.020	0.026	0.020
Peninsula-East coast	0.129	0.089	0.154	0.087	0.129	0.089	0.154	0.087

5.2 Improvement of irrigation water use for sugarcane

To enhance the sustainable land-use conversion from rice to sugarcane as above, the efficiency of irrigation water use should also be further promoted by the government. The sugarcane growing period can vary between 9-12 months with harvest. Plant crop is normally followed by 2 to 3 ratoon crops. For freshwater used, the adequate available moisture throughout the growing period is important for obtaining maximum yields because cane growth is directly proportional to the water transpired. Depending on climate, water requirements of sugarcane are around 1500-2500 mm evenly distributed over the growing season. **Table 5.3** shows the average theoretical water requirement and actual freshwater used for sugarcane cultivation under irrigation system (furrow) in Chao Praya watershed. The results show that based on the sugarcane yield of about 15 ton cane/rai, the rainwater and irrigation water used are about 1100 and 1100 m3/rai/yr, respectively. The over irrigation water supplied to sugarcane field about 510 m^3 as compared to the theoretical irrigation water requirement obtained from crop evapotranspiration which sugarcane will require only 590 m^3/rai/yr is due to the irrigation efficiency. The assessment shows that the irrigation efficiency of furrow system is about 54%. Nevertheless, the irrigation water used can be reduced by using the higher irrigation system such as big gun sprinkler, boom irrigator and sub-surface drip.

Table 5.3 Water requirements and water used for sugarcane cultivation in Chaophraya watershed

	Yield (ton/rai)	**Theoretical CWR (m^3/rai/yr)**		**Total water used (m^3/t cane)**		**IRW deficit (-)/over (+)**
		RW	**IRW**	**RW**	**IRW**	
Chao Phraya watershed	15	1100	590	1100	1100	(+) 510 m^3/rai/yr Irrigation efficiency (furrow) = 55%

RW: Rainwater; IRW: Irrigation water

Based on the theoretical irrigation water requirement of about 590 m^3/rai/yr as indicated in Table 5.3, Table 5.4 shows the potential reduction of irrigation water used if the existing irrigation system like the furrow has been changed to others in order to achieve 15 tons cane/rai. The amount of irrigation water that can be saved is estimated to be around 310, 410 and 490 m^3/rai/year for big gun sprinkler, boom irrigator and sub-surface drop, respectively.

Table 5.4 Comparative irrigation water used for different irrigation technics for sugarcane plantation

Irrigation system	Irrigation efficiency (%)*	IRW requirement for supply (m^3/rai/yr)	Potential reduction of irrigation water used after replacing the existing irrigation system by "sub surface drip system" (m^3/rai/yr)
Furrow	55	1100	-
Big gun sprinkler	75	790	310
Boom irrigator, Centre pivot	85	690	410
Sub surface drip	97	610	490

*Source: OCSB (2014)

Chapter 6 Conclusion

Sustainable food and biofuels development is essential to many of the emerging economies. However, biofuel promotion creates a unique linkage between food, water, land and energy. The rapid increase and widespread use of biomass for biofuels production are facing the challenge of resource scarcity. The magnitude of impact will vary significantly across regions and countries depending on the size of the biofuel targets adopted, the key technologies, biomass feedstocks identified and especially the water availability and scarcity level of that particular region of biofuel promotion. Sugarcane is nowadays playing and important role in the Thai economy not only for sugar production but also for biofuel and bioenergy production. Promotion of sugarcane cultivation for satisfying the increasing demands for biofuels has raised concerns on land-water competition with other food crops e.g. rice. This project researcher therefore presents the Land-Water-Food-Fuel-Climate nexus challenges of rice and sugarcane production in Thailand. The life-cycle based indicators including water scarcity footprint, carbon footprint, and land footprint or ecological footprint have been used as the integrated tool for nexus assessment in the study. The conclusions from the assessment are as follows:

The assessment revealed that the combined use of the carbon, water scarcity and ecological footprints can give a more comprehensive picture of the Land-Water-Energy nexus of agriculture. As for the case of sugarcane in Thailand, the different sugarcane cultivation systems in the Chao Phraya and Chi watersheds have been assessed using those three footprints. The study revealed that freshwater resources are the vital factor for improving sugarcane productivity. The irrigation system can help spur the yield of sugarcane as compared to the non-irrigated system by around 23% (Chaiyaphum) - 54% (Nakhon Sawan). Although the use of irrigation system will increase the consumption of energy i.e. diesel, which in turn also induces additional GHG emissions per hectare, however, accounting for the yields improvement due to irrigation, the carbon and ecological footprints of sugarcane are decreased by around 11-36% and 15-35%, respectively. The promotion of an efficient irrigation system is therefore an important factor to drive sustainable sugarcane production in the future because it helps improve the land, water and climate performance. The subsurface drip irrigation which has higher efficiency than existing furrow irrigation should be promoted as it would save the irrigation water by about 2,860 m^3/ha for the case of Nakhon Sawan and 4,380 m^3/ha for the case of Chaiyaphum. For policy makers, the water stress index which is derived from the ratio of water demand and water availability in each region should be further taken into account as one of the criteria to identify the suitable areas for future sugarcane expansion. Stakeholder engagement is required for the formulation of land-water-energy nexus management for agriculture in the future especially for the water resource management. The economic performance should further be integrated in the nexus assessment in order to identify and address the trade-off between costs of investment, environmental burdens and the economic benefits from yield improvement.

For the case of rice cultivation in Thailand, the study integrated the volumetric freshwater use, water stress index and water scarcity footprint as a tool for enhancing sustainable rice cultivation in Thailand in view of water sustainability. The major and second rice cultivation systems in the central region (Chao Phraya and Tha Chin watersheds) and the northeastern region (Mun and Chi watersheds) have been investigated and assessed. The results revealed that a wide range of freshwater used among the watersheds i.e. 0.9 – 3.0 m^3/kg of major rice and 0.9-2.3 m^3/kg of second rice. The variability of water used stems from the factors such as rice productivity, cultivation practices of farmers, irrigation water availability, etc. Although the total water used shows high water consumption of rice grown in the northeastern regions like Mun and Chi watersheds. However, based on the results of the water scarcity footprint, the second rice cultivation in the central region like Chao Phraya and Tha Chin watersheds should be focused by the policymakers to identify measures for improving efficiency of irrigation water use. This is because of the higher water scarcity footprint values obtained from second rice cultivation in both watersheds. Hence, the water scarcity footprint approach can be useful for identifying the water risks of irrigation water use in view of water deprivation potential instead of focusing only the total amount of water used. To enhance the water use efficiency for rice cultivation, the alternate wetting and drying (AWD) was found to be a promising approach to substitute the pre-germinated seed broadcasting system which is the common practice for second rice cultivation in the central region of Thailand. From this practice change, the irrigation water requirement for rice would be reduced by around 570 m^3/hectare or around 17% irrigation reduction. Further recommendations for policy makers in order to improve the water use efficiency of rice and the use of water stress index and water scarcity assessment as the tool for agricultural zoning policy have been discussed.

The study also shows the implications of LUC policy of rice field conversion to the monthly water stress index of the relevant watersheds. The results reveal that the policy on converting 2.3 million rice planted areas to sugarcane potentially reduce the water withdrawal for agriculture which in turn will affect to the reduction of the water stress index of the relevant watersheds i.e. Mun, Chao Phraya, Bang Pakong, Tha Chin, Mae Klong, Sakae Krang, etc. The WSI of June – September would be reduced. The amounts of agricultural water required during June to September decreases around 62, 221, 144, and 122 million m^3, respectively. It can be concluded that the policy on converting 2.1 M.rai low-productivity rice field to sugarcane in the Northeast and Central regions of Thailand will help reduce the amount of water requirement for agriculture in those regions. Nevertheless, the enhancing irrigation water use efficiency of the agricultural sectors are essential and necessary for improving land-water-energy-climate nexus of Thai agricultural system.

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Appendix A: Poster Presentation

Land-Water-Energy Nexus of Sugarcane Production in Thailand

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Objectives

This study aims to assess the land-water-energy nexus of different sugarcane production systems by trade-off between the impacts on land, water use, and GHG emissions due to different farming practices

Methodology

- Inventory data have been collected primarily from 30 sugarcane growers in Nakhon Sawan and Chaiyaphum

Indicator	Description	References
Carbon footprint	The total GHG emissions from the entire the life cycle of sugarcane cultivation (kg CO_2eq/t cane) $GHG_{Total} = GHG_{ec} + GHG_{field} + GHG_{td}$	IPCC (2016)
Water scarcity footprint	The amount of water deficiency to downstream human users and ecosystems. A low water scarcity footprint indicates lower impacts on water consumed ($m^3 H_2O$eq.) $\text{Water Scarcity Footprint}_{sugarcane,region\ i} = \text{Irrigation water use}_{sugarcane,region\ i} \times WSI_i$	Gheewala et al. (2014)
Ecological footprint	The sum of time integrated direct occupation (EF_{direct} and indirect land occupation (m^2a) related to CO_2 emissions from fossil energy use (EF_{CO2}) $EF = EF_{direct} + EF_{CO2}$	Frischknecht et al. (2007)

Map index	Watersheds	WSI
(1)	Salawin	0.017
(2)	Kok	0.018
(3)	Ping	0.023
(4)	Wang	0.021
(5)	Yom	0.044
(6)	Nan	0.016
(7)	Khong	0.014
(8)	Chi	0.471
(9)	Mun	0.927
(10)	Chao Phraya	0.339
(11)	Sakae Krang	0.031
(12)	Pasak	0.060
(13)	Thachin	0.287
(14)	Mae Klong	0.018
(15)	Petchaburi	0.022
(16)	West Coast Gulf	0.168
(17)	Prachin Buri	0.016
(18)	Bang Pakong	0.026
(19)	Thole Sap	0.019
(20)	East-Coast Gulf	0.016
(21)	Peninsula-East coast	0.067
(22)	Tapi	0.060
(23)	Thale sap Songkhla	0.014
(24)	Pattani	0.026
(25)	Peninsula-West coast	0.012

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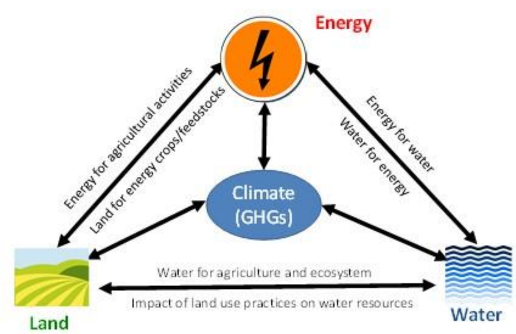
Land-Water-Energy-Climate Nexus in Agriculture



Footprint assessment results

Indicators	Nakhon Sawan (Chao Phraya)		Chaiyaphum (Chi)	
	Irrigated	Non-irrigated	Irrigated	Non-irrigated
Sugarcane (t cane/ha)	111	72	86	70
Water scarcity footprint ($m^3 H_2O$ eq/t cane)	11	5	21	5
Carbon footprint (kg CO_2eq/t cane)	30	47	32	36
Ecological footprint (m^2a/t cane)	242	377	301	353

WF hotspots: Irrigation water 57%, agrochemicals 19% and Urea 11%

EF hotspots: Agricultural land use 82%, Diesel use 7% and Urea 4%

CF hotspots: Cane trash burning 33%, Diesel use 21% and Urea 14%

Land-Water-Energy Nexus Management

- An appropriate irrigation system is the key linkage to the improvement on land, water, energy and GHG performance of sugarcane
- Irrigation increases water use and GHG emissions, but if tradeoff with the yields improvement, the net GHGs, Water scarcity footprint and EF of sugarcane would be decreased.
- For policy makers, water stress index which is derived from the ratio of water demand and water availability in each region should be further taken into account as the criteria to identify the suitable areas for agriculture

Appendix B: Manuscript

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Land-water-energy nexus of sugarcane production in Thailand

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ABSTRACT

Agriculture is a key economic sector for developing countries confronting challenges on the over-exploitation of land and water resources for food and biofuels crop production. Sugarcane is recognized as a promising crop serving both food and bioenergy needs that are being promoted leading to expansion of the plantation areas. The study assesses the land-water-energy nexus of irrigated and non-irrigated sugarcane production systems in the Chao Phraya and Chi watersheds of Thailand using carbon footprint, ecological footprint, and water scarcity footprint. The results indicate that freshwater resource is essential to sugarcane productivity improvement. Irrigation helps increase the sugarcane yields around 23–54% as compared to the non-irrigated system; the carbon and ecological footprint of sugarcane products are also consequently decreased by around 11–36% and 15–35%, respectively. Nevertheless, the water scarcity potential would be increased. Hence, the efficient irrigation technology like drip irrigation is an important factor to drive sustainable sugarcane production in the future. Land-water-energy nexus management measures for improving sustainability of sugarcane production are also recommended.

1. Introduction

Agriculture is known as the key economic sector for developing countries vis-à-vis their socio-economic development; human well-being and economic prosperity of people rely heavily on the development of agro-industry supply chains. The rapid development nowadays raises the demands for food, feed and fuels, and brings about increased concerns on the competition between land, water and energy resources as well as consequences on greenhouse gases (GHG) emissions. The demands for freshwater, land, and energy for food have been projected to increase significantly in the next decades due to population growth, urbanization and economic development (Hoff, 2011). Water crises have become one of the top five key global risks over the past five years (2011–2016) as reported by the World Economic Forum (WEF, 2017). Meanwhile, agriculture is the most freshwater consumptive sector accounting for around 85% of global freshwater consumption (Hoekstra and Chapagain, 2007). To meet the global demands for food in 2050, food production needs to be increased by about 60% (FAO, 2011). This has raised concerns on water scarcity caused by the over-exploitation of water for food and biofuels along with climate change effects (Zhang et al., 2013; Gheewala et al., 2014, 2017). In view of the impact from climate change, food production accounted for 19–29% of the global anthropogenic GHG emissions, 80% of which was from agriculture (Vermeulen et al., 2012). The promotion of biofuels to substitute fossil fuels will induce more requirements for land and water resources which in turn will compete with food production systems (Popp et al., 2014). In addition, increasing crop production either by intensification of agriculture or by expansion of land can lead to increase in GHG emissions (Tilman et al., 2002; Searchinger, 2010). The volatility of water and food prices are also anticipated due to the increased production of bioenergy (World Bank, 2008; Peri et al., 2017). All these issues indicate that the interrelationships of land, water, energy and crop production systems need to be understood by the decision makers to formulate appropriate policy measures for enhancing the efficient use of these resources (Flammini et al., 2014; Rasul and Sharma, 2016). However, to formulate the appropriate policy measures especially for agriculture, it is necessary to investigate specifically for each region by considering the local context such as geographical and climate conditions, irrigation infrastructure, local freshwater resource availability as well as farming practices.

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0959-6526/

Sugarcane is a major crop grown in the tropical and subtropical regions and is nowadays recognized as an outstanding crop serving for both food and bioenergy production because of its high proportion of biomass in both solid and liquid forms. It was estimated that around 1.8 billion tonnes of sugarcane biomass were produced from more than 100 countries around the world in 2012 (Souza et al., 2015). Brazil is the world's largest sugarcane producing country with around 736 Mt/y contributing about 39% of the global sugarcane production, followed by India (19%), China (6%) and Thailand (6%), respectively. With a total sugarcane production of about 94 Mt/y and sugar export of about 6.5 Mt in 2016, Thailand has become the world's second largest sugar-exporting country (OAE, 2016). The sugarcane plantation areas have on average increased about 3% per year from year 2005–2015 with about 1.65 M ha in 2016 (OAE, 2016). Currently, bioethanol production in Thailand is about 3.2 ML/day with around 59% from sugarcane molasses along with 3% directly from sugarcane juice. However, the Alternative Energy Development Plan 2015 (AEDP) of the government has set the goal for bioethanol production in the country to be about 11.3 ML/day in the year 2036 (DEDE, 2015). This has brought about the requirement for boosting productivity of sugarcane cultivation in the country to fulfill the demands for sugarcane as biofuel feedstock.

The expansion of sugarcane plantation areas by substituting the low-productivity paddy fields has also been introduced as an option to increase farmers' income, reduce water consumption and to fulfill the excess capacity of the existing sugar mills. Nevertheless, from the nexus point of view as mentioned earlier, the expansion of sugarcane cultivation in different regions can bring about a difference in the scale of impacts on land, water and GHG emissions depending on factors such as soil condition, rainfall, water stress situation, agricultural practices and productivity. There have been several carbon and water footprint studies of sugarcane cultivation carried out in Thailand in the last few years (Pongpat et al., 2017; Gheewala et al., 2014; Yuttitham et al., 2011); however, most of the studies were single-issue based thus not capturing the trade-off among the impacts on land, water, energy and GHG emissions. Moreover, the scarcity situation of resources such as freshwater in the sugarcane cultivation areas was not taken in account in the studies so far. This study therefore aims to assess the land-water-energy nexus of different sugarcane production systems in two regions of Thailand where the expansion of sugarcane is being promoted. The local water scarcity index of different regions where the sugarcane is grown is specifically considered. The trade-off between the impacts on land, water use, and GHG emissions due to different farming practices are determined using a set of indicators including carbon footprint, ecological footprint, water consumption and water scarcity footprint in order to provide the recommendations for improving the sugarcane production system.

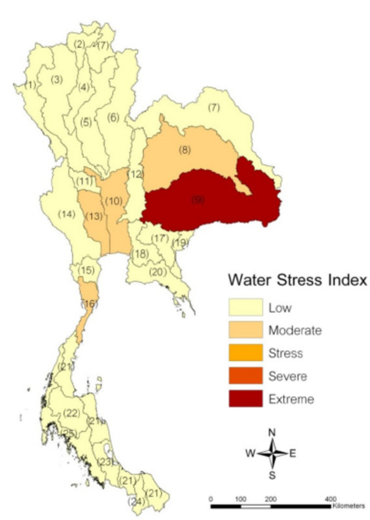
2. Materials and methods

2.1. System boundary of the assessed sugarcane cultivation systems

Thailand is located in the South Eastern region of Asia; the country's climate is mainly tropical i.e. exhibiting hot and humid conditions throughout the year, where sugarcane can be grown well. The studied areas are the sugarcane cultivation systems in two provinces i.e. Nakhon Sawan and Chaiyaphum representing the Chao Phraya and Chi watersheds, respectively. The Chao Phraya watershed mainly covers the central and some parts in northern Thailand. The total area of the Chao Phraya watershed is 20,266 km^2 covering 11 provinces including Nakhon Sawan, Chai Nat, Sing Buri, Lop Buri, Ang Thong, Ayutthaya, Saraburi, Pathum Thani, Nonthaburi, Samut Prakan and Bangkok. The average annual rainfall of this watershed is approximately 1140 mm with around 3786 million m^3 accounted for as the average annual runoff. Around 60% of the cultivated area in the Chao Phraya watershed is irrigated. On the other hand, the Chi watershed is located in north eastern Thailand, and is a part of the Mekong river basin. The total area of the Chi watershed is 49,130 km^2 covering 12 provinces including Khon Kaen, Chaiyaphum, Kalasin, Maha Sarakham, Roi Et, Yasothon, Ubon Ratchathani, Nakhon Ratchasima, Loei, Nong Bua Lam Phu, Udon Thani and Si Sa Ket. The average annual rainfall in this watershed is approximately 1208 mm with around 11,160 million m^3 accounted for as the average annual runoff. It was found that only 12% of the cultivated areas in Chi are under irrigation. Those two regions were selected as the studied areas for comparison because the infrastructure like irrigation systems, water resource availability, water stress situation, agricultural practices and socio-economic of farmers are different. Fig. 1 shows the water stress index (WSI) for the 25 major river basins of Thailand. The WSIs were estimated using the Annual Water Withdrawal to Annual Water Availability ratio. The results indicated that currently the Chi watershed has more water stress than the Chao Phraya watershed as indicated by the WSI values of about 0.471 and 0.339, respectively (Gheewala et al., 2014).

Sugarcane is newly planted once and then harvested repeatedly after 12 months of growth for 3–4 years. Fig. 2 shows the system boundary of sugarcane cultivation systems which can be classified into four main stages i.e. land preparation, planting, treatment and irrigation, and harvesting. The reference unit for the footprint assessments of sugarcane is set as a tonne of sugarcane product. Land preparation includes the step of ploughing by riper, two or three times of disk ploughing and disk harrowing. For provinces like Nakhon Sawan in the Chao Phraya watershed, the land is generally prepared and the sugarcane planted in November to December and harvested in December to January of the following year. Water is normally required since the beginning of planting using irrigation system such as furrow irrigation. However, for the northeastern region, like in the Chi watershed, planting is in the rainy season for which land clearing starts in April and harvesting is around January to March of the following year.

Planting, nowadays mostly mechanized, is carried out by billet planters. Chemical fertilizers and agrochemicals such as herbicides and insecticides are used in varying amounts depending on



Watersheds	WSI
(1) Salawin	0.017
(2) Kok	0.018
(3) Ping	0.023
(4) Wang	0.021
(5) Yom	0.044
(6) Nan	0.015
(7) Khong	0.014
(8) Chi	0.471
(9) Mun	0.927
(10) Chao Phraya	0.339
(11) Sakae Krang	0.031
(12) Pasak	0.050
(13) Tha Chin	0.287
(14) Mae Klong	0.018
(15) Phetchaburi	0.022
(16) West Coast Gulf	0.158
(17) PrachinBuri	0.016
(18) Bang Pakong	0.026
(19) Thole Sap	0.019
(20) East-Coast Gulf	0.015
(21) Peninsula-East coast	0.067
(22) Tapi	0.060
(23) Thale sap Songkhla	0.014
(24) Pattani	0.025
(25) Peninsula-West coast	0.012

Fig. 1. Water stress index classified by 25 watersheds of Thailand (Gheewala et al., 2014).

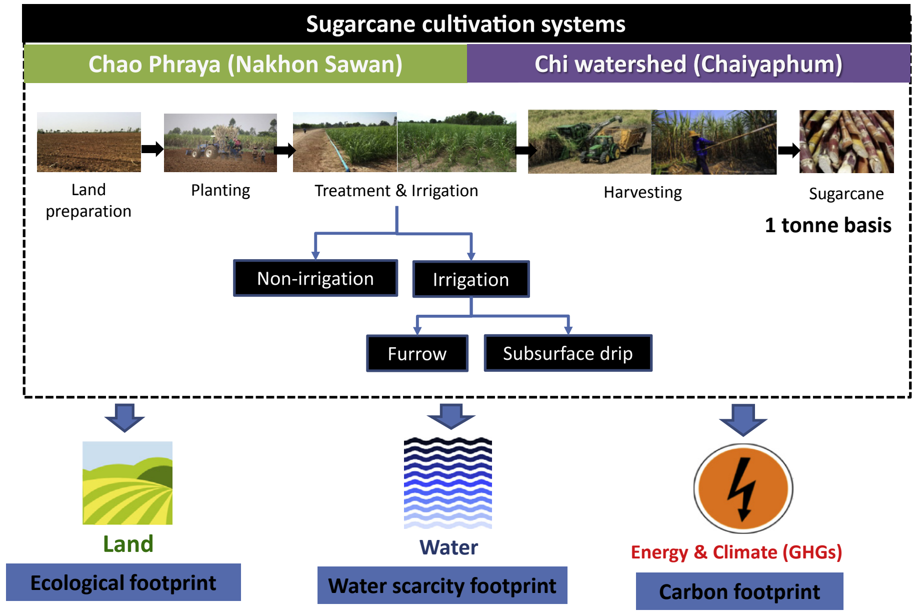


Fig. 2. System boundary of nexus assessment.

farmers' practices. The most common irrigation system used is furrow irrigation. Harvesting begins 10–14 months after planting. However, mechanized harvesting is currently gaining attention by farmers as well as the sugar millers due to the lack of farm workers. Nevertheless, manual harvesting along with cane trash burning before harvesting is still the common practice sharing about 70% of total harvested sugarcane going into the mills.

2.2. Nexus assessment approaches

The Water-Energy-Food nexus assessment approach has been proposed as the way to enhance efficiency and balance the different uses of the ecosystem resources like land, water and energy by various stakeholders in a particular region (Flammini et al., 2014; Azapagic, 2015; Sanders and Masri, 2016; Smajgl et al., 2016). The benefits of the nexus approach are to improve resource use efficiency along with economic efficiency and livelihood options (Bazilian et al., 2011). There is a variety of approaches to assess the WEF nexus e.g. life cycle based-approached like water footprint as well as the full life cycle assessment (LCA) (Vanham, 2016; Scholz et al., 2015; Jeswani et al., 2015; Brancoli et al., 2017), simulation and optimization (Garcia and You, 2016), and numerical modeling/econometrics/economic modeling (Jalilov et al., 2016; Pacetti et al., 2015). Nevertheless, there are still gaps in applying nexus assessment for policy recommendations because the results from a study in one location may not be able to be used for policy recommendations in another location since the arable land and freshwater resources are limited by geographical conditions.

Nowadays, the life-cycle based evaluation approaches for single environmental issues such as carbon footprint, water footprint and ecological footprint have gain attention worldwide (Finkbeiner et al., 2010). Each footprint indicator generally has its own focus and way of interpretation. Hence, to assess the nexus on land, water, energy and GHGs that occurs from anthropogenic activities such as agriculture, it is necessary to understand the scope of the each footprint and how its indicator links to the resources used and GHG emissions. For example, somehow, an indicator like ecological footprint can be used to explain the land-energy-climate change nexus from the agricultural activities because the indicator will account both land occupation for crop growing and the carbon dioxide emissions from fossil energy used for machines. However, this inclusion of carbon dioxide emission in ecological footprint may not be enough to capture some important impacts on climate change from agricultural activities such as the non-CO_2 GHG emissions like N_2O caused by fertilizers application, and CH_4 from burning of agricultural biomass e.g. cane trash burning. Those non-CO_2 GHG emissions will be completely taken into account only when performing the carbon footprint. Moreover, the water scarcity impact from agriculture, which is an important issue for agriculture, will not be explained unless the water scarcity footprint is also conducted. Hence, to understand the land-water-energy nexus of agriculture for the better management of land, water and energy used in the future, those three footprints need to be considered together in the nexus assessment even though there is some overlap between them. This section therefore aims to determine the impacts of agriculture on each footprint indicator by classifying into the key resources of interest for agriculture i.e. land use, water use, agrochemicals use, and energy use.

In this study, the life cycle approach has been used to account the total direct and indirect effects of sugarcane production systems on land, water and climate change in the terms of "Footprint" indicators. The footprint assessment will help quantification of the environmental burdens including greenhouse gas emissions, biologically productive land use and freshwater consumption caused by different sugarcane production systems in Thailand. Fig. 3 shows the simplified land-water-energy-climate nexus in agriculture.

2.2.1. Ecological footprint

The ecological footprint (EF) is a measure of the area of biologically productive land and water that is required for an individual or an activity to produce all the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management practices (Wackernagel and Rees, 1997). However, in the concept of LCA, the ecological footprint of a product is defined as the sum of time-integrated direct land occupation and indirect land occupation for capturing CO_2 emissions from fossil energy use and cement burning (Huijbregts et al., 2008). In this study, the ecological footprint of sugarcane cultivation is scoped as

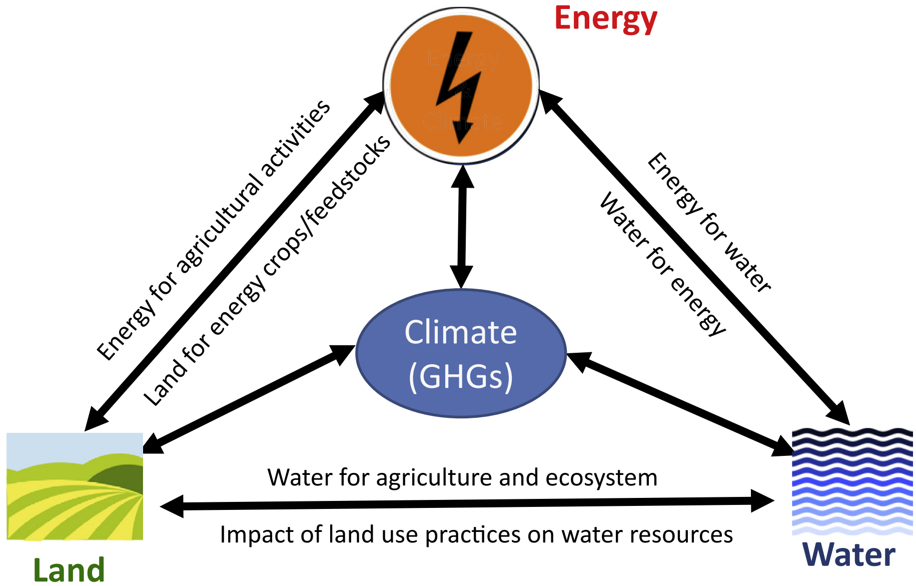


Fig. 3. Simplified land-water-energy-climate nexus in agriculture.

the sum of direct land occupation (EF_{direct}) and indirect land occupation (m^2a) related to CO_2 emissions from fossil energy use (EF_{CO2}) (Frischknecht et al., 2007) as shown in Equation (1).

$$EF = EF_{direct} + EF_{CO2} \tag{1}$$

For interpretation, the study classified the ecological footprint result into two categories i.e. direct ecological footprint which refers to the direct land occupation for sugarcane cultivation, and the indirect ecological footprint which refers to the indirect land occupation for the production of material used during sugarcane cultivation and indirect land occupation for capturing atmospheric CO_2 emissions from fossil fuel combustion.

2.2.2. Water scarcity footprint

Water footprint is a metric that quantifies the potential environmental impacts related to water as defined by the International Organization for Standardization (ISO) in ISO 14046. In this study, the direct water use for sugarcane cultivations in the Chao Phraya and Chi watersheds is accounted by separating into rainwater and irrigation water. Since the water scarcity impact from water use will be different depending upon not only the amount of water consumed but also the water stress level in the area where the water was extracted, the water scarcity footprint has therefore been applied in the study. The water scarcity footprints of sugarcane cultivation in the two different regions can be evaluated based on the "water stress index (WSI)" of the 25 watersheds of Thailand (Gheewala et al., 2014) as indicated in Equation (2). The water scarcity footprint is measured in terms of "m^3 H_2Oeq". This water scarcity footprint value implies the amount of water deficiency to downstream human users and ecosystems. A low water scarcity footprint indicates lower impacts on water consumed (Pfister et al., 2009). The study classified the water scarcity footprint result into two categories i.e. direct water scarcity footprint which refers to the water scarcity impact potentially caused by the direct irrigation water use during sugarcane cultivation; meanwhile, the indirect water scarcity footprint refers to the water scarcity impact potentially caused by the water use from raw materials production. The water scarcity indicator for raw materials used characterization factors from Pfister et al. (2009) in SimaPro 8 software.

$$\text{Water Scarcity Footprint}_{\text{sugarcane,region i}} = \text{Irrigation water use}_{\text{sugarcane,region i}} \times \text{WSI}_{\text{region i}} \tag{2}$$

Prior to determining the water scarcity footprint, firstly, the crop water use (WU_c) is determined using Equations (3) and (4). Crop water use, denoted as crop evapotranspiration (ET_c), refers to the volume of water lost via evapotranspiration including evaporative water from soil and crop surfaces and transpired water from crop to atmosphere. Equation (3) shows the general formula to estimate ET_c [mm/day] which consists of two terms i.e. weather and crop specifics for crop cultivated in different locations (Allen et al., 1998). K_c represents crop coefficient [dimensionless], and ET_0 represents the reference Penman-Monteith crop evapotranspiration [mm/day]. The ET_0 for each province and the crop coefficient (K_c) of sugarcane have been taken from the Irrigation Water Management Division (IWM), Royal Irrigation Department of Thailand (IWM, 2008, 2011). Equation (4) shows the formula to calculate the crop water use. The factor 10 is used to convert water depth in millimeters into water volume per land surface in m^3/ha. The summation will be done over the period from the day of planting (day 1) to the day of harvest (lgp stands for length of sugarcane growing period in days).

$$ET_c = K_c \times ET_0 \tag{3}$$

$$WU_c = 10 \times \sum_{d=1}^{lgp} ET_c \left(m^3/ha\right) \tag{4}$$

The procedure to classify the crop water use into rainwater and irrigation water is as follows: (a) calculating the (ET_c) for sugarcane grown in each region; (b) calculating the effective rainfall in each region during the sugarcane growing period; (c) the rainwater use for sugarcane can be evaluated by comparing the monthly evapotranspiration (ET_c) of sugarcane with the effective rainfall during the growing period. Then, if ET_c > effective rainfall, the rainwater used by sugarcane will be equal to the effective rainfall and then the "irrigation water requirement" in order to achieve the crop evapotranspiration of sugarcane can be estimated from "irrigation water requirement" = ET_c - effective rainfall. However, if ET_c < effective rainfall, "irrigation water requirement" = 0. The study has also compared the amount of irrigation water requirement with the actual irrigation water used by farmers obtained from the field data.

2.2.3. Carbon footprint

Carbon footprint is an indicator showing the total amount of GHG emissions over the entire life cycle of a product or service and expressed in terms of "kg CO_2eq". The GHGs considered include both CO_2 and non-CO_2 gases. The characterization factors for converting one gram of N_2O and CH_4 emissions into CO_2eq are 298 g and 25 g of CO_2, respectively (IPCC, 2006). The general formula for determining the total GHG emissions of sugarcane cultivation is shown as Equation (5).

$$GHG_{Total} = GHG_{ec} + GHG_{field} + GHG_{td} \quad (5)$$

Where GHG_{Total} represents the total GHG emissions from the entire the life cycle of sugarcane cultivation (kg CO_2eq/t cane); GHG_{ec} represents the GHG emissions from the production of input materials including fertilizers and agrochemicals; GHG_{field} represents the GHG emissions occurring during the cultivation activities e.g. N_2O emissions from applied fertilizers and GHG emissions from combustion of fuels in agricultural machinery; GHG_{td} represents the GHG emissions caused by the transportation of raw materials used and transportation during the field operations.

2.3. Data sources

Primary data for sugarcane cultivation in the irrigated and non-irrigated areas are collected from sugarcane growers located in the Nakhon Sawan (Chao Phraya watershed) and Chaiyaphum (Chi watershed) provinces. The reference unit of the assessment is a tonne of sugarcane at farm gate. Primary data for sugarcane cultivation are collected from 30 sugarcane growers in two provinces i.e. Nakhon Sawan (covering planted areas around 350 ha) and Chaiyaphum (covering planted areas around 140 ha). There are two types of irrigation systems compared in the study i.e. furrow irrigation and subsurface drip irrigation. Fuel used for both irrigation systems is estimated based on 5.5 hp pump which is generally used by the sugarcane growers. The water pumping specification used in the assessment is about 1100 L/min and diesel consumption 2 L/hour. Table 1 shows the key input-output materials for the surveyed sugarcane plantations. The life cycle inventory (LCI) for the production of input fertilizers, agrochemicals, and fuels used are referred from the Thai national LCI database (MTEC, 2014) and the international life cycle inventory databases such as Ecoinvent (Ecoinvent, 2012).

The difference in the data of non-irrigated system in Chao Phraya and Chi such as the amount of organic fertilizer used and fuel consumption is due to the different farming practices. Sugarcane growers in the Chi watershed (northeastern region of Thailand) generally have low household incomes; thus, manure is highly relied on as a fertilizer. In addition, the farming practice is mainly manual for both planting and harvesting. On the other hand, sugarcane growers in the Chao Phraya watershed (central region) generally apply more chemical fertilizers as they have higher household incomes. In addition, there is more use of machinery for both sugarcane planting and harvesting due to lack of labor in the central region unlike in the northeastern region.

3. Results and discussion

3.1. Comparison of footprint indicators

Table 2 shows the water scarcity footprint, carbon footprint and ecological footprint results per tonne of sugarcane under irrigated and non-irrigated cultivation conditions in Nakhon Sawan (Chao Phraya watershed) and Chaiyaphum (Chi watershed). The results reveal that the irrigation system can help spur the yield of sugarcane as compared to the non-irrigated system by around 23% (Chaiyaphum) - 54% (Nakhon Sawan). One of the reasons that causes the irrigated sugarcane cultivation in Nakhon Sawan to have a higher yield improvement than Chaiyaphum is because the actual irrigation supplied by farmers in Nakhon Sawan is estimated to be

Table 1
Weighted average of input-output of the studied sugarcane cultivation systems.

	Inventory	Unit	Nakhon Sawan (Chao Phraya)		Chaiyaphum (Chi)	
			Irrigated	Non-irrigated	Irrigated	Non-irrigated
Sample sizes	Total planted areas	ha	163	184	48	90
Product	Sugarcane yields	t/ha	111	72	86	70
Land preparation	Diesel	L/ha	126	131	106	106
	Manure	kg/ha	–	23	315	1018
Planting	Diesel	L/ha	16	34	14	2
Treatment	N-fertilizer	kg/ha/y	58	102	104	57
	P-fertilizer	kg/ha/y	40	82	46	57
	K-fertilizer	kg/ha/y	26	60	85	56
	Urea	kg/ha/y	109	114	13	25
	Diesel (fertilizers & chemical applications including weed control)	L/ha/y	6 (manual & knapsack-type applicator)	3 (manual & knapsack-type applicator)	26 (mechanical application)	2 (manual & knapsack-type applicator)
	Diesel (irrigation)	L/ha/y	21 (furrow irrigation)	–	9 (subsurface drip irrigation)	–
	Agrochemicals	kg/ha/y	18	27	25	9
Harvesting	Diesel	L/ha/y	30	29	28	8
Transport	Truck 20t	t.km	4440	2880	3440	2800

Table 2
Ecological footprint, water scarcity footprint and carbon footprint of sugarcane production in different conditions.

Aspects	Indicators	Nakhon Sawan (Chao Phraya)		Chaiyaphum (Chi)	
		Irrigated	Non-irrigated	Irrigated	Non-irrigated
Crop yield	Sugarcane (t cane/ha)	111	72	86	70
Water use	Rain water (m^3/t cane)	68	105	66	81
	Irrigation water requirement (m^3/t cane)	34	52	67	82
	Actual irrigation water used (m^3/t cane)	17	–	32	–
	Water scarcity footprint (Direct) (m^3 H_2O eq/t cane)	6	–	15	–
	Water scarcity footprint (Indirect) (m^3 H_2O eq/t cane)	5	5	6	5
	Total Water scarcity footprint (m^3 H_2O eq/t cane)	11	5	21	5
Climate change	Life-cycle GHG emissions (kg CO_2eq/t cane)	30	47	32	36
Land	Ecological footprint (m^2a/t cane)	242	377	301	353
	Direct land occupation (m^2a/t cane)	197	303	256	313
	Indirect land occupation from raw materials (m^2a/t cane)	1	2	1	1
	Carbon dioxide (m^2a/t cane)	44	72	44	39

about 17 m^3/t cane which is closer to the irrigation water requirement of sugarcane i.e. 34 m^3/t cane (which was calculated from the crop evapotranspiration (ET) of sugarcane and the rainfall data in the region). Meanwhile, the actual irrigation supplied by farmers in Chaiyaphum is found to be around 32 m^3/t which still far from the irrigation water required for sugarcane growing in Chaiyaphum which is around 67 m^3/t cane. The furrow irrigation system was commonly found from the field survey in both provinces. However, nowadays, there is an increasing use of the higher efficiency irrigation systems such as the subsurface drip irrigation and big gun sprinkler by sugarcane growers in Thailand. This would help improve the water use efficiency for sugarcane cultivation in the future because the furrow irrigation has an irrigation efficiency of just about 55% while the subsurface drip irrigation has an efficiency of about 97% (OCSB, 2015).

The use of irrigation will increase the consumption of energy i.e. diesel, which in turn also induces additional GHG emissions per hectare. However, accounting for the yields improvement due to irrigation, the carbon footprint and ecological footprint of sugarcane product are decreased by around 11–36% and 15–35%, respectively. Nevertheless, the increased freshwater resources used for irrigation bring about an increase in the water scarcity footprint of irrigated sugarcane as also revealed by Table 2. The direct water scarcity footprint results of irrigated sugarcane in Nakhon Sawan and Chaiyaphum are about 6 and 15 m^3 H_2Oeq/t cane, respectively.

3.2. Environmental hotspots of sugarcane cultivations in view of footprint indicators

Table 3 shows the key hotspots on biological productive land use, water scarcity, energy use and GHG consequences that can be identified from the different footprints using the case of irrigated sugarcane cultivation in Nakhon Sawan province. For water scarcity footprint, the results show that direct irrigation water use is the main contributor to the impact on water scarcity potential accounting for about 57% of the total water scarcity footprint, followed by the indirect water scarcity footprint from agrochemicals and urea production which contributed about 19% and 11%, respectively. For ecological footprint, the results reveal that the direct arable land use for sugarcane cultivation contributes about 82% of the total ecological footprint, followed by the indirect impact from diesel fuel and urea fertilizer production which shared about 7% and 4%, respectively. The energy use in agricultural machines such as diesel is one of the key hotspots on the GHG emissions i.e. sharing about 21% of the total carbon footprint. However, the highest GHG emissions for sugarcane cultivation are from cane trash burning during sugarcane harvesting which is still the common practice for the small sugarcane growers in Thailand i.e. around 70% of total cane production in Thailand was found to be the burnt cane (OCSB, 2015). The N_2O emissions caused by the N-fertilizer application to the soil is also accounted in the carbon footprint and is one of the key contributors to the carbon footprint of sugarcane.

Table 3
Environmental hotspots of irrigated sugarcane cultivation in Nakhon Sawan province classified by water scarcity footprint, ecological footprint, and carbon footprint.

Process	Water scarcity footprint (m^3 H_2O eq./t cane)		Ecological footprint (m^2a/t cane)				Carbon footprint (kg CO_2eq/t cane)	
	Value	%[a]	Land occupation	CO_2	Total	%[a]	Value	%[a]
Direct agricultural land use	–	–	197	–	197	82%	–	–
Direct irrigation water use	6	57%	–	–	–	–	0.6	2%
Cane trash burning	–	–	–	–	–	–	10	33%
N_2O from N-fertilizer applied	–	–	–	–	–	–	3	11%
Diesel (excluding irrigation)	0.2	2%	0.0	16	16	7%	5.4	19%
Urea	1	11%	0.1	11	11	4%	4	14%
N fertilizer	0.5	5%	0.1	2	3	1%	1	3%
P fertilizer	0.5	4%	0.3	1	2	1%	0.6	2%
K fertilizer	0.1	1%	0.0	0.3	0.4	0%	0.1	0%
Agrochemicals	2	19%	0.1	5	5	2%	2	6%
Transport	–	–	–	8	8	3%	3	10%
Total footprint	**11**		**198**	**44**	**242**		**30**	

[a] % represents the contribution percentage of that process to the total footprint results.

3.3. Land-water-energy nexus management

The next step after the land-water-energy nexus assessment by footprint indicators is the nexus management which should be analyzed. As mentioned earlier, although there is a partial overlap between water scarcity footprint, ecological footprint and carbon footprint, none of these indicators alone can be used to explain the land-water-energy nexus of agriculture. The results revealed that the land-water-energy impacts directly come from the sugarcane cultivation stage i.e. land occupation and irrigation water use for sugarcane production. The indirect land-water-energy impacts caused by the materials and agrochemicals production as well as transportation are much lower than the sugarcane cultivation stage. To improve the efficiency of land use, water and energy during cultivation, treatment and harvesting of sugarcane should therefore be focused. The nexus management can be proposed as follows:

(1) The nexus assessment shows that the key linkage to the improvement on land, water, energy and GHG emissions performance of sugarcane cultivation is the promotion of an appropriate irrigation system. Freshwater resource is the vital factor for the crop's productivity improvement. However, in reality, the freshwater resource management for agriculture is a challenge for both the farmers and policy makers because the resource is limited to a certain area and period. The water management plan of the Royal Irrigation Department (RID) has reported that for agriculture in dry season, of the total sugarcane planted areas of about 68,670 ha in Chaiyaphum and 96,896 ha in Nakhon Sawan provinces, only 1% and 4% are under irrigation (RID, 2014). Expanding irrigation infrastructure entails a high cost for the government meanwhile, installing irrigation technology in the farm is a high cost to the sugarcane growers. Additionally, the freshwater resource has to be shared by many stakeholders in the region; therefore, the water user groups need to be set up and engaged for making a water management plan. This is quite a contrast to the land which generally the farmers will have their rights to use and manage; as well as the energy that farmers have their purchasing power for potentially unlimited use. However, nowadays, there is an increase in contract farming which would be helpful in terms of soft loans from sugar millers to their contract farmers for investing in irrigation systems as well as the mechanized farming system.

(2) The water use is found to be the key factor in land-water-energy nexus management of sugarcane. This is because, firstly, water is one of the key factors to improve the yield of sugarcane. The ecological footprint in view of direct land occupation could be reduced significantly for the case of irrigated sugarcane due to the higher yields as compared to non-irrigated case. At the same time, the additional energy use for irrigation is found to not significantly increase GHG emissions i.e. only around 2% of total carbon footprint of sugarcane as presented in Table 3. The challenge is only the irrigation infrastructure development for supporting sugarcane growers as well as the management of the remaining water availability in that area.

(3) High efficiency water irrigation system such as drip irrigation which is known to be the most precise and efficient to deliver water and nutrients to crops should be encouraged for sugarcane farmers. This is especially for the sugarcane planted areas located in the high water stress areas like in Chao Phraya, Chi and Mun watersheds of Thailand as revealed by Fig. 1. The furrow irrigation system which so far has been the common system used for irrigated sugarcane cultivation, has an irrigation efficiency of only about 55% (OCSB, 2015). Meanwhile, other irrigation systems like the big gun sprinkler, center pivot and subsurface drip irrigation have efficiencies of around 75%, 85% and 95%, respectively (OCSB, 2015). The irrigation water requirement for sugarcane cultivation in Nakhon Sawan and Chaiyaphum were estimated to be around 3736 m^3/ha and 5722 m^3/ha, respectively. To achieve the water requirement of sugarcane, using drip irrigation to substitute furrow irrigation will reduce the irrigation water use by about 2860 m^3/ha for the case of Nakhon Sawan province and 4380 m^3/ha for the case of Chaiyaphum province. Apart from the water use reduction, the diesel use for irrigation would be decreased which in turn leads to the reduction in carbon footprint. For example, the water scarcity footprint and carbon footprint of sugarcane for the case of Nakhon Sawan would be decreased from 11 to 9 m^3 H_2O eq/t cane and 30 to 29 kg CO_2eq/t cane, respectively if subsurface drip irrigation were used to substitute furrow irrigation.

(4) For agricultural zoning policy, so far, the land suitability is used as well as the rainfall; these are considered as the key criteria for identifying crops appropriate to each agricultural zone. However, due to climate change as well as the increased concerns on freshwater resource availability, the water stress index derived from the ratio of water demand and water availability in each region should be further taken into account for identifying areas to promote sugarcane. This is because the irrigation water must be one of the key factors for modern farming of sugarcane in the future, considering only the rainfall availability but not considering the existing or future demands on water in the region will affect water competition in the long run.

4. Conclusions

The combined use of the carbon, water scarcity and ecological footprints can give a more comprehensive picture of the land-water-energy nexus of agriculture. The different sugarcane cultivation systems in the Chao Phraya and Chi watersheds have been assessed using those three footprints. The study revealed that freshwater resources are the vital factor for improving sugarcane productivity. The irrigation system can help spur the yield of sugarcane as compared to the non-irrigated system by around 23% (Chaiyaphum) - 54% (Nakhon Sawan). Although the use of irrigation system will increase the consumption of energy i.e. diesel, which in turn also induces additional GHG emissions per hectare, however, accounting for the yields improvement due to irrigation, the carbon and ecological footprints of sugarcane are decreased by around 11–36% and 15–35%, respectively. The promotion of an efficient irrigation system is therefore an important factor to drive sustainable sugarcane production in the future because it helps improve the land, water and climate performance. The subsurface drip irrigation which has higher efficiency than existing furrow irrigation should be promoted as it would save the irrigation water by about 2860 m^3/ha for the case of Nakhon Sawan and 4380 m^3/ha for the case of Chaiyaphum. For policy makers, the water stress index which is derived from the ratio of water demand and water availability in each region should be further taken into account as one of the criteria to identify the suitable areas for future sugarcane expansion. Stakeholder engagement is required for the formulation of land-water-energy nexus management for agriculture in the future especially for the water resource management. The economic performance should further be integrated in the nexus assessment in order to identify and address the trade-off between costs of investment, environmental burdens and the economic benefits from yield improvement.

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Implications of Water Use and Water Scarcity Footprint for Sustainable Rice Cultivation

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Abstract: Rice cultivation is a vital economic sector of many countries in Asia, including Thailand, with the well-being of people relying significantly on selling rice commodities. Water-intensive rice cultivation is facing the challenge of water scarcity. The study assessed the volumetric freshwater use and water scarcity footprint of the major and second rice cultivation systems in the Chao Phraya, Tha Chin, Mun, and Chi watersheds of Thailand. The results revealed that a wide range of freshwater use, i.e., 0.9–3.0 m^3/kg of major rice and 0.9–2.3 m^3/kg of second rice, and a high water use of rice was found among the watersheds in the northeastern region, like the Mun and Chi watersheds. However, the water scarcity footprint results showed that the second rice cultivation in watersheds, like in Chao Phraya and Tha Chin in the central region, need to be focused for improving the irrigation water use efficiency. The alternate wetting and drying (AWD) method was found to be a promising approach for substituting the pre-germinated seed broadcasting system to enhance the water use efficiency of second rice cultivation in the central region. Recommendations vis-à-vis the use of the water stress index as a tool for agricultural zoning policy were also discussed.

Keywords: rice; water; water scarcity footprint; AWD system; sustainability; Thailand

1. Introduction

Rice (paddy) is the staple food crop feeding more than half the global population, accounting for about 19% of the world's dietary energy supply [1]. Especially for Asian countries like China, India, Indonesia, Bangladesh, Vietnam, as well as Thailand, rice cultivation is recognized as a vital economic sector vis-à-vis their socio-economic development. It is estimated that food production needs to be increased by around 60% to meet the global demands for food in 2050 [2]. Freshwater demands for food production have been projected to increase significantly in the coming decades due to population growth, urbanization, and economic development [3]. Meanwhile, agriculture is the most land- and freshwater-consuming sector, accounting around 37.5% of the global land area [4] and 85% of the global freshwater consumption [5]. The water crises nowadays are prioritized as one of the top five global risks [6]. In addition, several countries have promoted biofuels as one of the measures to boost the livelihood of farmers in rural areas along with improving the national gross domestic product (GDP). The rapid expansion of crops production leads to concerns on food and fuels competition, particularly on water scarcity caused by the overexploitation of water for food and biofuel crops [7–10].

The concern is not limited to the water competition between food and fuels but also among other water users in the water basins. Hence, the improvement of water use efficiency and productivity, as well as appropriate water and land and resources management are essential for the sustainability of agricultural production [11].

Water footprint is recognized as a tool for evaluating the relationship between agricultural production, water resources, and environmental impacts in order to enhance water use efficiency, sustainability of water use within the watersheds, mitigating the impact of water use and improving water resource management [12–15]. The same term "water footprint" is used by two approaches, i.e., Water Footprint Network and life cycle assessment (LCA), although their definitions in the two approaches are different [16,17]. The two approaches can provide different views of useful information to support the policy decision for enhancing water resource management as well as for water impacts mitigation to avoid the water risks [8,18]. The volumetric quantification of water use for agricultural products in water footprint assessment of the Water Footprint Network approach provides useful information in terms of water use efficiency and water productivity by considering the freshwater consumption over the production chain of crops. Meanwhile, the water footprint assessment based on the LCA approach will combine the volumetric freshwater consumption with the water stress index of the region where the water is extracted in order to determine the impact of freshwater consumption in view of water deprivation potential [19,20].

The water footprint of rice has so far been conducted by focusing on the volumetric water consumption of rice cultivation in various countries as the virtual water footprint [21–23]. The results revealed that although the water footprint of rice in Asia is high, the contribution to water scarcity is relatively low because the rice is generally grown in the wet season (rainfed paddy field) and rainwater is the major water source. However, the environmental impact due to the irrigation water use in rice production should be specifically analyzed based on the location and timing of the water use [21]. This is consistent with the concept of water scarcity footprint in which the potential environmental impact of water use is assessed considering the water stress situation of each location and also the time [24,25]. There is still a lack in assessing the potential impact of rice cultivation in terms of water scarcity footprint, especially for the case where rice cultivation systems are shifted due to limited water resources. This study aims to integrate water footprint based on the LCA approach as a tool for providing recommendations to support the policy makers on promoting sustainable rice cultivation in view of water efficiency and water scarcity footprint reduction. The water scarcity footprint of different rice cultivation systems of Thailand have been investigated. The studied areas covers the four key watersheds of rice cultivation in Thailand, including Mun, Chi, Chao Phraya, and Tha Chin.

2. Materials and Methods

2.1. Rice (Paddy) Production in Thailand and the Studied Areas

Thailand is located in the tropical region where a variety of crops, fruits, and plants are grown. Of the country's total land area of about 51.3 million hectares, 46% is agricultural land, followed by forest land at 32%, and other lands at 22% [26]. For the agricultural land, rice fields occupy the highest at around 11.2 Mha or 47% of the total, followed by perennial crops and fruit orchards, cropland, vegetables and flowers, and others at about 23%, 21%, 1% and 8%, respectively. This has led Thailand to be the 6th largest rice producer and one of the world's leading countries for rice exports. In 2015, Thailand produced around 30 Mt and exported around 10 Mt of rice [26]. Rice is grown nationwide but the capacity of rice cultivation in each region is different, depending on the availability of water. In general, rice cultivation in Thailand can be classified into two crops depending on the period of plantation. The first crop, or "major rice", is grown in the rainy season (between May and October), while the second crop, or "second rice", is grown in the dry season (between November and April) using water from irrigation. The main region of paddy plantation in Thailand is the northeast, contributing around 51% of the total planted areas [26]. The northeastern region dominates in terms of the largest major rice production (rainfed paddy fields). However, the central region is outstanding in terms of the irrigated paddy fields and the ability to cultivate two crops a year. Table 1 summarizes the rice planted areas, production, and yields in Thailand from a geographical perspective.

Table 1. Rice productions and yields in Thailand classified by regions (Year 2015).

Watershed	Plantation Areas (ha)			Rice Production (Tonne)			Yields (t/ha)		
	Major Rice	Second Rice	Total	Major Rice	Second Rice	Total	Major Rice	Second Rice	Total
North	2,042,903	594,660	2,637,563	6,801,718	2,339,551	9,141,269	3.33	3.93	3.47
Northeast	5,790,946	188,870	5,979,815	12,230,973	606,677	12,837,650	2.11	3.21	2.15
Central	1,321,831	523,134	1,844,965	4,904,410	2,244,669	7,149,079	3.71	4.29	3.87
South	134,476	47,058	181,534	374,438	156,018	530,456	2.78	3.32	2.92
Total country	9,290,156	822,030	10,112,186	24,311,539	5,346,915	29,658,454	2.62	6.50	2.93

From a hydrological perspective, Thailand can be divided into 25 major watersheds, as shown in Figure 1. The hydrological boundary is essential for policy makers to use for water resource management. The study highlights the four key watersheds, i.e., Chao Phraya, Tha Chin, Mun, and Chi, in the water use and water scarcity footprint assessment of rice (paddy) production in Thailand. This is because the Chao Phraya and Tha Chin watersheds represent the central region with the irrigated cultivation system where both major and second rice can be grown. Meanwhile, Mun and Chi are located in the northeastern region where major rice is widely grown under the rainfed cultivation system.

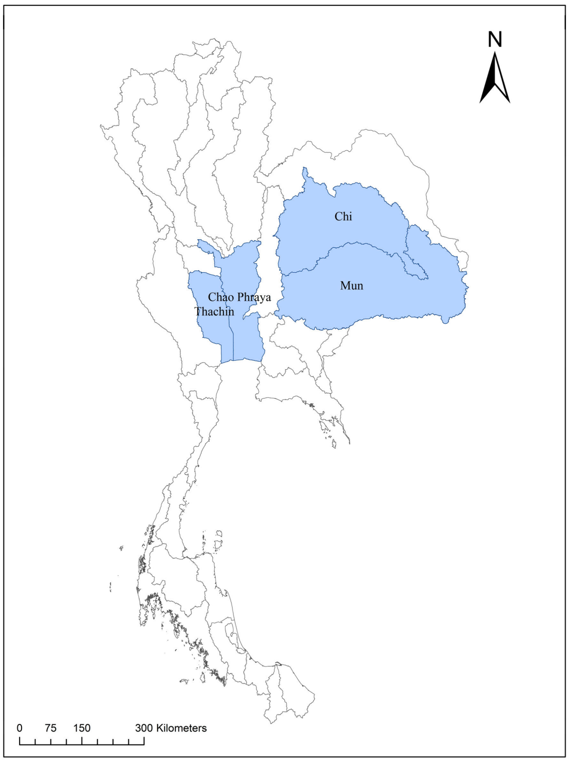

Figure 1. Mun, Chi, Chao Phraya, and Tha Chin watersheds of Thailand.

2.2. Rice Cultivation Systems

Rice cultivation in Thailand uses mainly the wet system, i.e., rice fields are prepared and the soil is kept saturated. There are three major types of rice cultivation found in the studied areas viz. (1) transplanting, (2) dry ungerminated seed broadcasting, and (3) pre-germinated seed broadcasting. Transplanting is a traditional technique for growing rice, done by transplanting seedlings that are firstly grown in nurseries. This method requires less seeds and is easy for controlling weeds, but is labor intensive and the crop takes longer to mature [1]. Dry ungerminated seed broadcasting, or so called "dry direct seeding", is a technique for rainfed ecosystems, where farmers will sow the ungerminated seeds onto the dry soil surface and then incorporate them either by ploughing or by harrowing. Pre-germinated seed broadcasting, or so called "wet direct seeding", is a technique commonly used for irrigated areas, i.e., seed is normally pre-germinated prior to broadcasting onto the recently drained, well-puddled seedbeds or into pre-standing water in the fields [1]. Figure 2 shows the simplified rice cultivation system and water use covering soil preparation, sowing, cultivation, and harvesting to get the rice grain product.

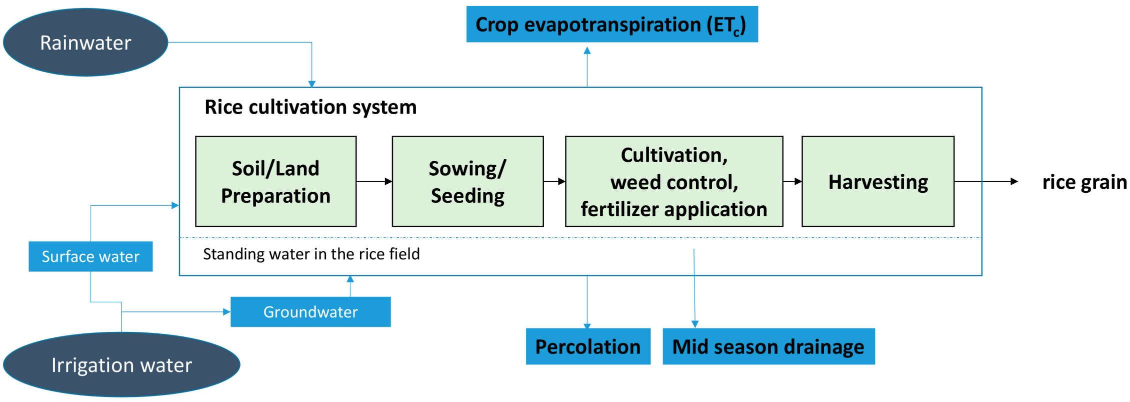

Figure 2. Rice cultivation system and water use.

Figure 3 shows the cropping calendar of rice which is referred to as the baseline for estimating crop water requirement (CWR). The dry season of Thailand runs from November through April (shaded in the figure). The geographical location of Chao Phraya and Tha Chin watersheds is in the central region where the rainfall occurs in mid-May to mid-August due to the southwest monsoon and another with northwest monsoon in mid-October to the end of November. Therefore, more than one crop of rice is generally grown if the farmers have enough water supply for land preparation. It was found that in the Ayuthaya, Nakhon Pathom, and Pathum Thani provinces, the farmers are able to grow rice twice a year. However, in case of the northeastern region (i.e., Mun and Chi watersheds), the rainy season generally comes a bit later than the central region, so the farmers generally start to prepare their rice fields in mid-July and then start sowing in mid-August in order to use the rainwater. Nowadays, the non-irrigated rice fields have been promoted by the Department of Agriculture to cultivate mung bean or other beans in order to improve soil quality.

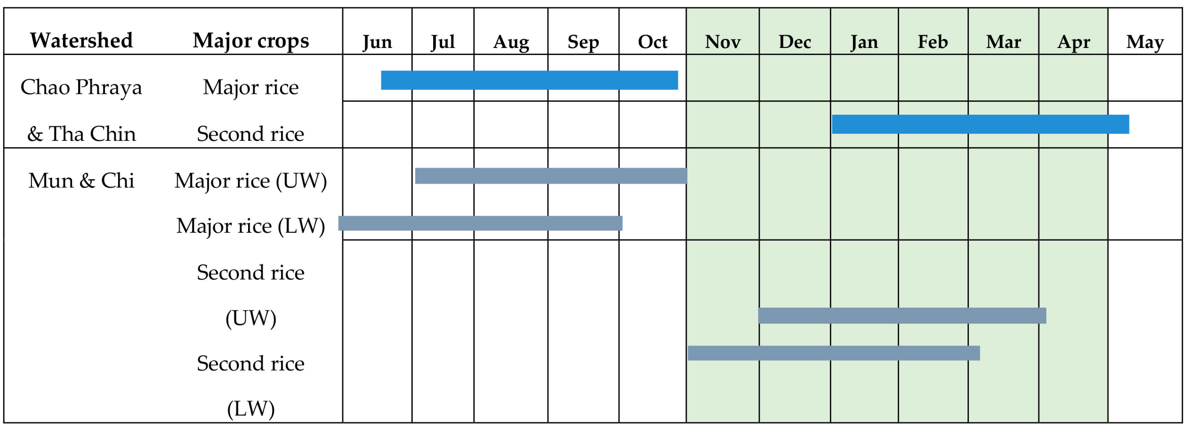

Figure 3. Cropping calendar for rice cultivation. Note: UW: Upper watershed; LW: Lower watershed.

Data on rice cultivation collected from farmers and local government authorities in 15 provinces covering the Mun, Chi, Chao Phraya, and Tha Chin watersheds are shown in Table 2. Selection of representative areas was done based on plantation area and management practices. Thus, the samples are identified by the provincial agricultural officers to represent various practices of farmers in the studied provinces. About 1257 local farmers were surveyed via questionnaires. The planted areas of rice in the Tha Chin and Chao Phraya watersheds are generally with lowland paddy rice for which the farmers are able to use irrigation water. Meanwhile, the cultivated areas in the Mun and Chi watersheds mostly rely on rainwater. In Chao Phraya and Tha Chin, the cultivation system of the surveyed samples for both major and second rice is pre-germinated seed broadcasting. However, in the Mun watershed, the cultivation systems for major rice consist of dry ungerminated seed broadcasting (50%), pre-germinated seed broadcasting (30%), and the transplanting method (20%); and the cultivation system for second rice is mainly dry ungerminated seed broadcasting. In the Chi watershed, the cultivation systems for major rice consist of dry ungerminated seed broadcasting (40%), pre-germinated seed broadcasting (27%), and the transplanting method (33%); and the cultivation system for second rice is mainly the pre-germinated seed broadcasting.

Table 2. Data sources.

Watershed	Provinces	Data Collection Area (Hectare)	
		Major Rice	Second Rice
Chao Phraya	Pathum Thani, Ayutthaya, Nakhon Sawan, Chai Nat, Lop Buri	3443	2607
Tha Chin	Suphan Buri, Kanchanaburi, Nakhon Pathom	322	297
Mun	Ubon Ratchathani ,Nakhon Ratchasima, Buri Ram	1020	362
Chi	Nakhon Ratchasima, Chaiyaphum, Kalasin, Khon Kaen	828	245

2.3. Crop Water Requirement Assessment

Crop water requirement (CWR) refers to the volume of water lost via the evapotranspiration process including evaporative water from soil and crop surfaces and transpired water from crops to the atmosphere. CWR is denoted as crop evapotranspiration (ET_c). The water use of rice is estimated based on the crop evapotranspiration calculation complemented with the rainfed and/or irrigated conditions of the planted areas as well as irrigation practices of farmers. Data on farming practices, irrigation techniques and efficiency are primarily collected, compiled, and aggregated from farmers. The general formula (Equation (1)) used for estimating CWR is expressed as follows [27,28].

$$ET_c = K_c \times ET_0 \quad (1)$$

where ET represents the crop evapotranspiration i.e., the amount of water evapotranspired by the crops in a specific climate regime and adequate soil water is maintained by rainfall, irrigation, or both; K_C represents the crop coefficient of Penman–Monteith; and ET_0 represents the reference crop evapotranspiration of Penman–Monteith [27]. Accordingly, the CWR of rice (major and second) can be estimated. The reference crop evapotranspiration (ET_0), crop coefficients, and monthly average rainfall data for different provinces of Thailand are referred from [29–31]. The calculated ET_0 by province and K_C values of rice are provided by the Royal Irrigation Department (RID). RID have measured ET_C of rice via both direct measurements performed at their irrigated water management experiment stations and indirect calculation-applied provincial climate data. Using Equation (1) for estimating ET_C of rice is also recommended by RID, as it will serve as a quick assessment and be valid for rice cultivation in the studied provinces. However, other factors influencing CWR, such as rice varieties and soil characteristics, should be considered for a more comprehensive assessment. The crop evapotranspiration (ET_C) and the effective rainfall are calculated for the given set of data on ET_0, monthly rainfall, K_C, and the crop calendar. Effective rainfall is the amount of rainfall actually used by the crops.

In general, rice cultivation begins with the land preparation by puddling. This is done by saturating the soil layer for one month prior to sowing. The volume of water that is necessary for saturated soil is about 200 mm [32]. For the lowland rice cultivation, standing water is required for weed control. The wet system has a constant percolation and seepage loss during this period. Since the percolation loss is primarily a function of soil texture, the study refers to the percolation loss factor based on RID, which is about 1 mm/day for the central region and 1.5 mm/day for the other regions of Thailand [33]. A water layer is assumed to be established during transplanting or sowing and maintained throughout the growing season, but the level of water can differ depending on the farmers' practices. This standing water is assumed to be used for the entire period of rice cultivation, except for the last 15 days when the field will be dried out to facilitate harvesting. The total freshwater demand for rice cultivation is therefore calculated from the summation of ET_C, standing water, and percolation for each time step.

To classify the crop water use into rainwater and irrigation water, if rice is grown in non-irrigated areas, the water used for growing rice is supposed to be equal to the amount of effective rainfall. If CWR is higher than effective rainfall, water withdrawal for rice in non-irrigated areas is equivalent to the amount of effective rainfall. On the other hand, if effective rainfall is higher than CWR, water withdrawal for rice in non-irrigated areas is equivalent to the amount of CWR. Water required for cultivating crops in irrigated areas is expected to meet the total amount of CWR. Thus, the sum of effective rainfall and irrigation water is accounted as the total water withdrawal for crops cultivated in irrigated areas. This irrigation water is the additional amount of water required to reach the total CWR. In general, to calculate the amount of irrigation water requirement for irrigated agriculture, irrigation efficiency and water loss through percolation are taken into account as expressed by Equation (2) [33]. Even though the irrigation efficiency at 0.65 (for surface irrigation) is suggested by the specialist from RID using a rule of thumb approach, this factor depends also on geographical conditions.

$$\text{Irrigation water} = \frac{(\text{crop water use} - \text{effective rainfall}) + \text{water loss (percolation)} \times 100}{\text{Irrigation efficiency}^{*}} \quad (2)$$

Remark: * Irrigation efficiency = 0.65 [derived from the efficiency of water conveyance (0.9) × efficiency of irrigation system (0.9) × efficiency of irrigation (0.8)].

2.4. Water Scarcity Footprint Assessment

The environmental impact of water use depends on not only the amount of water consumed but also the water stress situation of the area where the water was extracted. The water deprivation potential, or called as "water scarcity footprint", is therefore proposed as the proxy indicator to determine and compare the potential impact of water use in view of the amount of water deficiency to downstream human users and ecosystems [14,19]. A low water scarcity footprint indicates lower impacts on water consumed. Equation (3) shows the general formula for water scarcity footprint assessment. The water scarcity footprint is calculated based on the "monthly water stress index (WSI)" of the 25 watersheds of Thailand [10]. The monthly WSI is derived from the ratio of monthly total water withdrawals to hydrological availability of a watershed. This index does not account for water pollution which is captured by other indicators such as eutrophication, acidification, toxicity, etc. The temporal aspects of the monthly WSI for the 25 watersheds were evaluated based on the seasonal and monthly variations of water consumption in agriculture for each watershed due to different cropping systems and cycles [10]. Table 3 shows the monthly WSI of the Mun, Chi, Chao Phraya, and Tha Chin watersheds.

$$\text{Water scarcity footprint}_{\text{rice,i}} = \text{Irrigation water use}_{\text{rice,i}} \times \text{WSI}_{\text{i}} \quad (3)$$

where, irrigation water $\text{use}_{\text{rice,i}}$ represents the amount of irrigation water use for rice cultivation in the watershed i; WSI_{i} represents the water stress index of watershed (i). The water scarcity footprint is measured in terms of "m^3 H_2Oeq". Actually, only the actual amount of irrigation water consumption for rice should be used for calculating the water scarcity footprint. The standing water in a rice field that can percolate and recharge surface water and ground water should not be considered as a loss for the catchment area [34]. However, the volumetric irrigation water used for rice cultivation is referred to in the study because its timing of use will contribute to the local water availability in the region. Policy makers have also considered the amount of standing water as well as water percolation loss in their irrigation water allocation plan for rice cultivation.

Table 3. Monthly water stress index (WSI) of the four selected watersheds [10].

	Monthly WSI (Dimensionless)											
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Chao Phraya	1.00	1.00	0.99	0.08	0.04	0.52	0.90	0.86	0.28	0.05	0.35	0.98
Tha Chin	1.00	1.00	0.94	0.04	0.03	0.42	0.76	0.82	0.28	0.04	0.06	0.69
Mun	0.08	0.07	0.02	0.02	0.02	0.37	0.36	0.34	0.25	0.03	0.01	0.04
Chi	0.10	0.07	0.03	0.02	0.02	0.21	0.34	0.18	0.20	0.03	0.02	0.03

3. Results and Discussion

3.1. Water Use for Rice Cultivation in Different Watersheds

Table 4 shows the comparison of freshwater use for major and second rice cultivation in the Chao Phraya, Tha Chin, Mun, and Chi watersheds. For major rice, the results revealed that the total freshwater used per unit area for rice cultivation in those four watersheds is not different, i.e., ranging between 6800 and 7500 m^3/ha. Rainwater is the main water source for major rice cultivation, sharing around 75% of total freshwater used. Irrigation water is used only when the rainwater is not sufficient to meet the CWR. However, per kilogram of rice product, the results showed a significant difference between major rice grown in the central region (Chao Phraya and Tha Chin) and the northeastern region (Mun and Chi), i.e., about 0.9–1.4 m^3/kg and 2.2–3.0 m^3/kg of rice, respectively. This is due to the differences in rice yields of each region. Rice yield depends on a number of factors, such as the crop variety, soil quality, fertilization, and treatment practices; however, the Mun watershed has the famous Hom Mali rice (Thai jasmine rice), whose yield is generally lower than ordinary rice.

Table 4. Water use of rice production in different watersheds.

	Parameter	Unit	Chao Phraya	Tha Chin	Mun	Chi
Major rice	Yield	kg/ha	5088 (5019–5156)	5769 (5519–6631)	2669 (2569–2769)	2994 (2919–3069)
	Total water used	m^3/ha	7275 (7026–7528)	5596 (5077–7493)	7499 (6653–8389)	6796 (6421–7181)
		m^3/kg	1.43 (1.4–1.46)	0.97 (0.92–1.13)	2.81 (2.59–3.03)	2.27 (2.2–2.34)
	Rain water used	m^3/ha	5495 (5270–5723)	4096 (3698–5637)	5204 (4470–5981)	6317 (5983–6659)
		m^3/kg	1.08 (1.05–1.11)	0.71 (0.67–0.85)	1.95 (1.74–2.16)	2.11 (2.05–2.17)
	Irrigation water used	m^3/ha	1781 (1656–1908)	1500 (1214–2586)	2268 (1772–2796)	449 (359–552)
		m^3/kg	0.35 (0.33–0.37)	0.26 (0.22–0.39)	0.85 (0.69–1.01)	0.15 (0.12–0.18)
Second rice	Yield	kg/ha	5525 (5350–5700)	5300 (4844–6881)	3375 (3363–4688)	4088 (2813–5625)
	Total water used	m^3/ha	8453 (7918–9006)	4717 (3875–8258)	7763 (5178–11,156)	4660 (2813–8438)
		m^3/kg	1.53 (1.48–1.58)	0.89 (0.8–1.2)	2.30 (1.54–2.38)	1.14 (1.0–1.5)
	Rain water used	m^3/ha	2100 (1926–2280)	1325 (872–3303)	2363 (673–3609)	1390 (844–2250)
		m^3/kg	0.38 (0.36–0.4)	0.25 (0.18–0.48)	0.70 (0.20–0.77)	0.34 (0.30–0.40)
	Irrigation water used	m^3/ha	6354 (5939–6783)	3392 (2761–6124)	5400 (4506–7547)	3270 (1969–6750)
		m^3/kg	1.15 (1.11–1.19)	0.64 (0.57–0.89)	1.60 (1.34–1.61)	0.80 (0.7–1.2)

Contrary to the major rice, irrigation water is the major source contributing around 70–75% of total water used for second rice cultivation. The yields obtained from the second rice cultivation in Mun and Chi are increased as compared to major rice because only the irrigated rice fields can grow the second rice. Meanwhile, the major rice grown in those two regions are rainfed and might be cultivated in a deficit condition as compared to the CWR if the rainfall if not enough. However, for the central region, the yields between major and second rice do not differ much because they are generally irrigated and enough water will be supplied to the field as per the crop's requirement both for major rice and second rice cultivation. The total water used for second rice grown in Mun, Chao Phraya, Chi, and Tha Chin are about 2.30, 1.53, 1.14, and 0.89 m^3/kg rice, respectively. The amount of water used can be divided into two main purposes, i.e., (1) the water used for rice growing and (2) percolation loss and standing water. The water used for rice growing based on the crop evapotranspiration is estimated to be around 55% of the total water used; the remaining being the percolation loss. Considering the irrigation water used, which the policy makers have to manage and allocate to other users as well, the results show that the lowest irrigation water used per kilogram of rice is for the second rice grown in Tha Chin, followed by Chi, Chao Phraya, and Mun.

3.2. Water Scarcity Footprint of Rice in Different Watersheds

To compare the potential impact from the freshwater use for rice cultivation in the different watersheds, the scarcity footprint is then assessed by combining the volume of irrigation water used for rice with the water stress index of each watershed and each period of time that water is used as shown in Equation (3). The irrigation water is focused in the scarcity assessment because it is the resource that will be competed for with other water users. Table 5 shows the water scarcity footprints of major and second rice cultivation in the four studied regions. The results show that although the total water used for rice grown in Mun is the highest, i.e., 2.81 m^3/kg rice, the water scarcity footprint of major rice grown in Mun is almost equal to the Chao Phraya and Tha Chin watersheds, i.e., ranging between 0.28 and 0.31 m^3 H_2Oeq/kg rice. This implies that the water deprivation potential impact from freshwater used for major rice cultivation does not differ among the three studied watersheds. Only the rice grown in the Chi watershed has a much lower water scarcity footprint value, indicating lower potential impacts on water consumed [19]. The low water scarcity footprint of major rice cultivated in Mun and Chi is because of the lower water stress index during June to August of those two watersheds as compared to Chao Phraya and Tha Chin.

Table 5. Water scarcity footprint of rice production in different watersheds.

		Unit	Chao Phraya	Tha Chin	Mun	Chi
Major rice	Total water use	m^3/kg rice	1.43	0.97	2.81	2.27
	Water scarcity footprint	m^3 H_2Oeq/kg rice	0.31	0.28	0.29	0.04
Second rice	Total water use	m^3/kg rice	1.53	0.89	2.30	1.14
	Water scarcity footprint	m^3 H_2Oeq/kg rice	1.15	0.62	0.10	0.06

For second rice cultivation as well, the Chi watershed has to the lowest water deprivation potential, followed by the Mun, Tha Chin, and Chao Phraya watersheds. The high water scarcity footprint of second rice cultivated in Chao Phraya and Tha Chin watersheds is because, during January to March, the water stress index of both watersheds are indicated as severe. The irrigation water during those three months of dry season should therefore be considered as a scarce resource that needs to be used efficiently. In addition, the high amount of irrigation water used for second rice cultivation in the Chao Phraya watershed showed low efficiency of water use and need for further improvement. The water scarcity footprint results imply that second rice grown in Chao Phraya and Tha Chin should be focused on by the policy makers to identify measures for improving efficiency of irrigation water use. Otherwise, there will be a high risk of irrigation water competition between farmers who want to grow second rice and the other water users in those two watersheds. The obtained results of water scarcity footprint directly match the real situation in the country where there has been an increasing risk of freshwater shortage over the past two years that made farmers, especially in the central region like Chao Phraya and Tha Chin watersheds, lose production because of the lack of freshwater [35]. In case of drought, the second rice cultivation, which is recognized as water intensive, will be abandoned or delayed by the government in order to save water resources for domestic (sanitation) uses and for ecosystem preservation.

3.3. Recommendations for Enhancing Sustainable Rice Production

The results from water footprint assessment revealed that second rice cultivation in the central region of Thailand, like in the Chao Phraya and Tha Chin watersheds, will potentially face the challenge of water scarcity. To enhance sustainable rice production in those two watersheds, several measures should be encouraged or taken into account by the policy makers:

3.3.1. Improve Water Use Efficiency of Rice Cultivation

The study has compared the freshwater use for different rice cultivation systems including the traditional practices like the transplanting method, pre-germinated seed broadcasting, dry ungerminated seed broadcasting, and the alternate wetting and drying (AWD). The "AWD system", a water-saving technique for rice cultivation, is being encouraged to farmers in order to reduce irrigation water use in rice fields due to the increasing water scarcity situation, without decreasing yields. In AWD, irrigation water is applied a few days after the disappearance of the ponded water. Hence, the field is alternately flooded and non-flooded. The number of days of non-flooded soil between irrigation events can vary from 1 to more than 10 days depending on a number of factors, such as soil type, weather, and crop growth stage. To implement AWD, a "field water tube" is used to monitor the water depth on the field. Figure 4 presents the estimated water use for second rice cultivation in the irrigated rice fields in the central region (Ayutthaya province, Chao Phraya watershed). The results revealed that the transplanting method brings about the highest water use at 1.34–1.48 m^3/kg rice, followed by pre-germinated seed broadcasting (1.25–1.37 m^3/kg), dry ungerminated seed broadcasting (1.06–1.17 m^3/kg), and alternate wetting and drying (0.96–1.03 m^3/kg). The high water use for transplanting and pre-germinated broadcasting is due to the water requirement for land preparation and standing water as compared to the AWD method. Thus, the AWD method can be an option for farmers in the area. The focus of the AWD method should be for second rice cultivation because for major rice cultivation, the control of water level in the field is difficult in practice as the water source relies on rainfall.

The Office of Agricultural Economics (OAE) revealed that about 92% of the second rice planted areas in the central region of Thailand followed the pre-germinated seed broadcasting system. Hence, it is estimated that if the AWD method is applied to replace the pre-germinated seed broadcasting method for second rice cultivation in the central region, the irrigation water requirement for rice would be reduced by around 570 m^3/hectare or around 17% irrigation reduction. This estimation is based on the conservative assumption that the yield would not be affected by the difference in water delivery method, although several field experiments have indicated that the AWD would help increase the productivity of rice by around 10%. Of the total second rice planted areas in the central region of about 523,134 hectares, if 10% were changed to AWD method, the government would save around 298 million m^3 of irrigation water. However, the challenge is that the farmers must be able to control the water level in their fields appropriately, and manual weed control may be required because of less standing water in the field as compared to the traditional rice cultivation. Hence, more efforts of farmers for field management are required, which might in turn lead to the increased cost and working time spent as compared to the traditional practice.

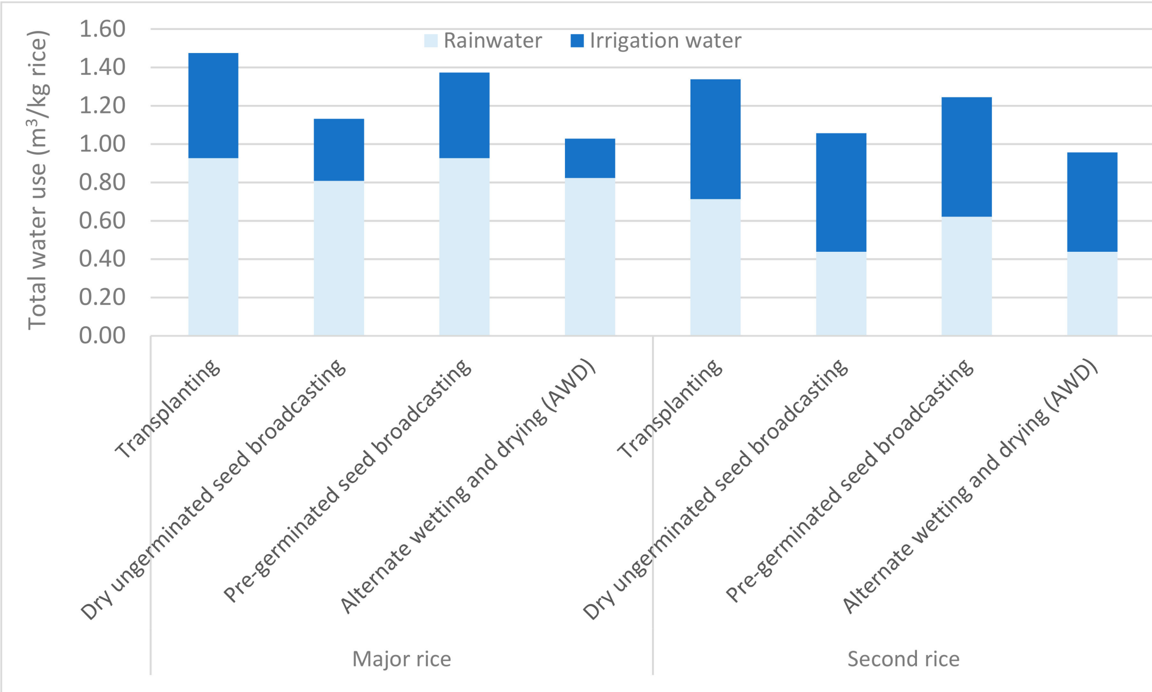

Figure 4. Water use for different rice cultivation methods in the central region of Thailand.

3.3.2. Expansion of Irrigated Areas

The assessment revealed that the irrigated rice fields bring about higher productivity than the rainfed ones. Thailand is an agro-industry-based country; however, the irrigation area is nowadays just only 4.8 million hectares or about 20% of the total agricultural areas. This is one of the constraints to the development of productivity and competitiveness of the Thai agriculture industry because the production is very dependent on rainfall. This is also one of the reasons that rice yields have been lower in Thailand than in other rice-producing countries. Apart from the expansion of irrigated areas, the irrigation efficiency should also be improved by reducing loss of water conveyance, setting the water distribution schedule appropriate to the crop growing, etc.

3.3.3. Agricultural Zoning by Integrating the Water Stress Index

The agricultural zoning system is gaining attraction by the policy makers. The crop zoning policy is expected to mitigate the risks of farmers on low-productivity crop production, simultaneously helping manage the supply of crops in the market to avoid overproduction, which in turn will bring about lower prices. The suitable agricultural zones are generally identified by using the agricultural land use data and matching it with the criteria such as (1) natural factors, e.g., soil conditions, water (rainfall), sunlight, and humidity data for a particular region like district and provinces; and (2) crop requirement for those natural resources in order to create the land suitability level for each crop and to identify how much of the current planted area of crops are on the suitable and non-suitable land. This approach is well recognized for identification of the suitable agricultural zones for the crops for a particular region because all the natural factors essential for crop growing are accounted in the screening process. However, it does not consider the external challenges such as the actual available water in that particular region, both the current situation (after accounting the water demands for other uses in the area) and future scenarios (if the land use for crops is changed according to the zoning policy as well as according to the demands for crops in the future). Water competition might occur in the future if zoning is set on areas that are currently facing water stress. The water stress index (WSI) should therefore be used as one of the criteria for future agricultural zoning. Also, the water scarcity footprint should be applied to identify the water use impact potential from rice cultivation in other regions.

Additionally, the implication of this research study is not only specific for enhancing sustainable rice cultivation in Thailand but can also extended to other rice-producing countries. This is especially for the countries in Asia where climatic modeling results show that the global temperature will rise and the flooded rice production areas are expected to shrink in the future [36]. It has been estimated that around 13 Mha of the irrigated wetland rice in Asia may confront physical water scarcity; meanwhile, around 22 Mha of the irrigated dry-season rice may suffer from economic water scarcity [37]. The potential use of research results is as follows: (1) use of the water scarcity index as well as water scarcity footprint assessment for each country for informing policy makers on rice cultivation planning, and (2) use of the alternative rice cultivation practices in the study, such as the alternate wetting and drying (AWD) method, as an option in the suitable areas.

4. Conclusions

The study integrated the volumetric freshwater use, water stress index, and water scarcity footprint as a tool for enhancing sustainable rice cultivation in Thailand in view of water sustainability. The major and second rice cultivation systems in the central region (Chao Phraya and Tha Chin watersheds) and the northeastern region (Mun and Chi watersheds) have been investigated and assessed. The results revealed that a wide range of freshwater is used among the watersheds, i.e., 0.9–3.0 m^3/kg of major rice and 0.9–2.3 m^3/kg of second rice. The variability of water used stems from factors such as rice productivity, cultivation practices of farmers, irrigation water availability, etc. The total water used shows high water consumption of rice grown in the northeastern regions, like the Mun and Chi watersheds. However, based on the results of the water scarcity footprint, the second rice cultivation in the central region, like the Chao Phraya and Tha Chin watersheds, should be focused by the policy makers to identify measures for improving the efficiency of irrigation water use. This is because of the higher water scarcity footprint values obtained from second rice cultivation in both watersheds. Hence, the water scarcity footprint approach can be useful for identifying the water risks of irrigation water use in view of water deprivation potential, instead of focusing only the total amount of water used. To enhance the water use efficiency for rice cultivation, AWD was found to be a promising approach to substitute the pre-germinated seed broadcasting system, which is the common practice for second rice cultivation in the central region of Thailand. From this practice change, the irrigation water requirement for rice would be reduced by around 570 m^3/hectare or around 17% irrigation reduction. Further recommendations for policy makers in order to improve the water use efficiency of rice and the use of water stress index and water scarcity assessment as the tool for agricultural zoning policy have also been discussed.

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