agronomy

Article

Assessing Ecosystem Services of Rice–Fish Co-Culture and Rice Monoculture in Thailand

Noppol Arunrat and Sukanya Sereenonchai *

Faculty of Environment and Resource Studies, Mahidol University, Nakhon Pathom 73170, Thailand; noppol.aru@mahidol.ac.th
* Correspondence: sukanya.ser@mahidol.ac.th

Abstract: Increasing production costs for rice monoculture and concerns about farming households' food security have motivated farmers to adopt integrated rice–fish farming. To date, there has been little research that comparatively assesses the ecosystem services (ESVs) of both rice–fish co-culture and the rice monoculture system in Thailand. Therefore, this study aims to estimate the ESV values of these systems based on the Millennium Ecosystem Assessment. A total of 19 rice–fish co-culture farms were investigated, covering three regions of Thailand (northern, northeastern, and central regions) and consisting of 13 sub-districts, 13 districts, and 11 provinces. For a fair comparison, 19 conventional rice farms were selected as comparison sites. Rice–fish co-culture had a higher net ESV value of 48,450,968.4 THB ha^{-1} year^{-1} than rice monoculture with a net ESV value of 42,422,598.5 THB ha^{-1} year^{-1}. Rice–fish co-culture generated average economic values 25.40% higher than in rice monoculture farming. The most positive change in ESV was found in the regulation of temperature and humidity, with 3,160,862.9 THB ha^{-1} year^{-1}. Moreover, agrotourism can generate revenue and increase the ESV in rice–fish co-culture. Our findings showed that rice–fish co-culture gives more economic and ecological benefits compared to the rice monoculture system. Further studies are recommended to explore and analyze the potential advantages of the rice–fish system in more detail.

Keywords: ecosystem services; rice–fish co-culture; rice monoculture; Thailand

check for updates

Citation: Arunrat, N.; Sereenonchai, S. Assessing Ecosystem Services of Rice–Fish Co-Culture and Rice Monoculture in Thailand. *Agronomy* **2022**, *12*, 1241. https://doi.org/10.3390/agronomy12051241

Academic Editors: Moritz Von Cossel, Joaquín Castro-Montoya and Yasir Iqbal

Received: 8 April 2022
Accepted: 20 May 2022
Published: 23 May 2022

1. Introduction

Rice is the primary source of nutrition for approximately two-thirds of the world's population [1], which accounts for up to 75% of the daily calorie intake of people in some Asian countries [2]. It is projected that the world population will require 560 million tons of rice by 2035, which increased to around 120 million tons after 2010 [3]. With 11.17 million harvesting hectares, 21.3 million tons of rice were produced in the crop year 2020/2021, making Thailand the world's 6th largest rice producer after China, India, Bangladesh, Indonesia, and Vietnam [4]. However, future food security and the precarious livelihood of poor people are great challenges for rice farming.

The rice–fish co-culture system is a solution to improve the functioning of ecosystems and alleviate farmers' poverty in many locations [5]. Rice yields from modern monoculture rice are not realistically sustainable due to falling yields from reduced soil fertility and pest problems [6], and the detrimental environmental effects of intense fertilization and pesticide use have now been properly addressed. According to previous studies, the rice–fish co-culture system can efficiently reduce the use of pesticides and herbicides [7], as well as the amount of nitrogen consumed and absorbed by rice plants and fish [8–10]. Despite the environmental benefits of the rice–fish co-culture system, their adoption is extremely low. In Asian countries, e.g., Bangladesh [11], China [8], Malaysia [12], and Vietnam [13], the adoption rate is only marginally greater than 1% [5].

Integrated rice and fish farming has been conducted in Thailand for more than 200 years [13]. Capturing wild fish seed for stocking rice fields was necessary in the beginning. The Department of Fisheries (DOF) began to promote rice–fish production in the 1940s by providing fish seed and improving technology. The central plains saw a boom in rice–fish farming, with fish yields ranging from 137 to 304 kg ha^{-1} $crop^{-1}$ [13]. Rice yields increased by 25 to 30% in fields that included fish. In the 1970s, however, the introduction of high-yielding rice varieties, as well as increasing fertilizer and pesticide applications, led to the near collapse of rice–fish farming in Thailand's central plains. Farmers had two options: separate their rice and fish operations or stop raising fish [13]. Currently, increasing production costs for rice cultivation (e.g., chemical fertilizers, insecticides, and herbicides) and concern for farming households' food security have motivated farmers to adopt integrated rice–fish farming due to its lower cost, higher economic returns, and additional food source. However, the number of rice–fish farms in Thailand remains low. Furthermore, integrated rice and fish farming is an organic agriculture system that the Thai government initially practiced in the 1980s. It has been promoted to persuade and subsidize farmers to adopt organic farming based on the philosophy of the late King Bhumibol Adulyadej as "sufficiency economy". There were only 2500 organic farmers in 2003, and this number increased to 44,418 organic farmers in 2019 [14,15], which accounted for only 0.003% of the total farmers in Thailand [16]. To increase the number of organic farmers, proactive policies need to be focused specifically on rice–fish co-culture farming; thus, comprehensive research is required.

To comprehensively understand the ecological and economic benefits, ecosystem services (ESVs) are widely considered appropriate quantitative and qualitative assessment methods. Following the Millennium Ecosystem Assessment, ESVs are defined as "the benefits people obtain from ecosystems" [17]. ESVs are classified into four types, namely cultural, provisioning, regulating, and supporting services [18], which connect ecological and sociological values for policy implications and decision making. ESVs are widely used and have achieved scientific results in rice–fish farming [8,19–22]. To date, there has been little research that comparatively assesses the rice–fish co-culture and rice monoculture systems in Thailand. Therefore, the objective of this study was to determine the ESV values of rice–fish co-culture and rice monoculture (conventional rice farming) in Thailand and to propose policy implications based on key findings to support government policy and decision making.

2. Materials and Methods

2.1. Study Sites and Description

The number of rice–fish co-culture farms in Thailand is very small, and there is no official record of the location and number of rice–fish co-culture farms. Thus, a purposive sampling method was used to select the farms. There were two criteria for rice–fish co-culture farm selection in this study: (1) the rice–fish co-culture farm must practice organic rice farming and feed fish in the paddy fields without using any chemical substances, and (2) the rice–fish co-culture farm must have practiced rice–fish co-culture for at least 2 years. Based on our survey in the crop years 2020 and 2021, 19 rice–fish co-culture farms were selected, and the data investigated. These farms covered three regions of Thailand (northern, northeastern, and central regions), consisting of 13 sub-districts, 13 districts, and 11 provinces (Table 1). For a fair comparison, 19 conventional rice farms were selected as comparison sites. These conventional rice farms were located near the rice–fish co-culture farms in each sub-district to avoid variations in soil texture, microclimate, and irrigation conditions (Table 1).

Table 1. Description of study areas.

Region	Province	District	Sub-District	Number of Rice-Fish Co-Culture (Farm)	Number of Rice Monoculture (Farm)	Climate *		
						T_{max} (°C)	T_{min} (°C)	Precipitation (mm year^{-1})
Northern	Mae Hong Son	Khun Yuam	Mueang Pon	1	1	33.0	20.0	1100.0
	Phichit	Dong Charoen	Samnak Khun Nen	1	1	32.9	23.3	1264.8
Northeastern	Amnat Charoen	Lue Amnat	Rai Khee	1	1	22.1	27.2	1581.7
	Sakon Nakhon	Phang Khon	Rae	1	1	22.0	31.7	1650.0
	Nakhon Phanom	Renu	Na Kham	1	1	21.8	31.8	1600.0
	Sisaket	Kantharalak	Phu Ngoen	1	1	22.3	33.6	1439.6
	Ubon Ratchathani	Khueang Nai	Ban Thai	3	3	22.1	33.0	1700.0
		Det Udom	Tha Pho Si	3	3			
	Surin	Prasat	Chok Na Sam	1	1	22.7	32.7	1432.2
		Rattanaburi	Rattanaburi	3	3			
	Buriram	Ban Kruat	Sai Ta Ku	1	1	22.2	33.0	1100.0
	Yasothon	Mueang	Nong Khu	1	1	22.5	32.3	1200.0
Central	Ang Thong	Pa Mok	Bang Sadet	1	1	22.0	34.0	1100.0

T_{max} = maximum temperature, T_{min} = minimum temperature. * Source: Thai Meteorological Department (TMD) in 2020.

2.2. Rice–Fish Co-Culture and Conventional Rice Systems

2.2.1. Rice–Fish Co-Culture System

Based on the 19 rice–fish co-culture farms in this study, two field types of rice–fish co-culture were identified, namely the canal refuge (Figure 1a) and pond refuge (Figure 1b). 'Khao Dawk Mali 105' (KDML 105), 'RD 6', and 'San Pah Tawng 1' varieties were found to be grown in paddy fields once a year. The transplanting method was used for planting, while harvesting was done by hand. The main species of farmed fish raised in the paddy fields were Nile tilapia (*Oreochromis niloticus*), Common snakehead (*Channa striata*), Common carp (*Cyprinus carpio*), Common silver barb (*Barbonymus gonionotus*), Mrigal carp (*Cirrhinus cirrhosus*), Seven-stripped carp (*Probarbus jullieni*), and Walking catfish (*Clarias batrachus* (Linnaeus)). Organic materials (rice husk, rice bran, pig manure, cattle manure, poultry manure, fruits and vegetables) were applied in the paddy fields to provide nutrients for rice and food for the fish.

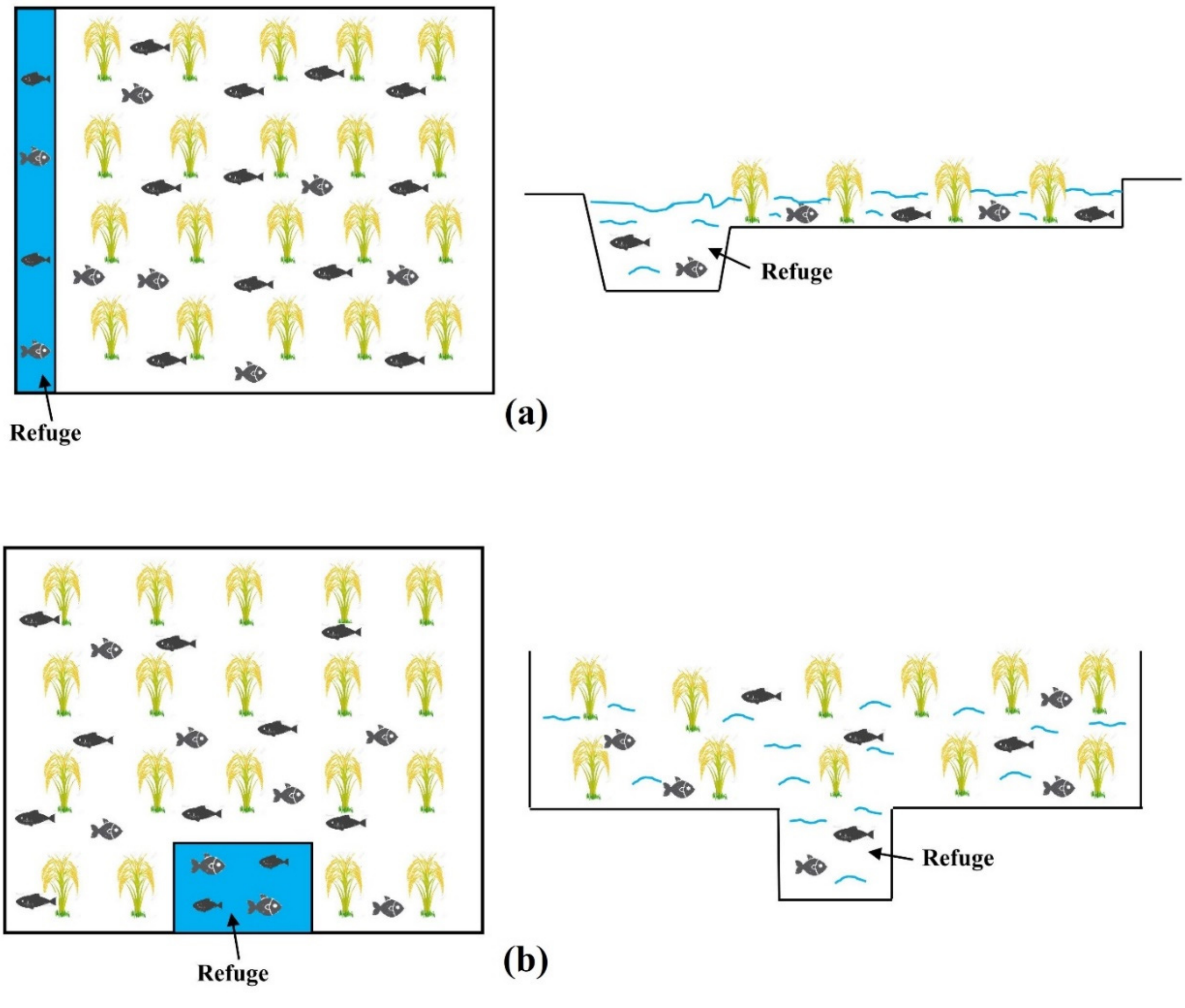

Figure 1. Rice–fish co-culture field type: (**a**) canal refuge and (**b**) pond refuge. Note: The refuges in our study sites were heterogeneous in size (depth and width).

2.2.2. Conventional Rice System

For a fair comparison, rice cultivation farms were chosen once a year. 'KDML 105', 'San Pah Tawng '1, 'RD 6', 'RD 41', 'RD 57', 'RD 79', and 'RD 85' varieties were grown on these farms. Chemical fertilizers (16-20-0, 46-0-0, 16-16-8, 16-8-8, and 15-15-15), insecticides, and herbicides were applied to enhance rice plant growth. Transplanting and broadcasting methods were found for conventional rice systems, depending on water availability. The broadcasting method is commonly used for areas subject to water shortages. A harvesting machine is usually used for harvesting.

2.3. Data Collection

Data on farm management practices in the two crop years (2019/2020 and 2020/2021) were collected from the owners of the rice–fish co-culture and conventional rice farms. The quantitative data were recorded from each farm, including rice field area, rice yield, fish yield, height of field ridge, volume of circular furrow, number of days of flooding in the field, annual irrigation volume, total number of tourists, and residence time. Moreover, the unit prices of rice, fish, and pesticides, reservoir engineering fee usage, water supply, and money received from tourism were recorded.

2.4. Ecosystem Service Value Evaluation Method

The Common International Classification for Ecosystem Services (CICES) version 5.1 (2018) was used [23] in this study. Based on the definition of ecosystem services in CICES version 5.1 (2018), Liu et al. [21] and Liu et al. [24] designed 23 ESV indicators and 3 sections (provisioning, regulation and maintenance, and cultural) (Table 2). Due to the lack of relevant studies in Thailand and limited data availability, 13 of the 23 indicators were applied in this study (Table 2).

Following The Economics of Ecosystems and Biodiversity (TEEB) method [25,26], three categories were widely used to express the ESVs in monetary units: the direct market method, equivalent factor method, and replacement costs method [27]. In this study, the direct market method was used to evaluate the "provisioning services", while the simulated market method was used to estimate the "development of tourism". Finally, the other ecosystem services were assessed based on the alternative market method. Based on Liu et al. [24], the formulas for calculating ESVs are presented below.

2.4.1. Provisioning Services

Rice and fish generate income for farmers depending on the yield and market prices.

$$V_1 = (Y_{rice} \times P_{rice}) + (Y_{fish} \times P_{fish})$$

where V_1 is the total income of primary products from paddy fields (THB ha^{-1} year^{-1}); Y_{rice} is rice yield (ton ha^{-1}); P_{rice} is the price of rice (THB ton^{-1} year^{-1}); Y_{fish} is the yield of fish (ton); and P_{fish} is the price of fish (THB ton^{-1} year^{-1}).

2.4.2. Gas Regulation

Rice farming regulates gases in the atmosphere by absorbing CO_2 and releasing O_2 through photosynthesis.

$$V_2 = E_{CO_2} + E_{O_2}$$

$$E_{CO_2} = Y_{Nrice} \times \alpha \times C_{CO_2} \times C_{STR}$$

$$E_{O_2} = Y_{Nrice} \times \varphi \times O_{cost}$$

$$Y_{Nrice} = Y_{rice} \times (1 - m)/\beta$$

where V_2 is the value of gas regulation from paddy fields (THB ha^{-1}), E_{CO_2} is the value of CO_2 fixed by rice (THB), Y_{Nrice} is the net rice yield (ton ha^{-1}), α is the amount of CO_2 fixed for 1 g of rice dry matter (1.63 g [24]), C_{CO_2} is the carbon content in CO_2 (27.27% [24]), C_{STR} is the Swedish carbon tax rate (133.26 USD ton^{-1} CO_2 on 1 November 2020 [28]), E_{O_2} is the value of rice-released O_2 (THB), φ is the amount of O_2 produced for 1 g of rice dry matter (1.19 g [24]), O_{cost} is the cost of industrial oxygen production (2092 THB ton^{-1} O_2, converted from Xu et al. [22]), Y_{rice} is rice yield (ton ha^{-1}), m is the moisture content of rice, and β is economic coefficient of rice (0.5 [24]).

2.4.3. Temperature and Humidity Regulation

Crop evapotranspiration and water evaporation in paddy fields can regulate heat and humidity in surrounding areas.

$$V_3 = W_{EV} \times H_{DS} \times \eta \times P_{Coal}$$

where V_3 is the value of temperature and humidity regulation from paddy fields (THB ha^{-1}), W_{EV} is the average daily water evaporation in the rice field (4.4 mm day^{-1}, generated using the CROPWAT 8.0 model), H_{DS} is the number of hot days in summer in the study area (days; obtained from the Thai Meteorological Department), η is the heat consumption for evaporating 50 mm of water in 1 ha of rice field (equal to burning 30.57 tons of coal) [24], and P_{Coal} is the price of standard coal (THB ton^{-1}).

2.4.4. Air Purification

Rice field ecosystems can purify the air by absorbing harmful gases (e.g., SO_2, NO_x, HF, and dust) in the atmosphere.

$$V_4 = (A_{SO_2} \times P_{SO_2}) + (A_{NO_X} \times P_{NO_X}) + (A_{HF} \times P_{HF}) + (A_D \times P_D)$$

where V_4 is the value of air purification from paddy fields, A_{SO2}, A_{NOX}, A_{HF}, and A_D are the average annual flux (kg) of SO_2, NO_x, HF, and dust absorbed by the paddy fields, respectively. Based on Ma et al. [29], the average annual flux of SO_2, NO_x, HF, and dust was 45.0, 33.3, 0.57, and 33,200 kg ha^{-1} year^{-1}, respectively. P_{SO_2}, P_{NO_X}, P_{HF}, and P_D are the costs of SO_2, NO_x, HF, and dust in the rice field, respectively (THB kg^{-1}). In this study, the costs of SO_2, NO_x, HF, and dust in the rice field were 7.53, 3.97, 4.34, and 0.94 THB kg^{-1}, respectively, which were converted from Ma et al. [29].

2.4.5. Pest Control

Fish can help reduce the weeds and pests in paddy fields by consuming them, resulting in a reduced demand for pesticides and herbicides.

$$V_5 = P_p \times R$$

where V_5 is the value of pest control from paddy fields (THB ha^{-1} year^{-1}); P_p is the average pesticide cost for the rice monoculture system (THB ha^{-1} year^{-1}); and R is the percentage of reduction in pesticide use for rice–fish co-culture.

2.4.6. Increase in Fauna Diversity and Microorganisms

Fish can control weeds and pests, which helps reduce the use of herbicides, pesticides, and chemical fertilizers, leading to increased species diversity.

$$V_6 = \tau \times V_P$$

where V_6 is the value of increase of fauna diversity and microorganisms from paddy fields (THB ha^{-1} year^{-1}), τ is the value-equivalent factor of the rice field ecosystem (0.21, [30]), and V_P is the equivalent product provisioning service (THB ha^{-1} year^{-1}).

2.4.7. Maintaining Soil Nutrients

Paddy fields are sources of GHG emissions, especially CO_2 and CH_4, whereas rice fields are sink pools of carbon through soil carbon sequestration.

$$V_7 = P_{OM} \times (IN_{OM} - OU_{OM})$$

$$IN_{OM} = (N_r \times C_r) + (N_s \times 11\% \times C_s)$$

$$OU_{OM} = (R_{CO_2} \times 0.27) + (R_{CH_4} \times 0.75)$$

where V_7 is the value of maintaining soil nutrient value from paddy fields (THB ha^{-1} year^{-1}); P_{OM} is the price of organic materials (7.69 THB kg^{-1} C, converted from Liu et al. [24]); IN_{OM} is the organic matter input from soil (kg C ha^{-1} year^{-1}); OU_{OM} is the output amount of soil organic matter (kg C ha^{-1} year^{-1}); R_{CO_2} is the amount of CO_2 emissions from rice fields (2123.63 kg ha^{-1} year^{-1}, [24]); R_{CH_4} is the amount of CH_4 emissions from rice fields (29.64 kg ha^{-1} year^{-1}, [24]); the constant values of 0.27 and 0.75 are the conversion coefficients of CO_2 and CH_4 into carbon, respectively; N_r and N_s are the biomass of the rice root system and straw (kg ha^{-1} year^{-1}), respectively; and C_r and C_s are the carbon content of the rice root system and straw (%), respectively.

In this study, a quadrat (1 m $\times$ 1 m) was used to randomly collect rice straw and rice roots with three replications from each field. Rice straw and rice roots were separated in the field and then put into plastic bags for laboratory analysis. The dry mass of rice straw and rice roots were determined after oven drying at 80 °C for 48 h. According to Ma et al. [31], the carbon content in rice straw and rice roots in this study was assumed to be 43.26% and 38.20%, respectively.

2.4.8. Water Conditions

Rice cultivation requires large amounts of water, mainly from rainfall, surface water, and groundwater. Moreover, paddy fields can provide water storage by storing rainwater on the surface and maintaining groundwater.

$$V_8 = E_{WS} + E_{GW}$$

$$E_{WS} = (H_R + V_{CF}/A) \times P_{RE}$$

$$E_{GW} = S_{WP} \times P_{WT} \times D_{FL}$$

where V_8 is the value of water conditions from paddy fields (THB ha^{-1} year^{-1}), E_{WS} is the value of the water storage function of the rice system (THB ha^{-1} year^{-1}), E_{GW} is the value of groundwater conservation (THB), H_R is the average height of the field ridge, V_{CF} is the volume of a circular furrow, A is the area of the rice field, P_{RE} is the unit price of the reservoir engineering fee usage (THB m^{-3}), S_{WP} is the soil water permeability in the rice field (6 mm, [24]), P_{WT} is the market price of water (THB m^{-3}, obtained from Provincial Waterworks Authority), and D_{FL} is the average days of flooding in the rice growing period (days).

2.4.9. Energy Losses for Irrigation

During the rice-growing period, maintaining the water level in the paddy field is very important, especially in rice–fish co-culture systems. However, water from rainfall may not be sufficient for rice cultivation throughout the growing period. Therefore, energy is required for pumping and lifting irrigation water from irrigation canals and groundwater.

$$V_9 = E_{IRR} \times P_{WS}$$

where V_9 is the value of energy losses from paddy fields (THB ha^{-1} year^{-1}), E_{IRR} is the average annual irrigation per area (m^3 ha^{-1} year^{-1}), and P_{WS} is the cost of the water supply in lifting irrigation (THB m^{-3}).

Table 2. Ecosystem services and goods and benefits valued from rice–fish co-cultures (following CICES V5.1; Liu et al. [21]; Liu et al. [24]).

CICES V5.1 Section	Division	Ecosystem Services of Rice–Fish Co-Cultures	Goods and Benefits Valued	Direction of Value
Provisioning	Biomass	1. Rice and fish provided food and nutrition	Provisioning service	Positive
Regulation and Maintenance	Transformation of biochemical or physical inputs to ecosystems	2. CO_2 fixation from photosynthesis	Gas regulation	Positive
		3. O_2 release from photosynthesis	Gas regulation	Positive
		4. SO_2, NOx, HF, and dust absorbed by the paddy field	Air purification	Positive
		5. Nutrient cycling and organic accumulation	Maintaining soil nutrients	Positive
		6. Reduction of GHG emissions	Maintaining soil nutrients	Positive
	Regulation of physical, chemical, biological conditions	7. Reducing land abandonment	X	X
		8. Improving soil salinization	X	X
		9. Pesticides and herbicides reduction	Pest control	Positive
		10. Regulation of temperature and humidity	Climate control	Positive
		11. Enhancing humidification and rain	X	X
		12. Increase of fauna diversity and micro-organisms	Biodiversity	Positive
		13. Increase water storage	Water storage and retention	Positive
		14. Groundwater conservation	Water storage and retention	Positive
		15. Energy losses in lifting irrigation	Energy losses for irrigation	Negative
Cultural	Other types of regulation and maintenance service	16. Securing the rural poor	X	X
	Direct, in situ, and outdoor interactions with living systems that depend on presence in the environmental setting	17. Development of tourism	Development of tourism	Positive
		18. Experiential use of plants, animals, and land	X	X
		19. Education opportunities	X	X
		20. Research subject	X	X
		21. Cultural value and heritage	X	X
		22. Artistic inspiration (theater, painting, sculpture)	X	X
		23. Willingness to preserve for future generations	X	X

Note: X represents ecological services that were not considered in this study due to no data available for calculation.

2.4.10. Development of Tourism

Paddy fields can serve as tourist attractions, enhancing the added value. The rice–fish co-culture system is a magnet used to attract visitors for relaxation and learning about rice–fish co-culture.

$$V_{10} = P_{TC} \times N_{TR} \times T$$

where V_{10} is the value of tourism development (THB ha^{-1} year^{-1}), P_{TC} is the amount of money from tourism consumption (THB person^{-1}), N_{TR} is the total number of tourists (person), and T is residence time.

3. Results

3.1. Farm Investigation

3.1.1. Rice–Fish Co-Culture Farms

The average height of the field ridge was 150 cm, and the average number of days of flooding during the rice–fish growing period was 110 days. The area of rice–fish fields was mostly around 0.15 ha, on average. The water level in rice–fish fields varied by 15–35 cm throughout the rice growing period. The amount of fish was approximately 1875–3125 fish ha^{-1}. One-month-old fish were released into the paddy field 30 days after rice planting. The water was drained out before rice harvesting at around 7–10 days; most of the fish escaped to the refuge pond and then were caught using nets after rice harvest.

The average rice yield was 3.6 ton ha^{-1} year^{-1}, with a range of 2.0 to 4.2 ton ha^{-1} year^{-1}. The average moisture content of rice was 14%. The average rice price ranged from 10 to 13 THB kg^{-1}. This is because the rice yield in rice–fish co-culture farms was organic rice, resulting in a higher price. The average yield of the fish products was 300 kg ha^{-1}, while the prices of the fish products ranged from 30 to 50 THB kg^{-1}. The average rice straw biomass was 12,008 kg ha^{-1}, while the average rice root biomass was 2401.6 kg ha^{-1}. The average rice root carbon content and rice straw carbon content were 37.2% and 42.1%, respectively. The average number of tourists who visited rice–fish co-culture farms was 53 persons year^{-1}.

3.1.2. Conventional Rice Farms

The average rice yield was 4.7 ton ha^{-1} year^{-1}, with a range of 3.8 to 5.6 ton ha^{-1} year^{-1}. The average moisture content of rice was 18%. The average rice price ranged from 7.5 to 8.0 THB kg^{-1}. The average biomass of the rice straw and rice roots was 1310 and 2135 kg ha^{-1}, respectively. The average rice root carbon content and rice straw carbon content were 32.1% and 37.4%, respectively.

3.2. Provisioning Services

The basic function of rice–fish co-culture is to provide rice and fish for food and nutrition, while the primary product of the rice monoculture system is rice. In 2020–2021, the revenue generated by rice–fish co-culture was approximately 50,400 THB ha^{-1} year^{-1}, on average. However, the average ecosystem service value of the rice monoculture system was estimated to be 37,600 THB ha^{-1} year^{-1}. Notably, ecosystem service values in this category increased 12,800 THB ha^{-1} year^{-1} annually, as rice–fish culture enhanced ecosystem services (25.40%) (Table 3). This is because the farmers received income from selling rice and fish.

Table 3. Ecosystem service values of rice–fish co-culture and rice monoculture systems during 2020–2021.

Ecosystem Services	Rice-Fish Co-Cultures (THB ha^{-1} $year^{-1}$)		Rice Monoculture System (THB ha^{-1} $year^{-1}$)		Changing of Ecological Service Values (THB ha^{-1} $year^{-1}$)
	Mean	SD	Mean	SD	
Positive value					
Rice and fish provided food and nutrition	50,400.0	868.8	37,600.0	618.8	12,800.0
CO_2 fixation from photosynthesis	358,092.2	139,500.7	456,106.6	90,978.7	−98,014.4
O_2 release from photosynthesis	14,697.9	5725.8	18,720.9	3734.2	−4023.0
SO_2, NOx, HF, and dust absorbed by the paddy field	31,681.5	0	31,681.5	0	0
Nutrient cycling and organic accumulation	23,798,852.3	0	21,678,588.0	0	2,120,264.3
Reduction of GHG emissions					
Pesticides and herbicides reduction	937,500.0	0	187,500.0	0	750,000.0
Regulation of temperature and humidity	23,179,661.4	0	20,018,798.5	0	3,160,862.9
Increase of fauna diversity and micro-organisms	10,584.0	182.4	7896.0	129.9	2688.0
Increase water storage	16,682.3	6341.9	295.0	6341.9	16,387.3
Groundwater conservation	13,992.0	1017.6	9540.0	1017.6	4452.0
Development of tourism	53,000.0	7000.0	0	0	53,000.0
Sub total	*48,465,143.6*	-	*42,446,726.5*	-	*6,018,417.2*
Negative value					
Energy losses in lifting irrigation	14,175.2	1786	24,128.0	2115.0	−9952.8
Sub total	*14,175.2*	-	*24,128.0*	-	*−9952.8*
Net value	**48,450,968.4**	**-**	**42,422,598.5**	**-**	**6,028,370.0**

3.3. *Regulation and Maintenance*

3.3.1. Gas Regulation

The mean value of the regulation service for CO_2 fixation from photosynthesis was 358,092.2 THB ha^{-1} $year^{-1}$ in the co-culture system, whereas the monoculture system earned 456,106.6 THB ha^{-1} $year^{-1}$. The annual decline in ESV can be seen in this regulation service. The O_2 released from photosynthesis in the two systems contributed to 14,697.9 and 18,720.9 THB ha^{-1} $year^{-1}$. A decrease of 4023.0 THB ha^{-1} $year^{-1}$ per annum was observed when evaluating the ESV in this service. The paddy fields absorb SO_2, NOx, HF, and dust, and this regulation service generates revenue of 31,681.5 THB ha^{-1} $year^{-1}$ in the co-culture system and 31,681.5 THB ha^{-1} $year^{-1}$ in the monoculture system (Table 3).

3.3.2. Nutrient Cycling and Organic Accumulation, and Reduction of GHG Emissions

The calculation of ESV from the ecosystem service related to nutrient cycling, organic accumulation, and reduction of GHG emissions was 23,798,852.3 THB ha^{-1} $year^{-1}$ in co-culture and 21,678,588.0 THB ha^{-1} $year^{-1}$ in monoculture. Remarkably, approximately half of the total ESV comes from this service in both systems. A significant annual increase in ESV was also found in this service (Table 3). This is because the biomass and carbon content in rice straw and roots of the rice–fish co-culture farms were higher than in rice monoculture.

3.3.3. Pesticide and Herbicide Reduction

Reducing the use of pesticides and herbicides enhances ecosystem services in several ways. The rice–fish co-culture system obtained an ESV of 937,500.0 THB ha^{-1} year^{-1}, while an annual ESV of approximately 187,500.0 THB ha^{-1} year^{-1} was received in the rice monoculture system. Moreover, the increase in ESV in this category was estimated to be 750,000.0 THB ha^{-1} year^{-1} (Table 3). Organic rice farming practiced in rice–fish co-culture does not require the application of chemical substances, leading to lower production costs and a reduction in environmental pollution.

3.3.4. Regulation of Temperature and Humidity

The valuation of the ecosystem service related to the regulation of temperature and humidity of rice–fish co-culture and rice monoculture systems resulted in 23,179,661.4 THB ha^{-1} year^{-1} and 20,018,798.5 THB ha^{-1} year^{-1}, respectively. This service generates nearly half of the total ESV in both systems. Furthermore, a significant increase in the annual ESV was notable, as rice–fish culture developed in an area (Table 3).

3.3.5. Increase in Fauna Diversity and Microorganisms

Increasing fauna diversity and microorganisms can improve the performance of ecosystem services. An ESV of 10,584.0 THB ha^{-1} year^{-1} was received from the co-culture and 7896.0 THB ha^{-1} year^{-1} from the monoculture. The ESV has risen annually by 2688.0 THB ha^{-1} year^{-1} (Table 3). Due to the higher provisioning services in rice–fish co-culture than rice monoculture, the ESV of fauna diversity and microorganisms increased. This demonstrates that avoiding the use of pesticides and herbicides can increase biodiversity in paddy fields.

3.3.6. Increase in Water Storage

The rice–fish co-culture system gained 16,682.3 THB ha^{-1} year^{-1} from this service, while the monoculture system earned 6341.9 THB ha^{-1} year^{-1}. The yearly increase in ESV was noteworthy (Table 3). Under the rice–fish co-culture system, the value of the water storage function increased due to the high volume of water stored on the surface, as well as the long period of flooding during the rice–fish growing period.

3.3.7. Groundwater Conservation

Groundwater conservation in co-culture and monoculture contributes 13,992.0 and 1017.6 THB ha^{-1} year^{-1}, respectively, with an annual increase of ESV 4452.0 THB ha^{-1} year^{-1} (Table 3). A longer period of flooding in rice–fish co-culture fields means that more groundwater can be stored through percolation and infiltration.

3.3.8. Energy Losses in Lift Irrigation

As a negative ESV, the valuation of energy losses in lifting irrigation was 14,175.2 THB ha^{-1} year^{-1} in the co-culture and 2115.0 THB ha^{-1} year^{-1} in monoculture. In this category, an ESV decrease of 9952.8 THB ha^{-1} year^{-1} occurred due to the development of rice–fish culture. Based on the field survey, most farmers used fossil fuel (diesel) for pumping water into paddy fields, while a few farms installed solar panels and used solar energy for water management in their fields. Using solar energy can reduce 19.5% of the energy cost compared with diesel fuel.

3.4. Cultural Services

Development of Tourism

Agrotourism is becoming increasingly popular in rice–fish regions. According to the farmers who participated in the survey, approximately 53 tourists were attracted by rice–fish activities in 2020–2021. Each tourist spends one day, and their average expenditure is 1000 THB. Therefore, the tourism contribution value of the rice–fish system was 53,000.0 THB ha^{-1} year^{-1}

(Table 3). Most of the visitors came to see the rice–fish co-culture and gain knowledge and experiences, and the rest visited to buy organic rice and fish products.

4. Discussion

4.1. Ecosystem Service Value of the Rice–Fish Co-Culture System

Integrated rice and fish have been recommended as a sustainable strategy for improving soil nutrient status and water resources, which provide carbohydrates and proteins to humans and reduce environmental pollution [8,32]. Moreover, the rice–fish co-culture system can alleviate local farmers' poverty and enhance social welfare [11,33]. When comparing the two systems in the current study, the rice–fish co-culture system has a higher net ESV value of 48,450,968.4 THB ha^{-1} $year^{-1}$ (Table 3). In addition, rice–fish co-culture generated average economic values 25.40% higher than rice monoculture farming (Table 3). The regulation services that occupied the largest portion of total ESV were nutrient cycling and organic accumulation, reduction of GHG emissions, and regulation of temperature and humidity (Figure 2). In contrast, the contributions of the remaining ESVs were not significant, and only a small portion of the net value was received from these services (Figure 2). Developing rice–fish co-culture has positive effects on provisioning services, as co-culture contributes to the increase of ESV in the area. Regarding gas regulation services, the benefits of the co-culture system cannot be seen in CO_2 fixation and O_2 release from photosynthesis. This is because rice yields from rice–fish co-culture farms were mostly lower than in the rice monoculture system. Furthermore, there was no significant change in the ESV of the two systems regarding SO_2, NOx, HF, and dust absorbed by the paddy field.

The most significant positive change in ESV can be seen in the regulation of temperature and humidity with 3,160,862.9 THB ha^{-1} $year^{-1}$ (Table 3). The service related to nutrient cycling and organic accumulation, and reduction of GHG emissions, takes second place in contributing to the improvement of ecosystem services (Figure 2). Paddy fields have the potential to improve soil physical and chemical properties, increase soil organic carbon, and mitigate CO_2 emissions in the atmosphere [21,34,35]. Increasing fauna diversity, microorganisms (bacteria, protozoa, algae, and fungi), and water storage, as well as groundwater conservation, make minor contributions to the increase in net ESV. These are in line with the studies of Nayak et al. [36] and Ren et al. [37], who reported that rice–fish co-cultures maintain the genetic diversity of aquatic organisms in paddy fields due to the reduction in the use of pesticides, insecticides, and chemical fertilizers. Wan et al. [38] found that finless eel and loach rice–fish co-cultural practices in China can help reduce the abundance of pests, leading to lower use of pesticides and a reduction in labor costs. This is consistent with our study, which found that even though the rice–fish co-cultural farms in our study areas practiced organic rice farming, the yields of organic rice were high, and there were fewer pests and diseases as well as weeds. This is because fish excrement can improve soil nutrients, and fish consume insects in paddy fields, while the water level can control the abundance of weeds. This is similar to the study of Xie et al. [8], which found that the level of water in paddy fields can reduce the abundance of rice planthoppers. Wan et al. [38] also found that the abundance of herbivore insects decreased by 24.07%, weed abundance was reduced by 67.62%, and invertebrate predator abundance increased by 19.48%.

Although agrotourism can generate revenue and increase the ESV, its proportion in the total value is not significant. However, tourists are interested in visiting rice–fish farming areas but not traditional monocultures. This means that the co-culture system has the potential to receive a higher ESV from this cultural service. Tourism can have direct benefits for farmers by creating marketing opportunities to sell their products to tourists [39] and may provide additional income to farmers from other agricultural activities, such as developing creative tourism, which provides a true experience of connection for tourists.

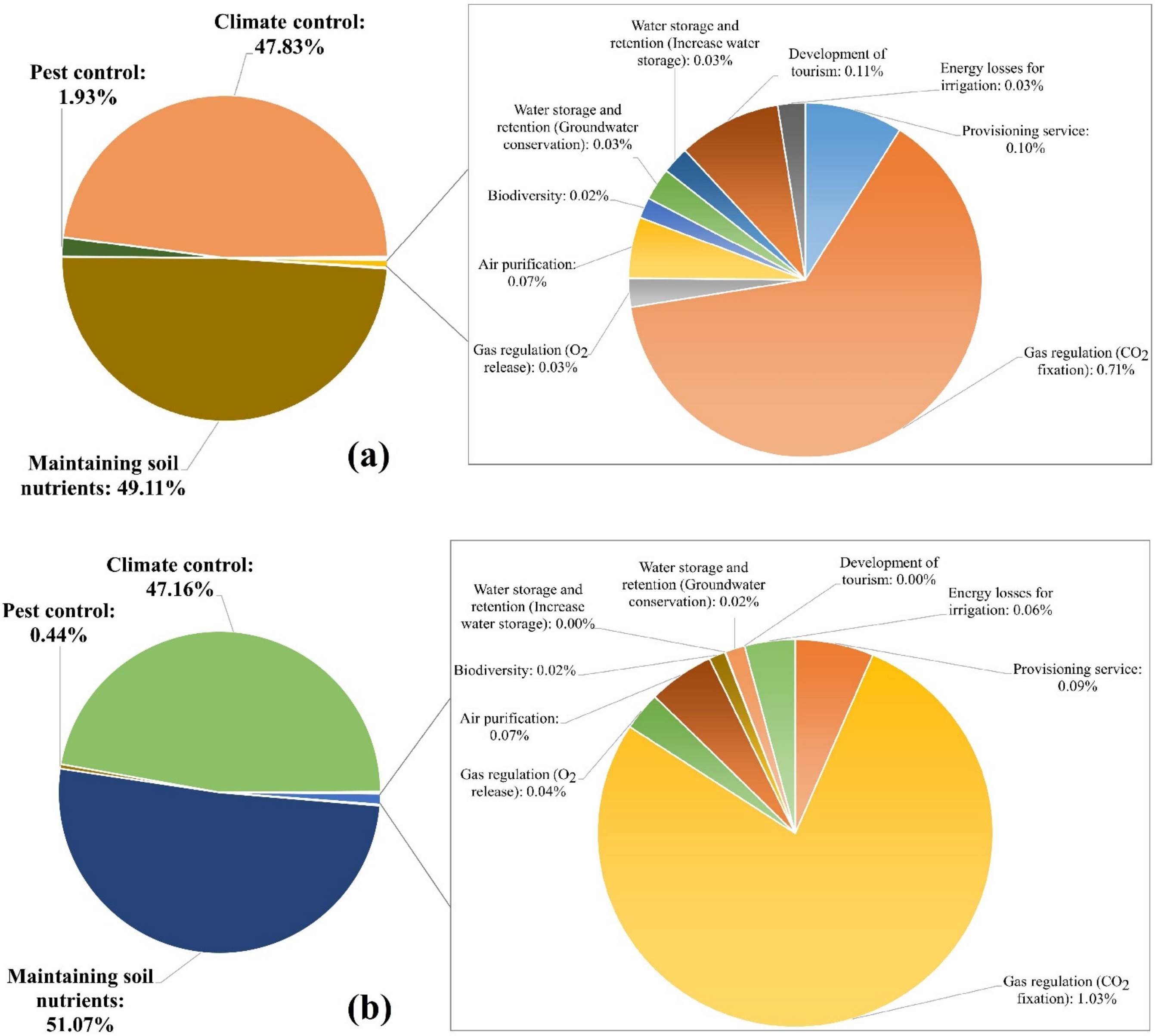

Figure 2. Proportion of service types: (**a**) rice–fish co-culture system, (**b**) rice monoculture system.

4.2. Policy Implications

Although integrated rice and fish farming has been practiced in Thailand for a long time, in recent years, the number of farms has been small, and the trend is declining. This is due to the intensification and modernization of rice cultivation focusing on maximizing yield, and urbanization involving converting paddy fields to commercial building and industrial factories. In addition, the impact of climate change is causing changes to the seasons and increasing the frequency and intensity of flood and drought events. Based on in-depth interviews, drought was the main cause of loss of rice and fish yields on farms in the northeastern region, while flooding caused damage in the northern and central regions. This indicates that rice–fish co-culture farming answers these challenges in Thailand.

The results demonstrated that rice–fish co-culture provides nutrient cycling and organic accumulation, reduction of GHG emissions, and regulation of temperature and humidity for the ecosystem (Table 3 and Figure 2). At the same time, rice–fish co-culture provides safe foods (rice and fish) and extra income for the farmers' households, implying that Thailand has great potential to be a rice–fish co-culture society because rice and fish are part of the ancestral food culture for Thai people. It is obvious that rice–fish co-culture could address more than one sustainable development goal (SDG), such as SDG 2 (zero hunger), SDG 12 (responsible consumption and production), SDG 13 (climate action), and SDG 14 (life below water). Therefore, policy implications should implement the following strategies to promote and support rice–fish co-culture: (1) develop innovation for better irrigation systems to reduce the impact from flood and drought events, (2) support the quantity of fish seed to increase the number of fish seed survival after release into paddy fields, (3) promote community learning centers for rice–fish co-culture to establish the farmer school, (4) strengthen the new innovative technology for pests and diseases control, (5) work as multi-stakeholders (farmer–officer–businessman–scholar), and (6) develop and promote the unique selling points of rice–fish co-culture, which are organic rice, organic fish, and destinations for travel. These strategies can help ensure the sustainability of the agricultural, environmental, and economic aspects of rice–fish co-culture in Thailand.

5. Conclusions

The rice–fish co-culture system has benefits for sustainability and ecology. At the same time, it must compete with commercial and advanced agricultural systems. Our findings showed that the rice–fish system provides more economic and ecological benefits than the rice monoculture system. The rice–fish co-culture system has a higher net ESV value of 48,450,968.4 THB ha^{-1} year^{-1} than rice monoculture (net ESV 42,422,598.5 THB ha^{-1} year^{-1}), which generated average economic values 25.40% higher than rice monoculture. The most positive change in ESV can be seen in the regulation of temperature and humidity, with 3,160,862.9 THB ha^{-1} year^{-1}. Services related to nutrient cycling and organic accumulation, and reduction of GHG emissions take second place in contributing to the improvement of ecosystem services. Further studies are recommended to explore and analyze the potential advantages of the rice–fish system in more detail.

Author Contributions: Conceptualization, N.A. and S.S.; methodology, N.A. and S.S.; investigation, N.A. and S.S.; writing—original draft preparation, N.A. and S.S.; writing—review and editing, N.A. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research project is supported by Mahidol University (Basic Research Fund: fiscal year 2021, contract number: BRF1-A8/2564). Moreover, this research project is supported by Mahidol University (contract number: A14/2564).

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of Institute for Population and Social Research, Mahidol University (IPSR-IRB) (COA. No. 2021/01-001 and COA. No. 2021/01-003).

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors extend their appreciation to Mahidol University (contract number: A14/2564 and BRF1-A8/2564). Furthermore, we would also like to thank Thailand Science Research and Innovation (TSRI) for their funding (contract number: BRF1-A8/2564).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wynn, T. *Rice Farming: How the Economic Crisis Affects the Rice Industry*; Rice Producers Forum USRPA: Houston, TX, USA, 2008.
2. Food and Agricultural Organization (FAO). *Rice in the World*; The Fifth External Programme and Management Review of the International Plant Genetic Resources Institute (IPGRI); FAO: Rome, Italy, 2001.
3. Global Rice Science Partnership (GRiSP). *Rice Almanac*, 4th ed.; International Rice Research Institute: Los Baños, Philippines, 2013.
4. Office of Agricultural Economics (OAE). *Agricultural Statistics of Thailand*; Ministry of Agriculture and Cooperatives: Bangkok, Thailand, 2021. Available online: https://www.oae.go.th/assets/portals/1/files/jounal/2565/yearbook2564.pdf (accessed on 20 December 2021).
5. Halwart, M.; Gupta, M.V. *Culture of Fish in Rice Fields*; FAO: Rome, Italy; The WorldFish Center: Penang, Malaysia, 2004.

6. Pingali, P.L.; Moya, P.F.; Velasco, L.E. *The Post-Green Revolution Blues in Asian Rice Production—The Diminished Gap between Experiment Station and Farmer Yields*; Social Science Division Paper No. 90-01; International Rice Researech Institute: Manila, Philippines, 1990.
7. Dwiyana, E.; Mendoza, T.C. Determinants of productivity and profitability of rice–fish farming systems. *Asia Life Sci.* **2008**, *17*, 21–42.
8. Xie, J.; Hu, L.L.; Tang, J.J.; Wu, X.; Li, N.; Yuan, Y.; Yang, H.; Zhang, J.; Luo, S.; Chen, X. Ecological mechanisms underlying the sustainability of the agriculture heritage rice–fish coculture system. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 1381–1387. [CrossRef] [PubMed]
9. Zhang, J.; Hu, L.L.; Ren, W.Z.; Guo, L.; Tang, J.J.; Shu, M.A.; Chen, X. Rice-soft shell turtle coculture effects on yield and its environment. *Agric. Ecosyst. Environ.* **2016**, *224*, 116–122. [CrossRef]
10. Frei, M.; Becker, K. Integrated rice–fish culture: Coupled production saves resources. *Nat. Resour. Forum.* **2005**, *29*, 135–143. [CrossRef]
11. Ahmed, N.; Garnett, S.T. Integrated rice-fish farming in Bangladesh: Meeting the challenges of food security. *Food Secur.* **2011**, *3*, 81–92. [CrossRef]
12. Ali, A.B. Seasonal dynamics of microcrustacean and rotifer communities in Malaysian rice fields used for rice-fish farming. *Hydrobiologia* **1990**, *206*, 139–148. [CrossRef]
13. Mackay, K.T.; Chapman, G.; Sollows, J.; Thongpan, N. Rice-fish culture in northeast Thailand: Stability and sustainability. In *Global Perspectives on Agroecology and Sustainable Agricultural System*; Allen, P., van Dusen, D., Eds.; University of California: Santa Cruz, CA, USA, 1987; pp. 355–372.
14. Willer, H.; Yussefi, M. The World of Organic Agriculture—Statistics and Emerging Trends 2006. International Federation of Organic Agriculture Movements (IFOAM), Research Institute of Organic Agriculture FiBL, 2006. Available online: https://orgprints.org/id/eprint/5161/2/willer-yussefi-2005-world-of-organic.pdf (accessed on 8 February 2022).
15. Office of Agricultural Economics (OAE). *Organic Agriculture Action Plan 2017–2022*; Ministry of Agriculture and Cooperatives: Bangkok, Thailand, 2020.
16. Lee, S. In the Era of Climate Change: Moving Beyond Conventional Agriculture in Thailand. *Asian J. Agric. Dev.* **2021**, *8*, 1–14. [CrossRef]
17. Millennium Ecosystem Assessment (MEA). *Ecosystems and Human Well-Beings: Synthesis*; Island Press: Washington, DC, USA, 2005; Available online: https://www.millenniumassessment.org/documents/document.356.aspx.pdf (accessed on 10 April 2021).
18. Costanza, R.; de Groot, R.; Braat, L.; Kubiszewski, I.; Fioramonti, L.; Sutton, P.; Farber, S.; Grasso, M. Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosyst. Serv.* **2017**, *28*, 1–16. [CrossRef]
19. Xie, J.; Liu, L.; Chen, X.; Chen, J.; Yang, X.X.; Tang, J.J. Control of Diseases, Pests and Weeds in Traditional Rice–fish Ecosystem in Zhejiang, China. *Bull. Sci. Technol.* **2009**, *25*, 802–810.
20. Berg, H.; Tam, N.T. Decreased use of pesticides for increased yields of rice and fish-options for sustainable food production in the Mekong Delta. *Sci. Total Environ.* **2018**, *619–620*, 319–327. [CrossRef]
21. Liu, D.; Tang, R.; Xie, J.; Tian, J.; Shi, R.; Zhang, K. Valuation of ecosystem services of rice-fish coculture systems in Ruyuan County. *China Ecosyst. Serv.* **2020**, *41*, 101054. [CrossRef]
22. Xu, Q.; Liu, T.; Guo, H.; Dou, Z.; Gao, H.; Zhang, H. Conversion from rice—Wheat rotation to rice—Crayfish coculture increases net ecosystem service values in Hung-tse Lake area, east China. *J. Clean. Prod.* **2021**, *319*, 128883. [CrossRef]
23. Haines-Young, R.; Potschin, M. *Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure*; Fabis Consulting Ltd.: Nottingham, UK, 2018; Available online: https://cices.eu/content/uploads/sites/8/2018/01/Guidance-V51-01012018.pdf (accessed on 10 April 2021).
24. Liu, D.; Feng, Q.; Zhang, J.; Zhang, K.; Tian, J.; Xie, J. Ecosystem services analysis for sustainable agriculture expansion: Rice-fish co-culture system breaking through the Hu Line. *Ecol. Indic.* **2021**, *133*, 108385. [CrossRef]
25. Costanza, R.; D' Arge, R.; de Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O' Neill, R.V.; Paruelo, J.; et al. The value of the world 's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. [CrossRef]
26. de Groot, R.; Brander, L.; van der Ploeg, S.; Costanza, R.; Bernard, F.; Braat, L.; Christie, M.; Crossman, N.; Ghermandi, A.; Hein, L.; et al. Global estimates of the value of ecosystems and their services in monetary units. *Ecosyst. Serv.* **2012**, *1*, 50–61. [CrossRef]
27. Christie, M.; Fazey, I.; Cooper, R.; Hyde, T.; Kenter, J.O. An evaluation of monetary and non-monetary techniques for assessing the importance of biodiversity and ecosystem services to people in countries with developing economies. *Ecol. Econ.* **2012**, *83*, 67–78. [CrossRef]
28. World Bank Group. Carbon Pricing Dashboard. Available online: https://carbonpricingdashboard.worldbank.org/ (accessed on 27 December 2020).
29. Ma, X.H.; Ren, Z.Y.; Sun, G.N. The calculation and assessment to the values of air purification by vegetation in Xi' An City. *Chin. J. Eco-Agric.* **2004**, *12*, 180–182. (In Chinese)
30. Xie, G.-D.; Zhang, C.-X.; Zhang, L.-M.; Chen, W.-H.; Li, S.-M. Improvement of the Evaluation Method for Ecosystem Service Value Based on Per Unit Area. *J. Nat. Resour.* **2015**, *30*, 1243–1254. (In Chinese)
31. Ma, S.; He, F.; Tian, D.; Zou, D.; Yan, Z.; Yang, Y.; Zhou, T.; Huang, K.; Shen, H.; Jingyun Fang, J. Variations and determinants of carbon content in plants: A global synthesis. *Biogeosciences* **2018**, *15*, 693–702. [CrossRef]

32. Hu, L.; Zhang, W.; Guo, L.; Cheng, Y.; Li, J.; Li, K.; Zhu, Z.; Zhang, J.; Luo, S.; Cheng, L.; et al. Can the co-cultivation of rice and fish help sustain rice production? *Sci. Rep.* **2016**, *6*, 28728. [CrossRef]
33. Berg, H.; Ekman Söderholm, A.; Söderström, A.-S.; Tam, N.T. Recognizing wetland ecosystem services for sustainable rice farming in the Mekong Delta, Vietnam. *Sustain. Sci.* **2017**, *12*, 137–154. [CrossRef] [PubMed]
34. Arunrat, N.; Kongsurakan, P.; Sereenonchai, S.; Hatano, R. Soil organic carbon in sandy paddy fields of Northeast Thailand: A Review. *Agronomy* **2020**, *10*, 1061. [CrossRef]
35. Arunrat, N.; Sereenonchai, S.; Kongsurakan, P.; Hatano, R. Assessing soil organic carbon, soil nutrients and soil erodibility under terraced paddy fields and upland rice in Northern Thailand. *Agronomy* **2022**, *12*, 537. [CrossRef]
36. Nayak, A.K.; Shahid, M.; Nayak, A.D.; Dhal, B.; Moharana, K.C.; Mondal, B.; Tripathi, R.; Mohapatra, S.D.; Bhattacharyya, P.; Jambhulkar, N.N.; et al. Assessment of ecosystem services of rice farms in eastern India. *Ecol. Process.* **2019**, *8*, 35. [CrossRef]
37. Ren, W.; Hu, L.; Guo, L.; Zhang, J.; Tang, L.; Zhang, E.; Zhang, J.; Luo, S.; Tang, J.; Chen, X. Preservation of the genetic diversity of a local common carp in the agricultural heritage rice-fish system. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, E546–E554. [CrossRef] [PubMed]
38. Wan, N.-F.; Li, S.-X.; Li, T.; Cavalieri, A.; Weiner, J.; Zheng, X.-Q.; Ji, X.-Y.; Zhang, J.-Q.; Zhang, H.-L.; Zhang, H.; et al. Ecological intensification of rice production through rice-fish co-culture. *J. Clean. Prod.* **2019**, *234*, 1002–1012. [CrossRef]
39. Hjalager, A.M. Agricultural diversification into tourism: Evidence of a European Community development programme. *Tour. Manag.* **1996**, *7*, 103–111. [CrossRef]