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Land suitability class and implications to Land-Water-Food Nexus: A case of rice cultivation in Thailand

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ABSTRACT

Arable land and water resource scarcity for food production to fulfill the growing demand is a global challenge. Expansion of rice cultivation in Thailand without planning increases land and water depletion especially for the low-productivity rice cultivation areas. The Thai government has an agricultural zoning policy on promoting rice cultivation using land suitability classes for efficient use of land and costs; however, there is still some rice grown on land with low suitability. The study evaluated the land suitability class implications on major and second rice cultivation in view of the Land-Water-Food Nexus performance using Chainat, a key province of rice cultivation in Thailand, as the study area. The land and water intensity indicators were calculated using a normalized approach as the Land-Water-Food Nexus Index (LWFNI). The geographic information system (GIS) tool was used to analyze land-use classification, interpolate the rainfall, and overlay the land suitability classification with the Land-Water-Food Nexus of rice. Rice cultivation on highly suitable areas has a higher LWFNI score for resource efficiency and economic value. Scenarios were considered for changing rice cultivation in marginally and unsuitable areas to alternative crops to conserve water and reduce costs. The option for alternative crops to replace the base case with major rice and mungbean scenario was the most water-saving at about 3,601 m^3/ha/year and made a profit increase of about 84,106 baht/ha. Additionally, the major rice and peanut scenario achieved the most profit increase of about 302,366 baht/ha and saved water at about 2,081 m^3/ha/year.

1. Introduction

Land, water, and energy are known as the essential resources for food production. Nowadays, there is an increasing concern about the sustainability of food production worldwide due to the security of arable land, water, and energy [1]. The growth in population suggests that food consumption will be even higher in the future. To meet the global demands in 2050, food production needs to be increased by about 50% between 2012 and 2050 [2]. Increasing demand for food globally has resulted in increased use of arable land, water, and energy [3]. Agriculture is the most freshwater consumptive sector accounting for around 70% of global freshwater consumption [4]. This has raised concerns about water scarcity caused by the overexploitation of water for food and bioenergy production which can affect food security [5,6]. Meanwhile, water shortage is becoming a serious issue across the world that can have an impact on limiting food production in many areas [7]. Poor irrigation systems and rapid urbanization have also led to water security problems [8]. Southern Africa is being severely impacted by climate change, which is affecting crop yields [9]. At the same time, Northwest and Northeast China are experiencing serious water scarcity [10]. In addition, there are the future uncertainties which lead to the increasing concern about water security such as the increasing of temperature and shifts in rainfall patterns would lead to droughts, which can cause agricultural dehydration [11]. The water-energy-food nexus has thus gained traction in the research community and policy decision-making as the strategy for understanding the interdependence of water, energy, and food systems which in turn will lead to efficient use of resources for sustainable food production [1,12]. There has been a significant amount of research on nexus assessment framework [13,14], nexus indicators development [15,16], and nexus applications such as the nexus assessment of irrigation technology adoption [17] and the nexus approach to policymaking [18,19]. The nexus approach recognizes the importance of engaging multiple stakeholders in the decision-making processes [20,21].

Several efforts have been made to explore the water-energy-food nexus for various aspects [22,23]. The nexus assessment demonstrates the importance of considering the interdependence between resources [24]. For example, the land-water-food nexus concept has been proposed to assess the trade-offs and synergies between the impacts of agri-

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cultural practices. Different interrelationships of the resource dimension have been explored in previous research that allows interactive comparison of environmental models of crops such as land-water [25,26], water-energy-food [27–29], and water-energy-land-food nexus [30,31]. Optimizing the utilization of land and water resources requires evaluating the water-land-food nexus [32,33]. Several studies indicated that the management of the nexus can solve issues of water use, land use, and agricultural productivity [34,35]. Irrigation water was revealed as a key factor for crop growth resulting in the increased efficiency of land use and reduce greenhouse gas reduction due to productivity improvement [36]. However, due to the uncertain rainfall, the potential for water shortages increases with rising food demand, decreasing agriculture productivity, and decreasing food production. In addition, for the developing countries where the small-scale farmers generally lack access to irrigation, the crop productivity therefore will generally be lower than its genetic potential. To mitigate this problem which in turn results in an economic loss to farmers, the concept of growing the right crop in the right place with the right practice is therefore gaining attention by the policy makers. The concept is aimed to maximize the benefits of fertile soil to help provide essential nutrients for plant growth and rainwater as the resources for crop production. The agricultural land zoning policy has therefore been established for enhancing use of resources in each country as well as in each region. To promote growing crops under their suitable land class can have an impact on activities with an economic impact and is therefore related to increasing income to farmers [37]. Nevertheless, the studies on nexus assessment so far still lack the exploration of soil suitability effects to land-water resources use efficiency for crop production. It is thus important to understand the implications of the agricultural land zoning policy on the land-water resource use when the crop is being grown under different land suitability classes.

This study aims to assess the implications of land suitability classes to land-water-food nexus of rice cultivation. The case study of rice is used because it is recognized as the world's key food crop. Rice is a staple food crop in the Asia-Pacific countries such as China, India, Indonesia, Bangladesh, Vietnam, Philippines, and Thailand [38]. Thailand is one of the world's largest producer and exporter of rice, ranking as the world's sixth largest rice producer and second largest rice exporter. In 2020/2021, Thailand produced about 32 million tonnes of rice, with the central region producing about 7 million tonnes [39]. However, rice cultivation is a water intensive activity as well as having high greenhouse gas (GHG) emissions due to the methane and nitrous oxide emissions from rice fields. To address the sustainable rice production, several studies have focused on assessing the water use, water footprint, and water scarcity footprint of rice to identify the measures for enhancing water use efficiency [40,41]. Although water is essential for rice cultivation, the productivity of rice also depends on a number of other factors such as soil fertility and farming practices. Thailand's 20-year national strategic plan focuses on the agricultural sector as a primary manufacturer and global exporter (2017–2036). The policy aims to keep Thailand on track to remain the world's leading rice exporter. In addition, the policy has goals explicitly concerning inequality reduction, environmental risks reduction, and resource scarcity. To support the policy, the Land Development Department (LDD), Ministry of Agriculture and Cooperatives has assessed and mapped the appropriateness of cultivating significant economic crops to suit the potential of soil, topography, climate, and water resources or so called "land suitability maps" [42]. The government is therefore trying to encourage farmers to grow crops that suit with their areas [43]. The land suitability map for rice has also been conducted and the cultivation of rice in a highly suitable area has the potential to be more cost-effective than growing rice in an unsuitable area due to differences in resources in the area. The novelty of this work is that the four levels of land suitability classes as defined by the government based on topography, soil characteristics, climate, and water conditions were analyzed in a comprehensive view of resources use efficiency by trade-offs with land-water especially irrigation water and water scarcity potential in the real situation. The approach by combining the normalized approach as Land-Water-Food Nexus Index (LWFNI) and the geographic information system (GIS) tool were thus introduced in the work. The GIS data has been integrated with the land and water intensity at a district level to display the distribution of the hotspot areas.

2. Methods

2.1. Research framework

Chainat province is located in the upper central region of Thailand with an area of about 250,020 ha (Fig. 1). The topography can be divided into three categories: lowland (55%), upland (20%), and hillside/mountain flat (25%). Most of the lowland areas are irrigated and the soil has clay characteristics. The main agriculture is major rice, second rice, fruit trees, and vegetables. Major rice is grown in the wet season from May through October. Second rice, on the other hand, is cultivated in the dry season from November until April. Most upland areas are non-irrigated, and the soil types are clay or silty loam. The main crops being cultivated are rice, cassava, sugarcane, and vegetables. The foothills or mountain plains areas have only rainfall as the water source for agriculture, and the soil types are sandy gravel or loam gravel. The main crops being cultivated are sugarcane and cassava. The agriculture in the province is using irrigation water and rainfall. Chainat province is one of Thailand's main rice producing areas. The major areas are located in the Chao Phraya river basin and some districts are located in the Tha Chin river basin. In 2018/19, the area under major rice cultivation was 134,993 ha, producing 590,147 tonnes of rice, with an average yield of 4.4 t/ha. Second rice had a cultivation area of 67,925 ha producing 327,171 tonnes of rice, with an average yield of 4.8 t/ha [44]. Rice is cultivated in a variety of topography with the aid of irrigation and rainfall.

The research framework has two scopes, as shown in Fig. 2. The first aim is to evaluate the environmental indicators of land and water resource, viz., crop water requirement, irrigation water requirement, rainfall, effective rainfall, water intensity, water scarcity footprint, and land intensity of rice cultivation. The inverse distance weighting (IDW) method was used to interpolate the rainfall distribution in the spatial areas. The second aim is to evaluate the land suitability class and implications for the Land-Water-Food Nexus of rice cultivation at the district scale of Chainat province. The overlay method combines the land suitability map with the land and water indicators to support the Land-Water-Food Nexus model assessment. Next, the scenarios for crop replacement are developed based on the criteria used by policymakers in the marginally suitable (S3) and unsuitable (N) locations. The evaluation of alternative agriculture focuses on the water saved and profits from crops. The results are used to recommend the potential alternative crops to replace rice cultivation to save water and reduce costs.

2.2. Crop water requirement

Crop water requirement (CWR) refers to the amount of water lost by evapotranspiration, which includes both water lost through plant transpiration, and soil and crop surface evaporation. The water use of rice is determined using the crop evapotranspiration calculation by rainfall and irrigation. The crop evapotranspiration is calculated as Eq. (1).

$$ET_c = K_c \times ET_0 \tag{1}$$

Where K_c represents for the crop coefficient and ET_0 represents the reference crop evapotranspiration (mm/day). The rice varieties cultivated in Chainat province may vary depending on the season, weather conditions, and topography. However, the main rice varieties in Chainat are the RD rice variety, Hom Mali rice and Pathum Thani Fragrant rice. To assess the water requirement for rice cultivation in the study, the RD rice variety is referred because it is the main variety that is grown widely in the province [45]. The weekly K_c values of the RD rice are referred

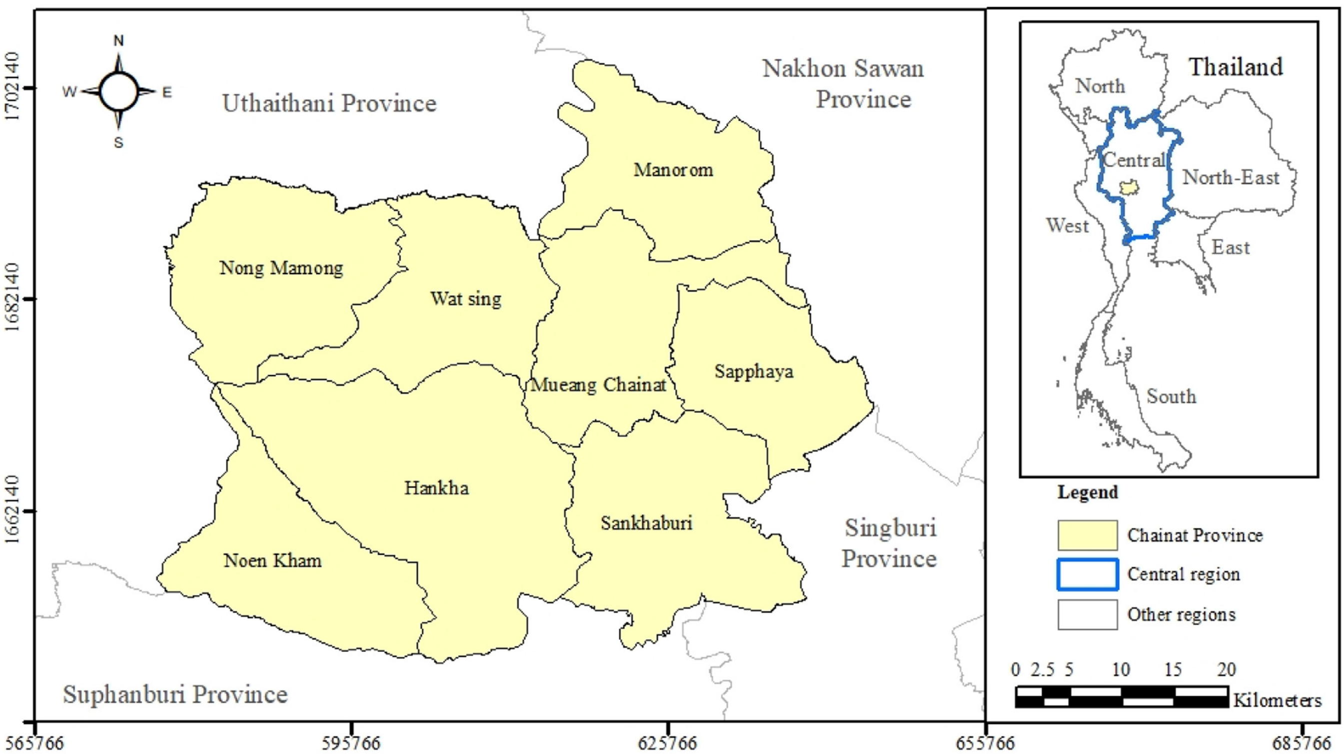

Fig. 1. The study area in Chainat province, Thailand.

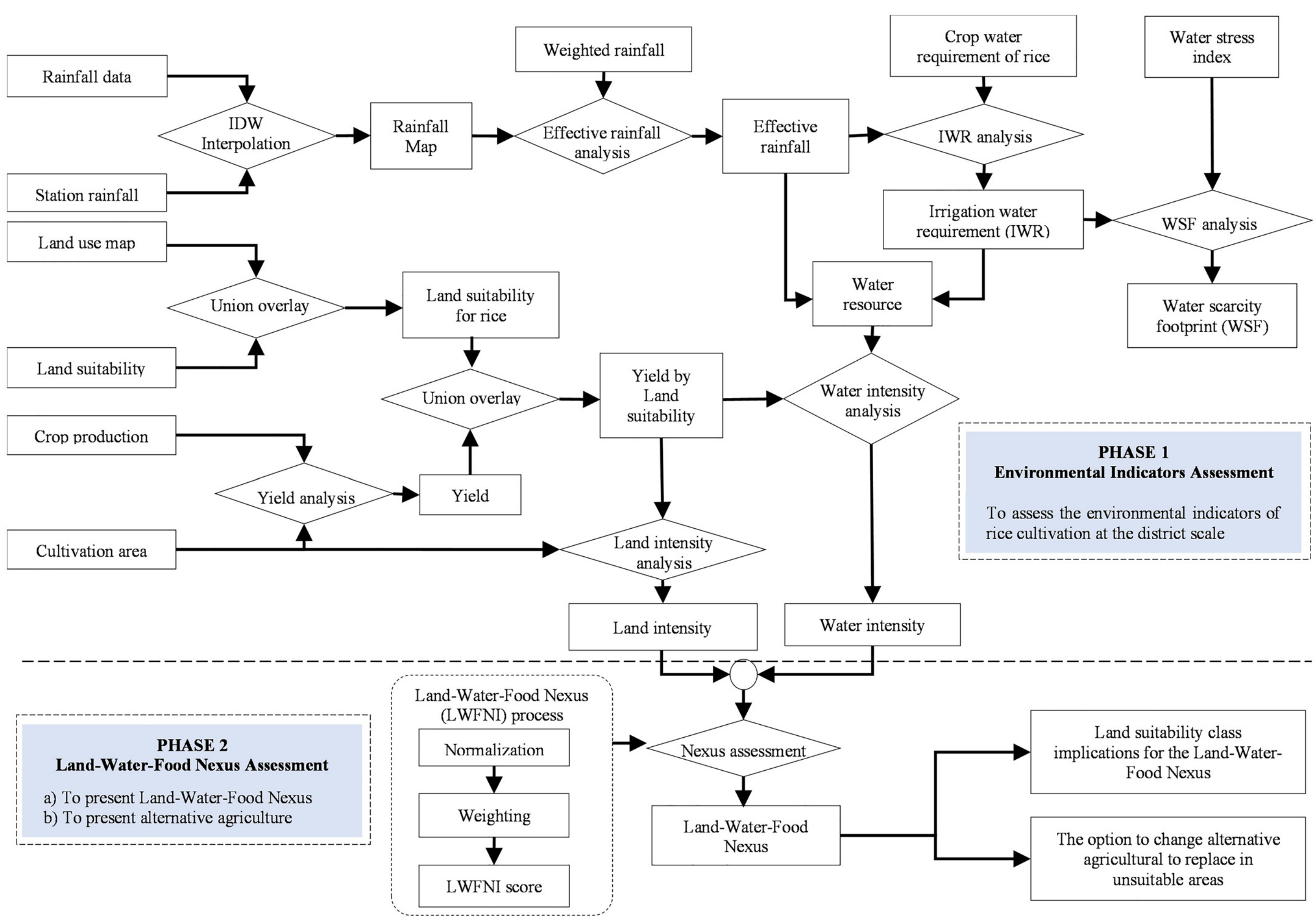

Fig. 2. Research framework of the study.

from the Royal Irrigation Department [46]. The direct sowing method by rice-seeding machine is used to plant rice seeds in the fields. ET_0 is represented as an evapotranspiration process of a reference crop mainly driven by climate conditions without being affected by crop characteristics and soil factors. The study refers the ET_0 by FAO Penman-Monteith method for Chainat province provided by the Royal Irrigation Department (RID). The water uptake at different growing stages of rice have been accounted for by the summation of crop evapotranspiration estimation at different stages.

The average monthly rainfall data for a ten-year period in Chainat and neighboring provinces were collected from 16 stations of the Thai Meteorological Department (TMD). The 10-years rainfall data is used to represent the recent situation of rainfall pattern of the study region. Nevertheless, it must be noted that more use of data can be useful for the assessment. The spatial analysis was performed using a raster of 10 × 10 hectares per grid cell, which provided relatively detailed rainfall data for spatial analysis. Inverse Distance Weighted interpolation was conducted with a deterministic spatial interpolation method that uses certain known values and related weighted values to estimate an unknown value [47] as shown in Eq. (2).

$$Z_0 = \frac{\sum_{i=1}^{N} z_i \cdot d_i^{-n}}{\sum_{i=1}^{N} d_i^{-n}} \tag{2}$$

Where Z_0 represents the estimated value of the variable z at point i, z_i represents the sample value at point i, d_i represents the distance between the sample point and the estimated point, and n represents the coefficient that sets the weight depending on the distance and N represents the sum of all predictions for each validation.

Rainfall data was used to compute the effective rainfall in order to assess the availability of rainwater for crop production. The method used to calculate effective rainfall is referred from the Royal Irrigation Department [48]. The method has provided the factors to estimate the effective rainfall for different ranges of monthly rainfall. For the monthly rainfall ranges 0–10 mm, 11–100 mm, 101–200 mm, 201–250 mm, 251–300 mm and more than 301 mm, the effective rainfall would be equal to 0, 80, 70, 60, 55 and 50% of monthly rainfall, respectively. The irrigation water requirement is determined based on the water balance concept for paddy by using the three components, i.e., evaporation, transpiration, and deep percolation [49] as shown in Eq. (3). Deep percolation (DP) refers to the downward movement of free water through the saturated soil in the flooded rice field [50]. In the study, the deep percolation losses under rice field conditions were estimated to be 1 mm/day based on the percolation rate of the central region of Thailand [46]. When the summation of crop water requirement and DP for producing rice exceeds the effective rainfall, the irrigation water requirement is thus calculated by the Eq. (3). Meanwhile, if the summation of crop water requirement and DP is less than the effective rainfall, the irrigation water requirement would be zero as only rainfall is enough for rice cultivation.

$$\text{Irrigation water requirement} = \text{Crop water requirement}\left(ET_c\right) + DP - \text{Effective rainfall} \tag{3}$$

2.3. Water intensity

Water intensity is a measure of the amount of water used in crop production per unit of output. It can be used to assess the environmental impact and identify the efficiency of water use. The water intensity assessment is classified into irrigation water intensity (water $\text{intensity}_{\text{Irrigation water}}$) and effective rainwater intensity (Water $\text{intensity}_{\text{rainwater}}$). The major rice uses effective rainfall, whereas the second rice mostly uses irrigation water. The irrigation water intensity is the ratio between volume of irrigation water used (m^3/ha) and the rice product obtained (t/ha) [51]. Meanwhile, the rainwater intensity is the ratio between volume of rainwater used for rice (m^3/ha) and the rice product obtained (t/ha). The crop water requirement can be calculated by Eq. (1). If the crop water requirement is greater than the effective rainfall, the effective rainfall is used for cultivation; otherwise, crop water requirement is used. The water intensity is measured in m^3/t rice and calculated using Eqs. (4)–(6).

$$\text{Water intensity}_{\text{Irrigation water}} = \text{Crop water requirement}_{\text{Irrigation water}} / \text{Crop yield} \tag{4}$$

$$\text{Water intensity}_{\text{Rainwater}} = \text{Crop water requirement}_{\text{Rainwater}} / \text{Crop yield} \tag{5}$$

$$\text{Crop yield} = \text{Crop production} / \text{Cultivation area} \tag{6}$$

Where water $\text{intensity}_{\text{Irrigation water}}$ (m^3/t rice) represents the irrigation water intensity per tonne of rice product, Water $\text{intensity}_{\text{Rainwater}}$ (m^3/t rice) represents the rainwater intensity per tonne of rice product, and Crop yield represents the amount of a rice product obtained per area (t/ha). Crop yields for different cultivation areas were calculated in the study using the rice product (t) and cultivation area (ha) data at the sub-district level from the Office of Agricultural Economics. This is to estimate the rice yield for the different soil suitability classes in the study area.

2.4. Water scarcity footprint

The impact of water use in terms of water deprivation potential is determined by the amount of water consumed and the local water stress situation. The water scarcity footprint has been proposed as a metric to assess and compare the impacts of water use [40,52]. Since Chainat province has two watersheds, the irrigation water requirement for each is allocated in proportion to the watershed area. The monthly water stress index (WSI) of major watersheds in Thailand was used to calculate the water scarcity footprint; Chao Phraya = 0.922, Thachin = 0.779 [53]. The water scarcity footprint is measured in $m^3H_2O_{eq}$ and calculated as Eq. (7).

$$\text{Water scarcity footprint} = \sum_{i=1,2} IWR_i \times WSI_i \times A_i \tag{7}$$

Where IWR represents the amount of irrigation water requirement for rice (m^3/ha), i represents the watershed, WSI_i represents the water stress index of the watershed, and A represents the allocation percentage based on watershed areas.

2.5. Land intensity

Different land management practices were used in each area, resulting in different rice production yields. Land intensity is defined as the ratio of the cultivation area (ha) and crop production (t) [54]. The land intensity is measured in ha/t and calculated as Eq. (8). The crop production and cultivation area were obtained from Office of Agricultural Economics.

$$\text{Land intensity} = \text{Cultivation area} / \text{Crop production} \tag{8}$$

2.6. Land suitability map

GIS was used to identify the current rice cultivation area. The land suitability map based on topography, soil characteristics, climate, and irrigation water, was obtained from the Land Development Department. The suitability levels for rice cultivation were classified into four levels. Level 1 is a high suitability area (S1) for crops with high yields. Level 2 is a moderate suitability area (S2) for high yield crops, however there are some manageable restrictions. Level 3 is a marginally suitability area (S3) with soil and water constraints as a result, crop production yields are low. The use of space requires a high cost to manage and there is a risk of flooding and lack of water. Level 4 is an unsuitable area (N). GIS data is merged with the results of the study in the process of evaluating and creating land suitability maps based on land-water-food nexus scores. The maximum combined area approach was used to consider the soil in each sub-district. After that, the soil data was linked with the crop yield by sub-district. The map is shown as a raster in a cell with a size of 10 × 10 hectares.

2.7. Land-water-food nexus assessment

As the indicators have various units, they must be normalized before being aggregated into a single number that can be used to make decisions. The study employed an Min-Max normalization technique that ranges from 0 to 1, for converting the water intensity and land intensity values into the normalized scores usings Eqs. (9) and (10). The aggregated LWFNI scores can be calculated for different regions and different soil suitability for supporting decision making. The calculation of the normalized scores between 0 (worst score) and 1 (best score) follows the Eqs. (9) and (10).

$$\text{Normalized score} = \frac{X_i - \text{Min}(X_i)}{\text{Max}(X_i) - \text{Min}(X_i)} \tag{9}$$

$$\text{Normalized score} = \frac{\text{Max}(X_i) - X_i}{\text{Max}(X_i) - \text{Min}(X_i)} \tag{10}$$

Where, X_i represents value of indicators, $\text{Min}(X_i)$ represents the minimum value of indicators, $\text{Max}(X_i)$ represents the maximum value of indicators. Eq. (9) is used when $\text{Min}(X_i)$ is the least preferred value and $\text{Max}(X_i)$ is the most preferred value of the indicator. On the other hand, Eq. (10) is used when the $\text{Min}(X_i)$ is the most preferred value and $\text{Max}(X_i)$ is the least preferred value of the indicator.

The land-water-food nexus index (LWFNI) is used to indicate the importance of interconnecting resources for agriculture as well as trade-offs based on economic value. The study calculated two main indicators, viz., water intensity and land intensity, both of which are important factors for agricultural production. The land-water-food nexus was calculated using normalized scores that link water intensity and land intensity into a single score using Eq. (11) [28].

$$LWFNI\ scores = \frac{\sum_{i=1}^{n}(W_i \times X_i)}{\sum_{i=1}^{n} W_i} \tag{11}$$

where W_i represents weighing score, X_i represents a normalized score of each environmental impact indicator. In the study, the weighing score for all indicators are given to one to represent that all aspects are equally important [29].

3. Results and discussion

3.1. Land suitability

The government plans to encourage crop production in the area classified as high (S1) and moderate suitability (S2) areas only. This is due to their suitable soil, climate, and water sources conditions for rice cultivation, which can lead to lower production investment cost and higher productivity. Limitations in soil and water in marginally suitable (S3) and unsuitable areas (N) contribute to low production. Flooding and dehydration risks are a cost of controlling space use. As a result, the rice should not be cultivated in marginally suitable (S3), and unsuitable areas (N) [42].

The study evaluated the suitable areas for major and second rice in Chainat province. The findings demonstrated that major rice cultivation areas are currently mainly situated on land that is classified as highly suitable area (S1) for rice cultivation at about 75%, about 9% in moderate (S2), about 4% in marginally suitable (S3) and about 11% in unsuitable (N) areas. Second rice cultivation takes place in 46% of the major rice cultivation areas. About 90% of the cultivation is in highly suitable area (S1), about 2% in moderately suitable (S2), about 1% in marginally suitable (S3), and about 8% in unsuitable (N) areas. Fig. 3 represents the suitable areas for major and second rice in the different districts of Chainat province. The result demonstrates that major and second rice areas are currently situated in highly suitable area (S1). Only the rice cultivation areas in Noen Kham district are mostly situated in the unsuitable area (N), and in Nong Mamong district are situated in the high (S1) and moderate (S2) suitability areas. Assessing the suitability of the land can help identify the most suitable areas for planting crops based on existing resources, thereby increasing productivity [55].

The guidelines for the development of land unsuitable for rice cultivation can be divided into two cases; the first case involves changing crops, and the second case involves not changing crops. In the case of changing crops, the government should offer incentives to change rice cultivation to new crops, such as supporting inputs, low-interest loans, and knowledge to increase agricultural production efficiency [56]. Financial support is a key factor that influences farmers' decisions to plant crops [57]. Moreover, several studies have shown that obtaining crop insurance contracts increases farmers' acceptance of and motivation to switch to different crops [58]. In the case of not changing crops, the government should support soil analysis on individual plots and adjust soil care based on the results of the soil analysis. Also crucial is the development of infrastructure such as water supply, which impacts changes in soil quality.

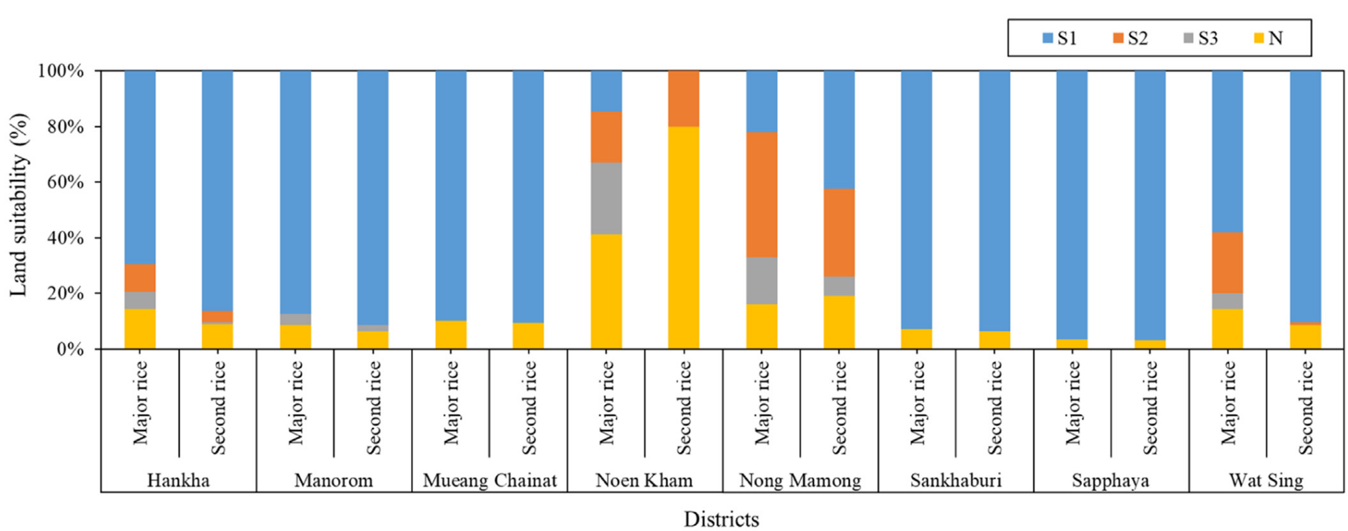

Fig. 3. Land suitability of major and second rice in Chainat Province.

Table 1
Rice cultivation indicators based on land suitability.

	Land suitability class	District							
		Hankha	Manorom	Mueang Chainat	Noen Kham	Nong Mamong	Sankhaburi	Sapphaya	Wat Sing
Major rice									
Yield	Highly	5.0	4.1	4.4	–	4.4	4.4	4.3	3.8
(t/ha)	Moderately	5.0	–	–	3.8	3.7	–	–	3.8
	Marginally	5.0	–	–	3.5	–	–	–	–
	Unsuitable	–	–	–	3.7	–	–	–	3.8
Land intensity	Highly	0.20	0.25	0.23	–	0.23	0.23	0.24	0.26
(ha/t rice)	Moderately	0.20	–	–	0.26	0.27	–	–	0.26
	Marginally	0.20	–	–	0.28	–	–	–	–
	Unsuitable	–	–	–	0.27	–	–	–	0.26
Water intensity	Highly	923	1128	1045	–	1056	1038	1085	1217
(m^3/t rice)	Moderately	924	–	–	1218	1238	–	–	1218
	Marginally	922	–	–	1307	–	–	–	–
	Unsuitable		–	–	1259	–	–	–	1220
Second rice									
Yield	Highly	4.8	4.7	4.3	–	3.9	5.3	5.0	4.9
(t/ha)	Moderately	–	–	–	–	4.0	–	–	4.9
	Marginally	–	–	–	–	3.9	–	–	–
	Unsuitable	–	–	–	2.8	–	–	–	–
Land intensity	Highly	0.21	0.21	0.23	–	0.25	0.19	0.20	0.20
(ha/t rice)	Moderately	–	–	–	–	0.25	–	–	0.20
	Marginally	–	–	–	–	0.26	–	–	–
	Unsuitable	–	–	–	0.36	–	–	–	–
Water intensity	Highly	1054	1088	1167	–	1284	953	1013	1026
(m^3/t rice)	Moderately	–	–	–	–	1271	–	–	1039
	Marginally	–	–	–	–	1298	–	–	–
	Unsuitable	–	–	–	1808	–	–	–	–

3.2. The relationship between rice cultivation and land suitability by district

Productivity is the key factor that indicates the efficiency of the cultivation area. The relationship between rice yield and land suitable for rice cultivation showed that major rice cultivation had a noticeably low yield in marginally suitable areas (S3). On the other hand, the second rice cultivation had a noticeably low yield in unsuitable areas (N). Table 1 shows that major rice in Hankha district located in highly (S1), moderately (S2), and marginally (S3) suitable areas has a similar yield of 5.0 t/ha. The Noen Kham district has low yield of 3.5 t/ha in marginally suitable soil area (S3). Second rice has a higher yield in Sankhaburi district located in highly suitable area (S1) at about 5.3 t/ha. The Noen Kham district having low yield of about 2.8 t/ha is in unsuitable area (N). Compared to other provinces, this one has a relatively high production of rice. In Thailand, major rice crop typically attains yields between 1.7–5.1 t/ha and second rice between 0.5–5.5 t/ha [59]. Strangely, the Hankha and Wat Sing districts demonstrated that the different soil characteristics had no effect on yield. Water may be a major factor in growth for crops and increased yields [60].

The efficient management of land use by the cultivation of crops that are suitable in each area helps to reduce land area requirement. Topography and soil characteristics are important elements for crop cultivation. The land intensity indicator measures an area's managed ability to produce one unit of raw materials or products from a crop cycle. The highest impact on the land intensity of major rice is located in Noen Kham in marginally suitable area (S3) at about 0.28 ha/t. Hankha district has the highest economic potential of land in highly (S1), moderate (S2) and marginally suitable areas (S3) at about 0.20 ha/t. Meanwhile, the highest impact on the land intensity of second rice is located in Noen Kham in unsuitable area (N) at about 0.36 ha/t. Sankhaburi, Sapphaya, and Wat Sing districts have the highest efficiency in highly suitable area at about 0.19–0.20 ha/t. Fertile soil is a sign of highly suitable land that demonstrates the soil's capacity to supply balanced nutrients for crop growth. Productivity is heavily influenced by the soil fertility. However, productivity may also be influenced by other factors.

Inefficient water resource management in food production systems contributes to the water scarcity which in turn will return the effect to farmers and society due to the water resource competition such as water shortage problems. The study of water intensity will help us to manage water use to be cost-effective and efficient. For major rice, the Noen Kham district has the highest impact on water intensity at 1307 m^3/t in marginally suitable area (S3). While in the same level of soil class, the Hankha district has the highest efficiency at about 922 m^3/t based on farmer practice. For second rice, the Noen Kham has the highest impact on water intensity located in the unsuitable area (N) at about 1808 m^3/t; the Sankhaburi district has the highest efficiency at about 953 m^3/t in highly suitable area (S1). The results of land and water intensity of Chainat province demonstrate differences in each district as shown in Fig. 4. This study demonstrates the efficiency of water use at the local level. Future land management may have different forms in each area such as appropriate water management in water deficit area and improvement of soil quality in unsuitable area by organic fertilizer. It can be inferred that highly suitable land results in high yields. Even in unsuitable areas, managing enough water to meet the crop's needs is also important for increasing crop yields.

At present, the land suitability of LDD is assessed based on soil, climate, and water for land use zoning of crops. The assessment results revealed that the appropriateness of each class of soil affected the productivity. Additionally, cultivation in different areas with the same soil class of land suitability can generate different yields due to difference in topography and soil fertility as well as the farmer practices.

3.3. Crop water requirement (CWR)

Water is required for several processes in crops, including photosynthetic activity, food intake by roots for growth, and dehydration for cooling. Each crop's water requirements depend on the cultivar, age, and crop cycle season. Therefore, it is crucial to supply water that fulfills the crop requirements. Rice cultivation has a high water requirement especially for cultivation in the dry season. The crop water requirement of major rice is 4610 m^3/ha, whereas second rice has a requirement of 5065 m^3/ha. The second rice is cultivated in the dry season, where there is high water loss from crop fields in the process of evaporation and transpiration. Fig. 5 presents the water use and irrigation water

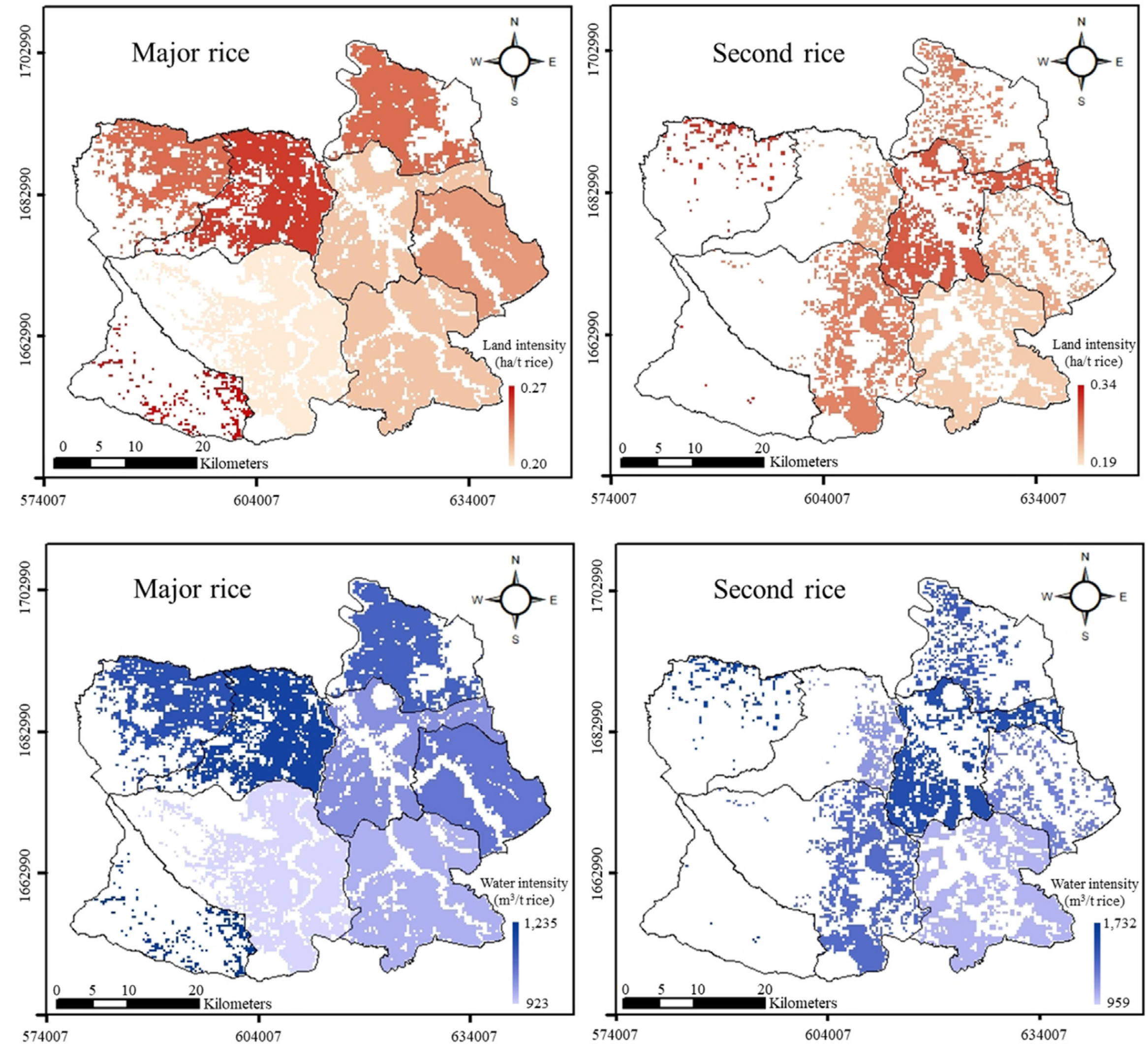

Fig. 4. Land and water intensity maps of major and second rice cultivation in Chainat province.

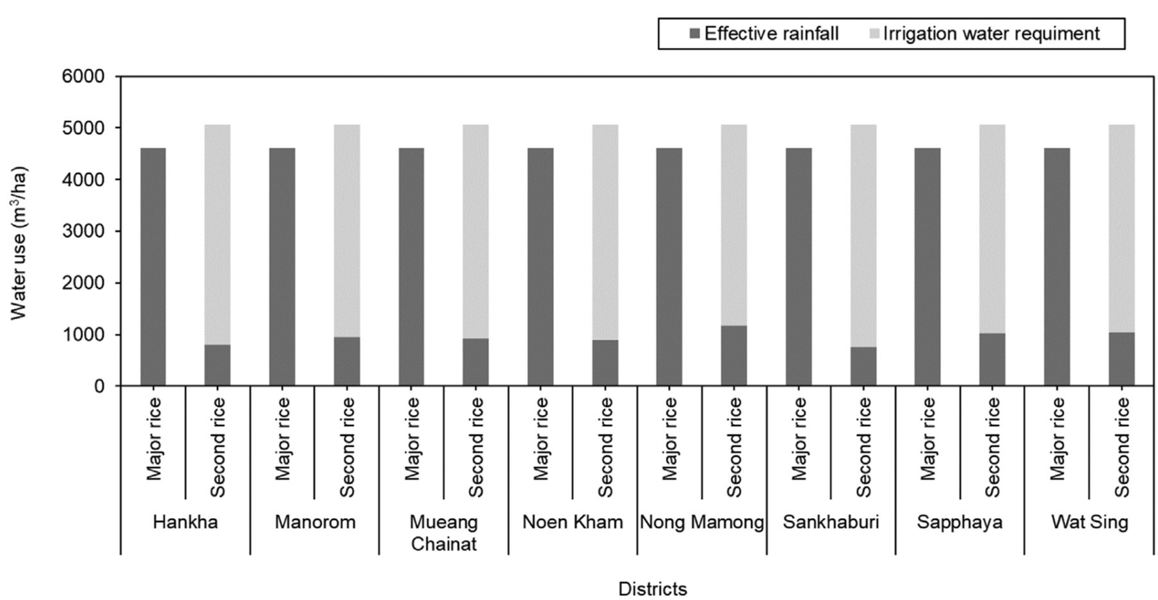

Fig. 5. Water requirement of major and second rice.

Table 2
Water scarcity footprint of second rice cultivation by district.

Indicator	District							
	Hankha	Manorom	Mueang Chainat	Noen Kham	Nong Mamong	Sankhaburi	Sapphaya	Wat Sing
Water scarcity footprint (m^3H_2Oeq/ha)	3338	3797	3603	3219	3034	3716	3726	3140

requirement of major and second rice cultivation in different districts of Chainat province. Rainwater is the main source of water for growing major rice in the wet season; the range of effective rainfall for major rice cultivation is between 5394–5654 m^3/ha. The effective rainfall exceeds the crop water requirement; this implies that rainwater is sufficient to meet the crop water requirements for major rice cultivation in all districts. However, for second rice cultivation both rainwater and irrigation water are required, with the latter being much higher. Since the effective rainfall for second rice cultivation is between 763–1165 m^3/ha, the irrigation requirement is between 3900–4302 m^3/ha. The Sankhaburi district has the largest irrigation water requirement due to low rainfall in the off season, followed by Hankha and Noen Kham districts. According to [61], Hankha and Noen Kham districts have a water deficit during the second rice cultivation. In addition, the drought report of Chainat Province identified four districts that experienced disaster-related issues due to the low rainfall, viz., Nong Mamong, Noen Kham, Wat Sing, and Hankha districts [62].

3.4. Water scarcity footprint (WSF)

Based on the water stress index of 25 watersheds that were developed to demonstrate the water stress in different watersheds in Thailand [53], the critical watersheds are located in the Central and Northeastern regions. These differences may affect different water investments. The water scarcity footprint refers to the potential consequences of excessive water use, regardless of water quality. From the perspective of water scarcity, water usage can be split into surface water and rainfall [63]. The potential impacts on water resources due to irrigation water use for second rice production have been assessed by the water scarcity footprint indicator. The pressure in the basin varies depending on the topography, precipitation, and resource utilization in the area. Currently, second rice plantation areas in Chainat can be allocated into the two watersheds, i.e., Chao Phraya and Tha Chin watersheds. Hankha, Noen Kham, and Nong Mamong districts are located in the Tha Chin watershed. Manorom and Sapphaya districts are located in the Chao Phraya watershed. There are three districts, i.e., Mueang Chainat, Sankhaburi, and Wat Sing, located partly in both watersheds.

Table 2 shows the water scarcity footprint of second rice production by district. Manorom district has the largest water scarcity footprint, at about 3797 m^3H_2Oeq/ha, followed by Sapphaya and Sankhaburi districts, at about 3726 m^3H_2Oeq/ha and 3716 m^3H_2Oeq/ha, respectively. The distribution of water scarcity footprint of second rice in the east of the province is shown in Fig. 6.

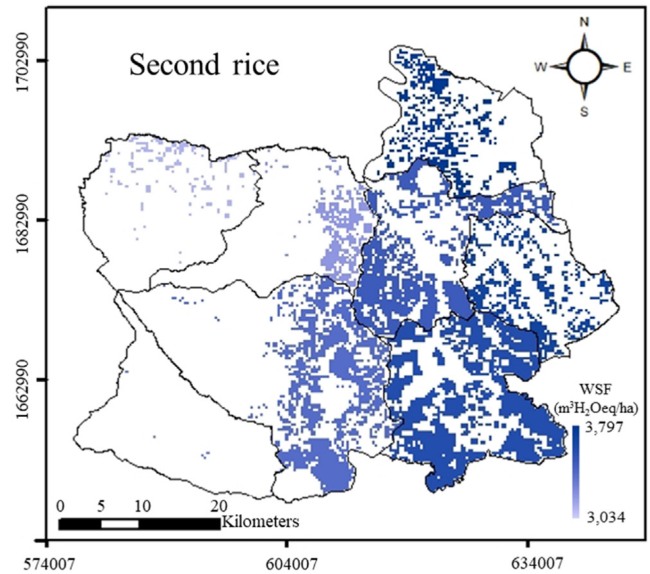

Fig. 6. Distribution of water scarcity footprint of second rice in Chainat province.

3.5. Land-water-food nexus

Fig. 7 representing the high LWFNI score also shows that major rice cultivation should be recommended for the Hankha district, and second rice should be recommended for the Sankhaburi district. The spatial distribution of Land-Water-Food Nexus is shown in Fig. 8. The assessment results pointed out that rice cultivation on suitable land utilizes less land and water resources while producing higher yields. In contrast, the Nong Mamong and Noen Kham districts were the least suitable for major and second rice, respectively. Both Nong Mamong and Noen Kham districts use a lot of land and water for rice production, which has a low productivity. This result indicates that production of major and second rice in Nong Mamong and Noen Kham districts has imposed environmental impacts of land and water resources. Thus, an increase of rice production in these districts will lead to severe impacts on local ecosystems and productivity. One solution for managing water resources is to expand the irrigated area so that each region has enough water for agriculture [25]. The land-water resources are interconnected and difficult to distinguish. The only way to fix the issue is to perform integrated system-wide analysis. Consequently, the Land-Water-Food Nexus is helpful in emphasizing the necessity for an integrated perspective to ensure an equitable allocation of the two resources.

3.6. Land suitability class implications for the land-water-food nexus

The nexus assessment revealed that the highest LWFNI score is in the high suitability area (S1) for major (0.44) and second (0.53) rice as shown in Fig. 9. Soil is a very important resource for agriculture. In particular, the quality of the soil influences the growth and yield of crops. High yields will be obtained in areas with fertile soil, a favorable climate, and effective land management practices [64]. On the other hand, poorly maintained soil will provide yields that are not worth the investment. In addition, this study reflects that unsuitable areas with enough water available will provide higher yields than similar areas without enough water. Other factors such as fertilizer can also aid in increasing productivity in unsuitable areas. Normally, rice cultivation in unsuitable areas often requires a lot of water and land resources and produces low yields. Fig. 10 shows that the highest LWFNI score is in the east of the province.

The area with the highest LWFNI score is one where soil and water resources are traded off in terms of Land-Water-Food Nexus within four levels of land suitability for rice. The higher LWFNI indicates effective trade-offs and Land-Water-Food Nexus, which requires less water and less land yet providing high yields. The areas with low LWFNI efficiency imply the high demands for water and land resources while still producing poor yields. The use of good land management practices such as soil and water conservation, cover crops, cultivation of low water-intensive

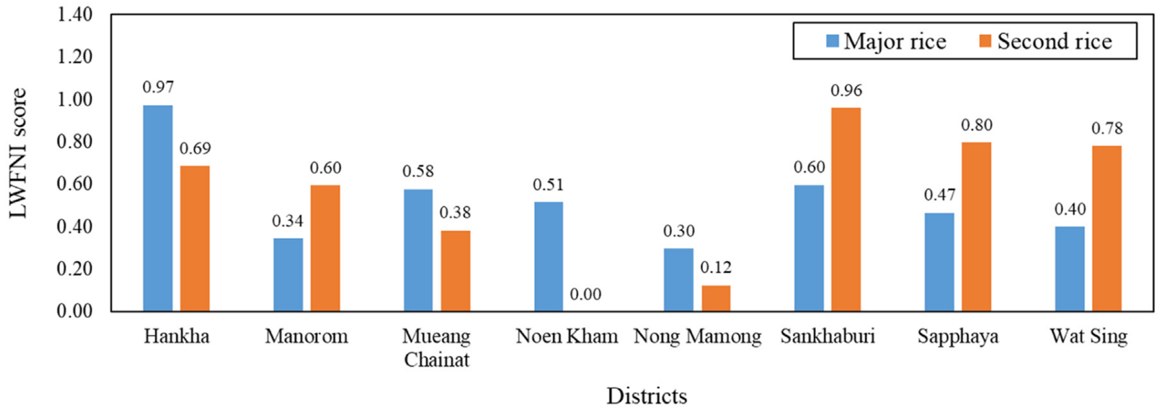

Fig. 7. Land-Water-Food Nexus by district in Chainat province.

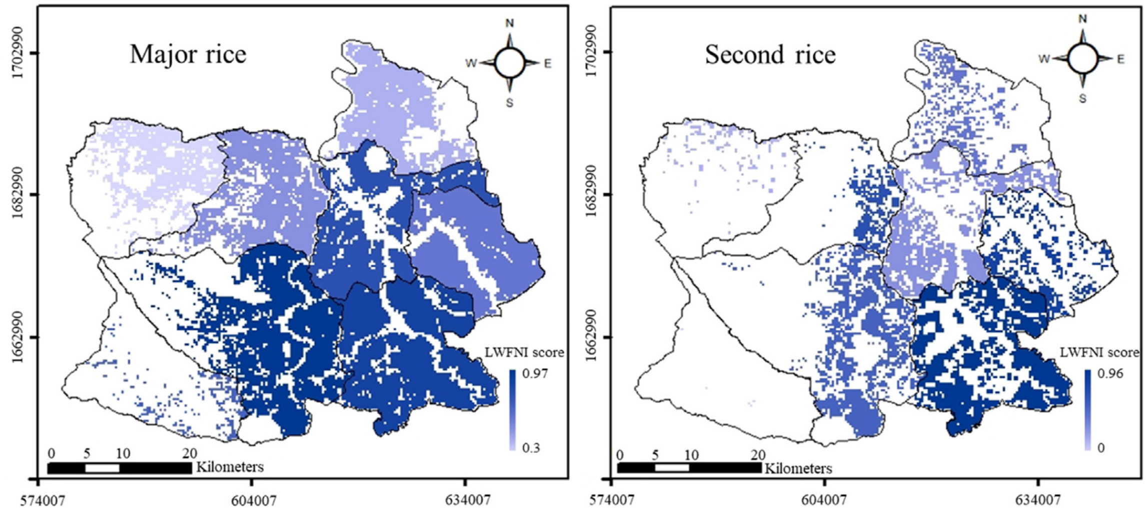

Fig. 8. Distribution of Land-Water-Food Nexus by district in Chainat province.

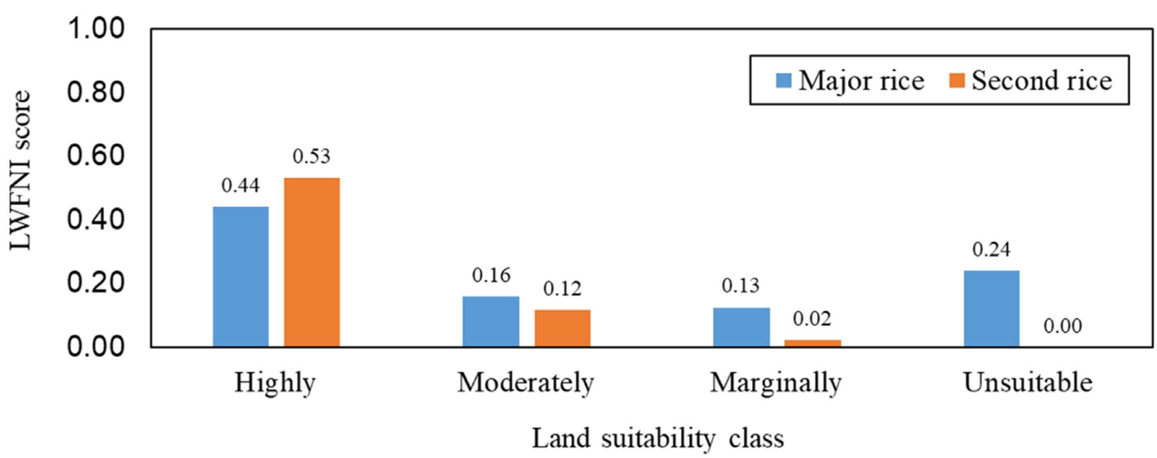

Fig. 9. Land suitability class implications for the Land-Water-Food Nexus.

crops in low-water areas, and improvement of the soil in unsuitable soil areas in accordance with nutrient management of analysis results may increase yield. Productivity is the primary key of the agricultural sector, and it must aim to reduce resources and costs.

The rice cultivation in unsuitable areas results in a low LWFNI score. The low Land-Water-Energy-Food Nexus index demonstrates a lack of nexus resource management with an integrated approach. Agriculture in unsuitable areas is characterized by low productivity and heavy resource use, resulting in high production costs [65,66]. Therefore, sustainable development is based on maximizing the use of local resources without affecting the environment. Studying the connected effects is important to consider.

The study approach by combining the normalized approach as Land-Water-Food Nexus Index (LWFNI) and the geographic information system (GIS) tool help provide the quantitative indicator to reflect whether and how the land suitability class has affected the land and water re-

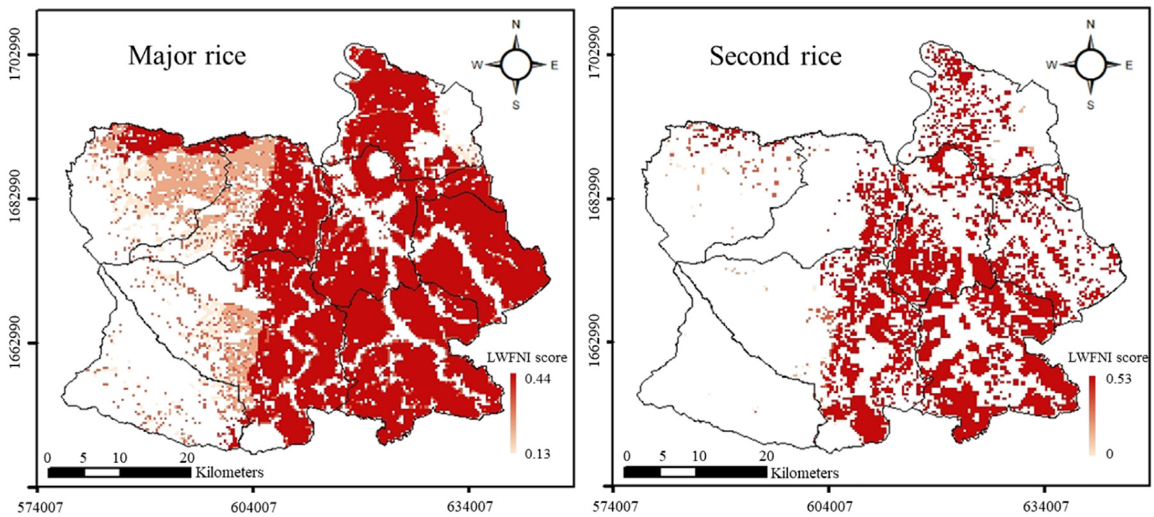

Fig. 10. Distribution of land suitability class implications for the Land-Water-Food Nexus.

sources used and help visualize the nexus hotspot of rice cultivation in Chainat. This can complement the previous studies about soil suitability assessment for crops which so far focused on the soil fertility, rainfall and topography for mapping the agricultural land zoning [55,67]. Further application of the work is that the government can apply the results as supporting information to establish the policy to encourage planting crops for getting the optimal growth and productivity in each region [43]. As the nexus assessment method used in the study aims to provide support to the policy makers, the assessment is thus done based on the reliable secondary data from government agencies. The validation of the actual irrigation water requirement and crop water requirement for plantation is then the limitation of the work that needs to be considered in the decision making process. It is recommended that the background data of government such as the updated irrigated and non-irrigated areas that can be applied to identify the potential irrigation water use in the specific areas, could be improved.

3.7. Alternative economic crops scenarios

The policy of Thailand has encouraged the development of agricultural goods appropriate to the area to achieve a supply-demand balance, lower costs, and boosting productivity. The practice is to promote agricultural production in potential areas at high (S1) and moderate (S2) suitability. In addition, the conversion of agricultural land in marginally suitable (S3) and unsuitable areas (N) to other economic crops is encouraged [43].

An analysis of agriculture cultivation was conducted to find the alternative economic crops that can potentially be promoted to replace the rice grown in the marginally suitable (S3) and unsuitable areas (N) to enhance the land and water use efficiency along with the economic benefits. Water saved and profit were used as the assessment criteria. The assessment was conducted on an annual basis to compare with the base case of rice cultivation (including two crops, i.e., major and second rice). The studied alternative economic crops were sugarcane, cassava, maize, mungbean, and peanut [68]. This list of alternative crops was obtained from the Chainat Provincial Agriculture and Cooperatives Office. Both production costs and product prices were obtained from the Office of Agricultural Economics. The currency exchange for Thai currency baht (THB) is about 35.11 THB/US Dollar [69]. The crop water requirements for sugarcane, cassava, maize, mungbean and peanut can be estimated by using the Eq. (1). The K_c for those alternative crops is also referred to from the Royal Irrigation Department.

The results revealed that in the baseline scenario, major and second rice cultivation had a total crop water requirement of about 9675 m^3/ha/year, while the irrigation water requirement was about 3628 m^3/ha/year. The rice cultivation was mainly deficit in the second rice due to dry conditions which implies an increased requirement for irrigation water. Table 3 shows the alternative crops to save water and make profit by replacing rice cultivation in marginally suitable area (S3) and unsuitable areas (N). The findings indicated that switching from second rice to a crop with the same calendar time was necessary. In this case, it is more lucrative and water-efficient to raise two short-term crops rather than one long-term crop per year. For example, major rice and mungbean scenario saved water at about 3601 m^3/ha/year and made a profit increase of about 84,106 baht/ha, major rice and peanut scenario saved water at about 2081 m^3/ha/year and made a profit increase of about 302,366 baht/ha, and major rice and maize scenario saved water at about 1481 m^3/ha/year and made a profit increase of about 34,275 baht/ha. The cassava cultivation scenario can replace the base case to save water at about 1696 m^3/ha/year and make a profit increase of about 10,230 baht/ha. This study presents four possible approaches to substituting unsuitable rice cultivation under water saving and profitable conditions. Mungbean is a short-lived crop that requires little water and is drought tolerant. It was found to be a good choice

Table 3
A comparison of other crops to replace marginally suitable and unsuitable areas of rice cultivation.

Scenarios	Total crop water requirement (m^3/ha)	Irrigation water requirement (m^3/ha)	Water saved (m^3/ha)	Total income (THB/ha)	Production cost (THB/ha)	Net profit (THB/ha)	Profit increase (THB/ha)
Base case: major and second rice	9675	3628	–	55,454	54,583	872	–
Major rice and Maize	8194	2147	1481	86,734	51,588	35,147	34,275
Major rice and Mungbean	6074	27	3601	123,868	38,891	84,978	84,106
Major rice and Peanut	7594	1547	2081	364,100	60,863	303,237	302,366
Sugarcane	10,577	4531	−903	171,202	65,513	105,689	104,817
Cassava	7979	1932	1696	49,594	38,492	11,102	10,230

for planting during the dry season [70]. For Chainat province, the study indicated the total rice planting area on the marginally suitable (S3) and unsuitable (N) areas is about 23,100 ha that should be further encouraged to change the crop cultivation. The government should take action to promote and support the conversion of unsuitable land for rice cultivation to other crops. Incentives such as seed, low-interest loans, support knowledge to increase agricultural production efficiency, and develop natural water sources should be created to adjust production in inappropriate areas.

It must be noted that the scenario proposed for converting rice to alternative crops is only for the farmers that are currently growing in the unsuitable lands yielding a low productivity. The option thus would benefit not only to the farmers but also the policy makers as the land and water resources can be efficiently used [43]. The consequential impacts from the proposed scenario to the rice exportation is low because the total areas in unsuitable land was only about 23,100 ha and the rice production would potentially be reduced just about 125,976 tonnes/year. This amount is much smaller than the annual production of rice in Thailand which is around 32 million tonnes and the provincial production which is 7 million tonnes.

4. Conclusions

The study applied the nexus assessment approach by combining the Land-Water-Food Nexus Index (LWFNI) and the geographic information system (GIS) tool to explain the relationship of land suitability classes and land-water-food nexus performance of rice cultivation in Chainat, Thailand. The land and water resource use efficiency for rice production in different land suitability classes for rice production was examined. The LWFNI score results showed that rice cultivation in the highly suitable area (S1) used land and water effectively. Farm management practices can boost productivity in unsuitable areas. The second rice, which is cultivated in the dry season, has a water deficit and must be supplemented with irrigation or other water sources for the whole period in which it is being cultivated. Therefore, scenarios were considered where major rice cultivation was maintained, but the second rice was changed to maize, mungbean, and peanut. Or, both major and second rice were changed to sugarcane and cassava. The assessment indicated that mungbean, peanut, and maize crops instead of the second rice could save water and reduce costs. The major rice and mungbean scenario saved the most water, while the major rice and peanut scenario had the highest profit increase. In addition, the cassava scenario can save water and make a profit increase. Although the sugarcane scenario has more profit potential than cassava, it requires more water use than cassava as well as the base case. The study results could help understand the existing land use efficiency, water scarcity potential, as well as the economic returns in view of the productivity obtained. The hotspots areas identified by the LWFNI score for rice cultivation can be the supporting information for agricultural land use policy promotion. However, as the assessment method used aimed to propose to the policy makers, the assessment was done based on the reliable secondary data that are currently available from the Thai government agencies. It is recommended improving the agricultural statistics of government such as the updated irrigated and non-irrigated areas and the detailed crop yield data by soil suitability would lead to more accuracy of the nexus assessment results which could better support the policy decision makers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

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