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Projection of Rainfed Rice Yield Using CMIP6 in the Lower Lancang–Mekong River Basin

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Abstract: Climate change has had a strong impact on grain production in the Lower Lancang–Mekong River Basin (LMB). Studies have explored the response of LMB rice yield to climate change, but most of them were based on climate projection data before CMIP6 (Coupled Model Intercomparison Project Phase 6). Based on the latest CMIP6 climate projection data and considering three emission scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5), this study used the crop growth model (AquaCrop) to simulate and project the LMB rice yield and analyzed the correlation between the yield and the temperature and precipitation during the growth period. The results show that the output of rice yield will increase in the future, with greater yield increases in the SSP5-8.5 scenario (about 35%) than in the SSP2-4.5 (about 15.8%) and SSP1-2.6 (about 9.3%) scenarios. The average temperature of the rice growth period will increase by 1.6 °C, 2.4 °C, and 3.7 °C under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively. The rice yield was predicted to have a significant positive response to the increase in temperature in the near future (2021–2060). In the far future (2061–2100), the rice yield will continue this positive response under the high-emission scenario (SSP5-8.5) with increasing temperature, while the rice yield under the low-emission scenario (SSP1-2.6) would be negatively correlated with the temperature. There will be a small increase in precipitation during the rice growth period of LMB in the future, but the impact of the precipitation on the rice yield is not obvious. The correlation between the two is not high, and the impact of the precipitation on the yield is more uncertain. This result is valuable for the management of the rice cultivation and irrigation system in the LMB, and it will help the government to adapt the impact of climate change on the rice production, which may contribute to the food security of the LMB under climate change.

Keywords: Lancang–Mekong River Basin; AquaCrop model; rice yield; temperature; precipitation

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1. Introduction

In recent years, global climate change has become a key topic, closely monitored by governments, experts, scholars, and society and closely related to human production and life [1]. Under the influence of climate change, the agricultural climate conditions are deteriorating. The occurrence of extreme rainfall events and the increase in drought pressure seriously threaten food production security [2–7]. Studies have pointed out that, in order to meet the expected demand for food of the growing global population, world food production must increase by 50% by 2050 [8,9]. Rice is one of the most important food crops in the world. More than half of the world's population has rice as its staple food, and its consumption increases year by year with population growth [10,11]. Climate change has always been one of the major constraints on the production of grain crops such as rice. Especially in developing countries, the planting and production of rice depend on weather conditions in many aspects [12–14].

In the Lower Lancang–Mekong River Basin (LMB, including large areas of Cambodia, Laos, Thailand, and Vietnam), rice is the main planting crop, with a planting area of about 15 million hectares, accounting for 28% of the total area of the region. Thailand and Vietnam are among the largest rice exporters in the world [15–17]. Nevertheless, there is still widespread poverty in the lower LMB, with millions of poor people facing severe food security risks [18]. The level of agricultural productivity in these countries is not high, and the ability to cope with the negative impact of climate change on food production is limited. The decline in rice production is worrying [15]. Many existing studies have analyzed the impact of climate change on water resources in the LMB, while less attention has been paid to the impact of climate change on rice cultivation [19–22], especially with the CMIP6 outputs. In addition, the results of the research have been contradictory. Some scholars have pointed out that higher temperatures and spatial and temporal deviations in precipitation will lead to lower rice yields; others believe that increased precipitation and higher CO_2 concentrations will increase rice yields. Some scholars and their views are shown in Table 1.

Table 1. Some scholars and their perspectives.

Scholars	Perspectives
Yamauchi et al. [16]	Climate change increases annual rainfall deviation, and insufficient precipitation in the early rainy season will lead to reduced rice yield.
Kang et al. [23]	Rice yield will increase due to increased CO_2 concentration and precipitation.
Jiang et al. [24]	Under rainfed conditions, seasonal changes in temperature rise and precipitation will significantly reduce rice yield, while the positive effect of CO_2 rise will significantly increase rice yield.
Poulton et al. [25]	Rice yield will decrease by about 4% for each 1 °C increase in air temperature over the baseline temperature.
Boonwichai et al. [26–28]	Higher temperatures will increase crop water requirements, and rice yields will decrease.

In general, these studies confirmed the positive impact of CO_2 on rice production, while the impact of the temperature on crops is two-sided. When the temperature exceeds certain thresholds, rice production is restricted, resulting in reduced yield, while the impact of precipitation on rice production is more uncertain.

Most studies on the impact of climate change on rice production in the LMB were not based on the newly available CMIP6 (Coupled Model Intercomparison Project Phase 6) projections. This study aims to explore this topic with the latest CMIP6 results, in order to better capture the impacts of climate change on rainfed rice. Considering three emission scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5), the rice yield in the historical period (HIS: 1981–2020) and two future periods, i.e., future short-term (NF) 2021–2060, and future far-term (FF) 2061–2100, of the LMB is evaluated and projected at the provincial level. This study is valuable for adjusting the rice cultivation and irrigation system and may contribute to the food security of the LMB under climate change.

2. Materials and Methods

2.1. Study Area

The Lancang–Mekong River is the main cross-border river in Southeast Asia. It extends from the Qinghai Tibet Plateau of China to the Lancang–Mekong Delta, with a total length of more than 4500 km and a drainage area of about 795,000 km^2. It is one of the seven major rivers in Southeast Asia [29,30]. The Lower Lancang–Mekong River Basin (LMB) is defined as the sub-basin of the Lancang–Mekong River located in Laos, Thailand, Cambodia, and Viatnam, with a total area of about 640,000 km^2, about three-quarters of the total area of the Lancang–Mekong River Basin. The terrain in the basin is complex; the upstream is mainly mountains and highlands, and the downstream is mainly plain with low altitude [31–33].

The farmland in the LMB is mainly distributed in the lower reaches of the basin. The study area includes 60 provinces in Cambodia, Laos, and Thailand. There are 20 provinces in Cambodia, 17 provinces in Laos, and 23 provinces in Thailand. With the high irrigation rate in the Vietnam Delta, the yield in the historical period was greatly influenced by irrigation; hence, it was difficult to distinguish the rainfall and irrigation effects without enough data support. Thus, Vietnam was not included in this study. The study area is located in the tropical monsoon zone, with a distinct rainy season and a dry season. The rainy season is from May to October, and the dry season is from November to April [34,35]. The main crop in the basin is rice. The planting dates vary from April to July, and the corresponding harvest dates are from September to November [36]. The study area is shown in Figure 1.

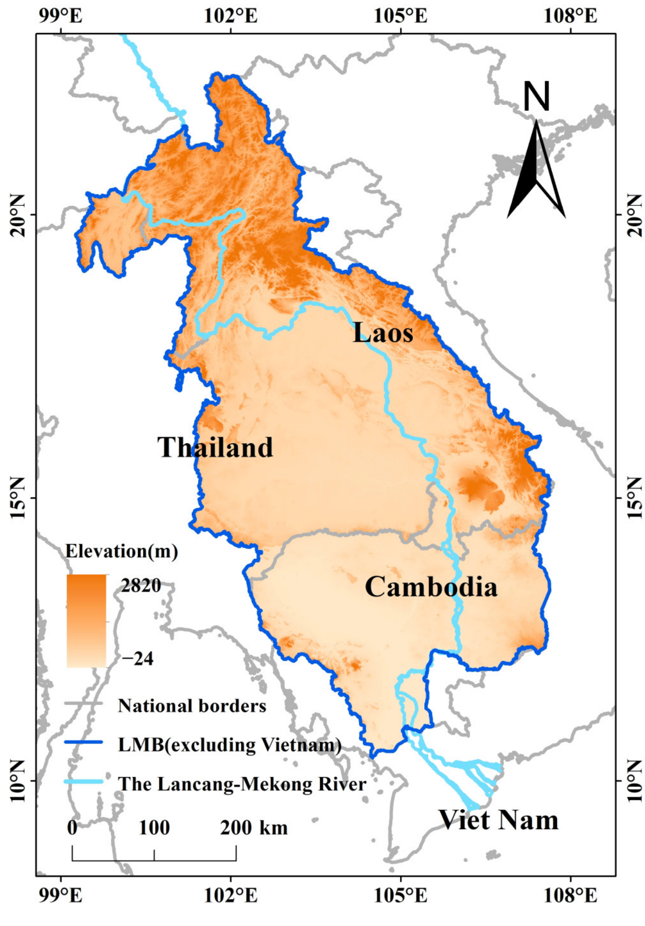

Figure 1. Topography of the LMB.

2.2. Historical Climate Data (1981–2020)

ERA5-Land is a reanalysis dataset published by the ECMWF (European Center for Medium-Range Weather Forecasts). It provides hourly data of global surface climate variables from 1981 to the near future with high spatial resolution [37]. Compared with the ERA5 and ERA-Interim, the horizontal resolution of the ERA5-Land has been improved from 31 km and 80 km to 9 km, and the ERA5-Land dataset has been extended to 1950 [38,39]. The ERA5-Land has higher accuracy and can be applied to the research of agricultural water resource planning, land use, and environmental management [39,40].

2.3. Future Climate Data (2021–2100)

The latest CMIP6 has a higher spatial resolution than the previous climate-coupled comparison projects, and its ability to simulate regional extreme rainfall and temperature has been significantly improved [41–43]. Unlike the representative concentration path (RCP) used by CMIP5, CMIP6 advocates emission scenarios according to the shared socioeconomic path (SSP) [44,45]. The research is based on eight models in CMIP6 under three SSPs (SSP1-2.6, SSP2-4.5, and SSP5-8.5); the details are shown in Table 2.

Table 2. The eight models of CMIP6 used in this research.

Model	Institution/Country	Resolution (km)	Grids (Latitude/Longitude)
CanESM5	Canadian Center for Climate Modelling and Analysis, Victoria, Canada	500	64 × 128
EC-Earth3-Veg	EC-Earth Consortium, Europe	100	256 × 512
FGOALS-g3	Chinese Academy of Sciences Flexible Global Ocean–Atmosphere–Land System Model, China	250	80 × 180
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory, NJ, USA	100	180 × 288
IPSL-CM6A-LR	Institute Pierre Simon Laplace (IPSL), Paris, France	250	143 × 144
MIROC6	Japan Agency for Marine–Earth Science and Technology (JAMSTEC), Kanagawa, Japan	250	128 × 256
MPI-ESM1-2-HR	Max Planck Institute for Meteorology (MPI-M), Germany	100	192 × 384
MRI-ESM2-0	Meteorological Research Institute, Ibaraki, Japan	100	160 × 320

https://wcrp-cmip.github.io/CMIP6_CVs/docs/CMIP6_source_id.html, accessed on 1 July 2022.

2.4. Research Method

The AquaCrop model was adopted in this study to simulate and project the rice yield in the LMB. The AquaCrop was developed by FAO's Water and Soil Division, which is used to solve food security problems and assess the impact of environment and management on crop production. AquaCrop simulates the yield response of herbaceous crops to water, which is especially suitable for the situation in the LMB, where water is the key limiting factor in crop production. Although the model is based on complex biophysical processes to ensure accurate simulation of crop response in the plant soil system, it only uses a few parameters and intuitive variables. This model estimates crop water demand by separating unproductive soil evaporation (*E*) and productive crop transpiration (*Tr*). The biomass yield (*B*) is estimated directly from the actual transpiration of crops using the water productivity parameter, which is then multiplied by the crop harvest index (*HI*) to obtain the final crop yield (*Y*). The calculation formula is as follows:

$$B = WP \times \sum Tr \tag{1}$$

$$Y = B \times HI \tag{2}$$

where *B* is the biomass, *WP* is the water productivity parameter, *Tr* is the actual transpiration of crops, *HI* is the harvest index, and *Y* is the final yield of crops.

The input data required by the model include climate data, crop data, soil data, and field management data.

The climate data mainly include the daily maximum temperature T_{max}, the daily minimum temperature T_{min}, the daily rainfall *P*, the daily reference evapotranspiration E_{t0}, and the annual average CO_2 concentration. The daily reference evapotranspiration was calculated using the Penman–Monteith formula recommended by the FAO, and the CO_2 data were from the Global Monitoring Laboratory of the National Oceanic and Atmospheric Administration (NOAA) of the USA.

The crop data mainly reflect the phenological characteristics of rice crops, including the planting date, harvest date, harvest index (*HI*), water productivity parameter (*WP*), crop coefficient (K_c), and some conservative parameters (see Table 3).

Table 3. Conservative parameters for rice.

Parameters	Description	Reference Value (Range)
WP	Water productivity normalized for ET_0 and CO_2	19 (g/m^2)
K_c	Crop coefficient when canopy is complete but prior to senescence	0.45–1.29
T_{base}, T_{upp}	Base and upper temperatures, respectively	8 °C, 30 °C
Z_{min}, Z_{max}	Minimum and maximum effective rooting depth, respectively	0.3 m, 0.5 m
CGC	Canopy growth coefficient	0.006–0.008
CDC	Canopy decline coefficient	0.005

FAO. Reference manual for AquaCrop version 6.0/6.1—Annexes. 2018. https://www.fao.org/aquacrop/software/aquacropstandardwindowsprogramme/en/, accessed on 24 February 2022.

The soil data include the soil type data of each province in the LMB, which were extracted from the Harmonized World Soil Database provided by the FAO (using the soil classification standard of the US Department of Agriculture, see Table 4).

Table 4. Soil types.

Code	Texture
1	Clay (heavy)
2	Silty clay
3	Clay
4	Silty clay loam
5	Clay loam
6	Silt
7	Silt loam
8	Sandy clay
9	Loam
10	Sandy clay loam
11	Sandy clay
12	Loam sand
13	Sand

FAO. Harmonized World Soil Database (Version 1.1, 2009) https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/, accessed on 4 April 2023.

The field management patterns include rainfed and irrigated patterns. Less than one-quarter of the total area is irrigated in the LMB; it is mostly concentrated in the delta plain of Vietnam, and the irrigation efficiency is not high within the area of this study [46,47]. Considering that the purpose of this study is to investigate the effect of climate change on rice, the rainfed model was set uniformly.

Figure 2 shows the spatial distribution of the soil types in each province in the study area.

2.5. Model Evaluation

According to the rice observation data of each province in the basin (Table 5), the calibration period was from the data start year of each country to 2015, and the verification period was from 2016 to the data end year of each country. Our survey found that rice production in Cambodia and Thailand was mainly in the rainy season, with over 80% of fields planting rice only in the rainy season [48–55]. Considering that the dry-season rice has a similar unit yield to the rainfed rice [49,56], although we could not distinguish the rainy-season rice yield from that of the dry season in the harvest data of Cambodia and Thailand, it is believed that such bias had a very small influence on the calibration of the model.

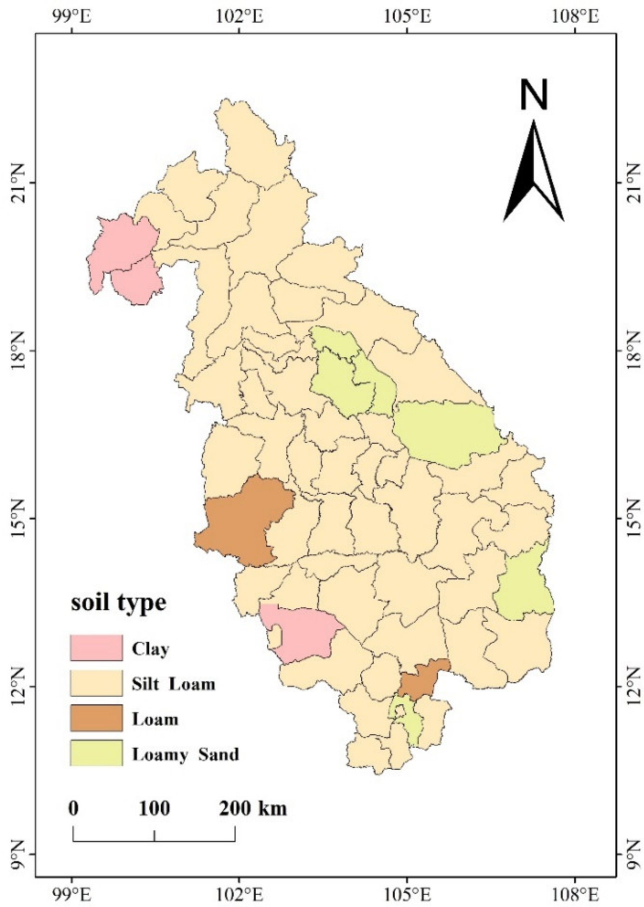

Figure 2. Soil types in the LMB.

Table 5. The observed data.

Country	Data Information	Source	Calibration Period	Verification Period
Cambodia (20 provinces)	2008–2019 Annual yield and harvested area	MRC Socioeconomic Database: https://www.mrcmekong.org, accessed on 15 May 2022. Cambodian National Bureau of Statistics: http://www.nis.gov.kh/index.php/km, accessed on 16 May 2022.	2008–2015	2016–2019
Laos (17 provinces)	2010–2019 Rainy season yield and harvested area	Lao National Bureau of Statistics (LAOSIS): http://www.lsb.gov.la/en/home/, accessed on 18 May 2022.	2010–2015	2016–2019
Thailand (23 provinces)	2011–2020 Annual yield and harvested area	Thailand National Agricultural Big Datacenter: https://www.nabc.go.th, accessed on 20 May 2022.	2011–2015	2016–2020

According to the observed rice yield, the accuracy of the simulation yield was evaluated, and the root-mean-square error and relative error were calculated to verify the simulation accuracy of the model. The calculation formulas of the root-mean-square error (*RMSE*) and relative error (*RE*) are as follows:

$$RMSE = \sqrt{\frac{1}{n}\left(\sum_{i=1}^{n}(S_i - O_i)^2\right)} \tag{3}$$

$$RE = \frac{S_i - O_i}{O_i} \quad (4)$$

where S_i refers to the simulated yield, and O_i refers to the observed yield.

2.6. Correlation Analysis

The Pearson correlation coefficient is widely used to measure the degree of correlation between two variables, and its value is between −1 and 1, as proposed by Pearson in the 1880s. In this study, the Pearson correlation coefficient was used to evaluate the correlation between the rice yield and temperature and precipitation during the growth period. The calculation formula is as follows:

$$\mathrm{r} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \quad (5)$$

where x_i is the temperature or precipitation, $\overline{x}$ is its average value, y_i is the yield, and $\overline{y}$ is its average value.

3. Results

3.1. Model Calibration Result

The results showed that the planting dates in the study area ranged from late May to mid-July. The planting dates of provinces in Cambodia and Laos varied widely. The planting dates of provinces in Thailand were relatively concentrated in June. Except for the harvest dates of provinces in Cambodia that spanned October and November, the harvest dates of Laos and Thailand were all concentrated in October. The average growth period of rice in the three countries was 130, 135, and 134 days, respectively, which was basically consistent with the existing research results [57]. The planting date and harvest date of each country are shown in Figure 3.

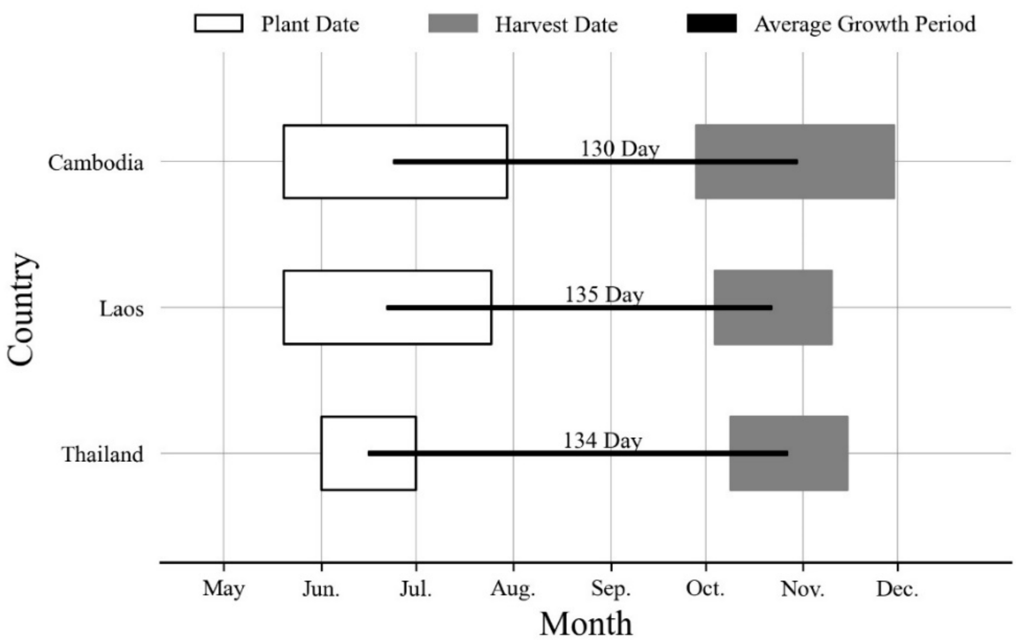

Figure 3. Growth period of rice.

The calibrated *HI* and observed and simulated multiyear average yields for each province for the rate period are shown in Figure 4. Cambodia, Laos, and Thailand had average His of 0.21, 0.21, and 0.16, respectively. Laos's Vientiane Province had the highest average yield (4.459 t/ha) and *HI* value (0.29). Thailand's Sa Kaeo Province had the lowest average yield (1.988 t/ha) and *HI* value (0.13).

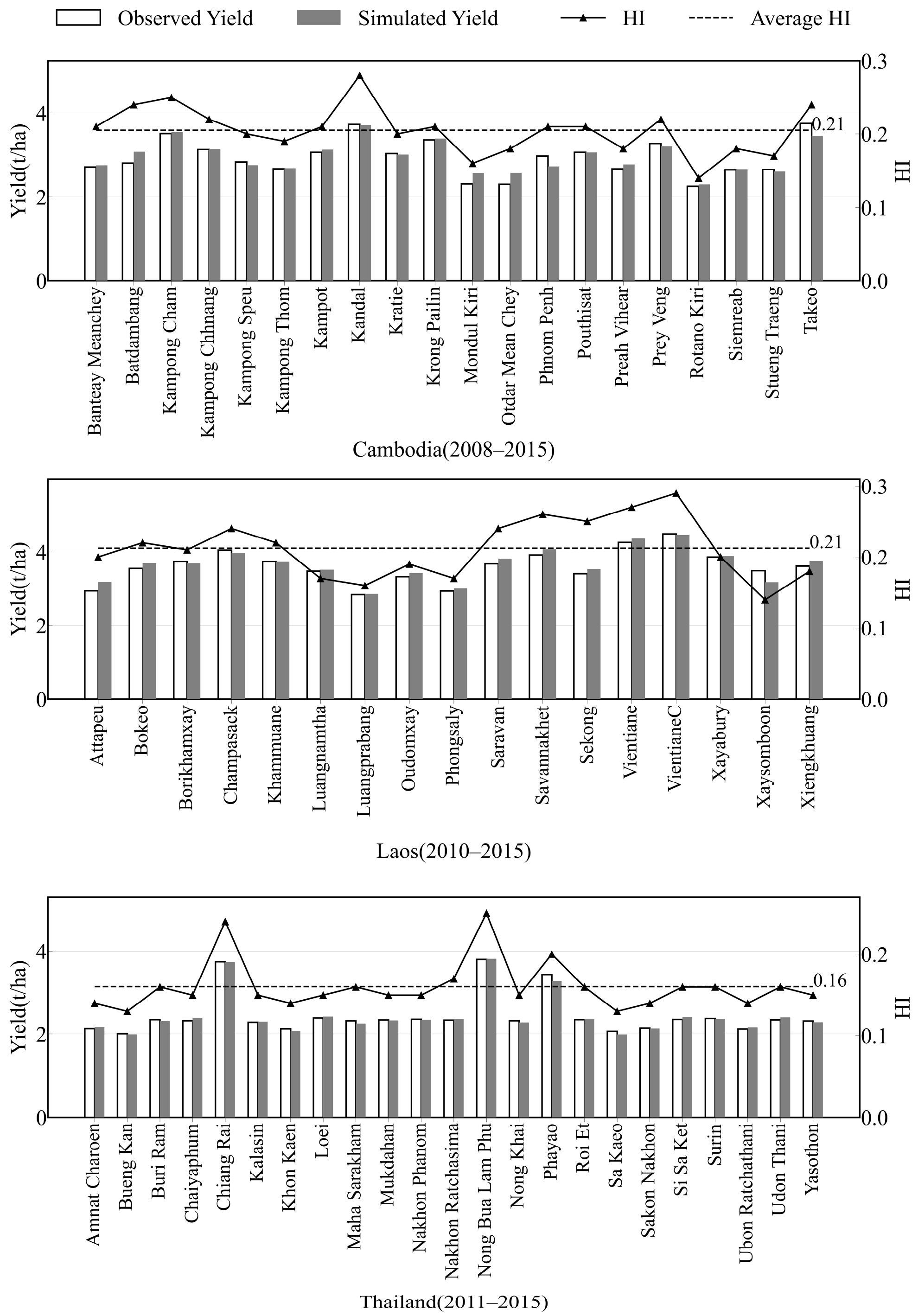

Figure 4. The yield and HI of different countries.

Figure 5 displays the observed and simulated yields for each province during the calibration period's *RMSE* and *RE*. The *RMSE* value was within a tolerable range for all provinces, ranging from 0.038 to 0.666 (t/ha), accounting for 1.7% to 20.9% of the simulated rice production; the *RE* was highest in Cambodia's Otdar Mean Chey province (0.115) and lowest in Laos's Khammuane province (0.0). The results for each province during the calibration and validation periods are shown in Tables 6–8.

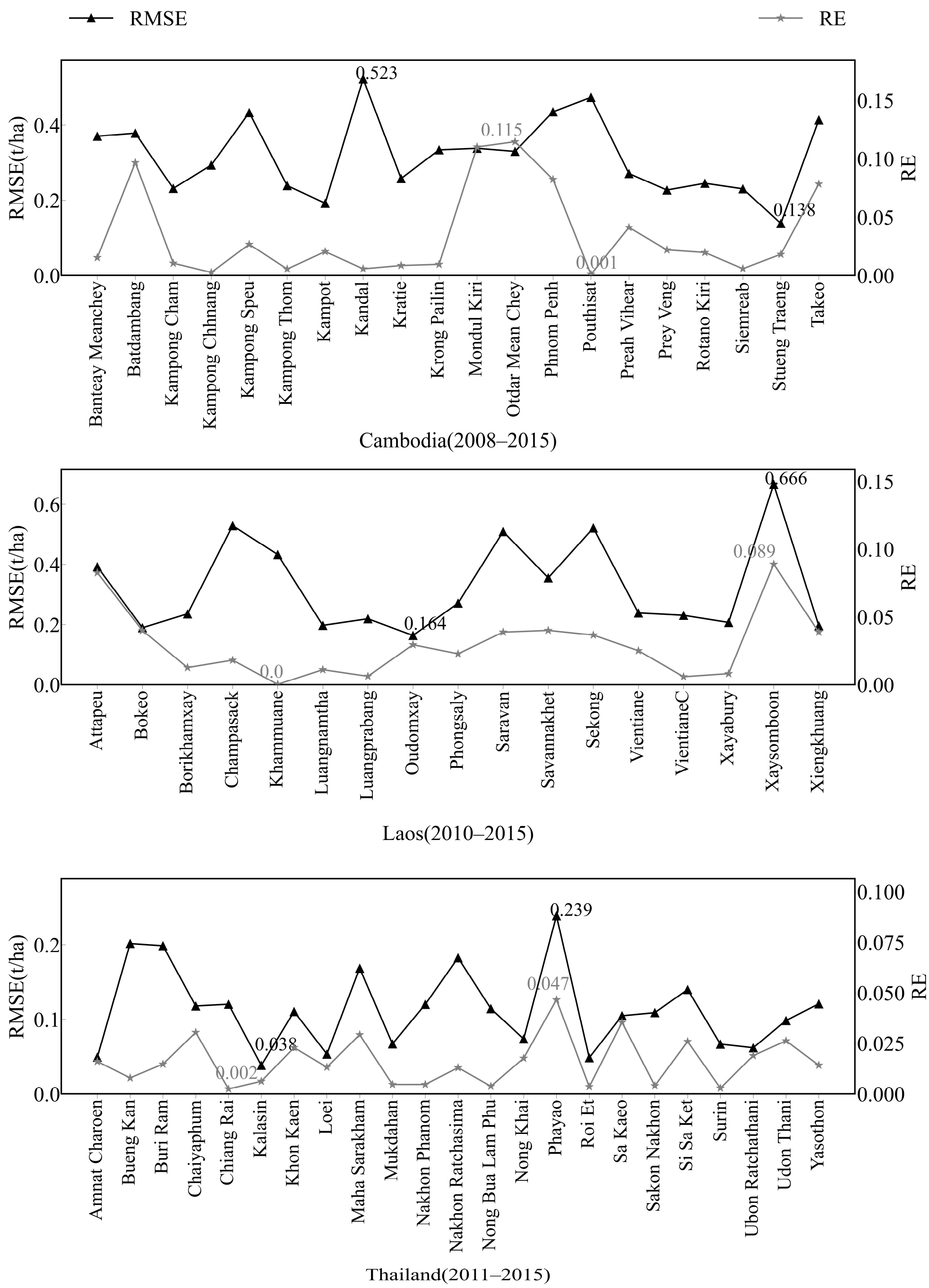

Figure 5. The *RMSE* and *RE* in the three countries.

The average observed yield, simulated yield, *RMSE*, and *RE* of each country are shown in Table 9. During the calibration period, the maximum *RMSE* was 0.233 (t/ha) in Laos, and the minimum was 0.057 (t/ha) in Thailand, accounting for 6% and 2.4% of the simulated average yield, respectively. The maximum RE was 0.018 in Laos, and the minimum was 0.001 in Thailand. During the validation period, the *RMSE* and *RE* values of Thailand were the lowest, and the model simulation accuracy was better than that of Cambodia and Laos. Overall, the *RMSE* and *RE* values for each country during the validation and rate periods were within 0.4 and 0.05, and the model simulations met the accuracy requirements.

Table 6. The rice yield of each province in Cambodia (2008–2019).

Province	Plant Date	Harvest Date	*HI*	Calibration Period (2008–2015)				Validation Period (2016–2019)			
				Observation Yield (t/ha)	Simulation Yield (t/ha)	*RMSE*	*RE*	Observation Yield (t/ha)	Simulation Yield (t/ha)	*RMSE*	*RE*
Banteay Meanchey	06/20	10/30	0.21	2.711	2.752	0.371	0.015	3.231	2.982	0.431	0.077
Batdambang	07/30	11/30	0.24	2.803	3.074	0.379	0.097	3.308	3.003	0.559	0.092
Kampong Cham	06/20	10/30	0.25	3.505	3.542	0.231	0.011	3.675	3.697	0.101	0.006
Kampong Chhnang	06/30	11/08	0.22	3.125	3.134	0.294	0.003	3.553	3.271	0.401	0.079
Kampong Speu	07/10	11/20	0.20	2.831	2.755	0.433	0.027	3.025	3.014	0.095	0.004
Kampong Thom	06/10	10/20	0.19	2.666	2.68	0.239	0.006	3.001	2.736	0.353	0.088
Kampot	06/10	10/17	0.21	3.061	3.123	0.192	0.02	3.225	3.197	0.113	0.009
Kandal	07/01	11/10	0.28	3.722	3.701	0.523	0.006	3.949	4.121	0.259	0.043
Kratie	06/10	10/20	0.20	3.031	3.005	0.258	0.009	3.25	3.062	0.195	0.058
Krong Pailin	06/10	10/17	0.21	3.356	3.388	0.334	0.01	3.135	3.432	0.366	0.095
Mondul Kiri	06/20	10/30	0.16	2.311	2.565	0.338	0.11	2.825	2.602	0.234	0.079
Otdar Mean Chey	06/20	10/30	0.18	2.304	2.568	0.33	0.115	2.802	2.593	0.392	0.075
Phnom Penh	06/10	10/20	0.21	2.97	2.726	0.435	0.082	2.83	2.997	0.209	0.059
Pouthisat	07/25	11/25	0.21	3.06	3.058	0.474	0.001	3.192	3.079	0.669	0.035
Preah Vihear	06/10	10/20	0.18	2.665	2.774	0.271	0.041	3.103	2.825	0.432	0.089
Prey Veng	06/20	10/30	0.22	3.271	3.199	0.227	0.022	3.627	3.324	0.314	0.084
Rotano Kiri	06/10	10/19	0.14	2.255	2.299	0.245	0.02	2.4	2.331	0.125	0.029
Siemreab	06/20	10/30	0.18	2.644	2.659	0.23	0.006	2.825	2.669	0.257	0.055
Stueng Traeng	06/10	10/19	0.17	2.652	2.604	0.138	0.018	2.653	2.664	0.158	0.004
Takeo	06/30	10/30	0.24	3.745	3.451	0.414	0.078	3.4	3.655	0.832	0.075

Table 7. The rice yield of each province in Laos (2010–2019).

Province	Plant Date	Harvest Date	*HI*	Calibration Period (2010–2015)				Validation Period (2016–2019)			
				Observation Yield (t/ha)	Simulation Yield (t/ha)	*RMSE*	*RE*	Observation Yield (t/ha)	Simulation Yield (t/ha)	*RMSE*	*RE*
Attapeu	07/03	11/10	0.2	2.945	3.189	0.392	0.083	3.317	3.212	0.647	0.032
Bokeo	06/01	10/16	0.22	3.553	3.695	0.189	0.040	3.815	3.758	0.181	0.015
Borikhamxay	06/01	10/16	0.21	3.738	3.691	0.235	0.013	3.939	3.751	0.287	0.048
Champasack	07/10	11/20	0.24	4.049	3.975	0.529	0.018	4.364	3.983	0.438	0.087
Khammuane	06/10	10/10	0.22	3.739	3.740	0.433	0.000	4.006	3.808	0.595	0.049
Luangnamtha	06/15	11/06	0.17	3.477	3.515	0.197	0.011	3.258	3.499	0.278	0.074
Luangprabang	06/20	10/30	0.16	2.842	2.860	0.219	0.006	2.791	2.858	0.310	0.024
Oudomxay	06/15	11/06	0.19	3.327	3.425	0.164	0.029	3.487	3.417	0.357	0.020
Phongsaly	05/20	10/04	0.17	2.941	3.008	0.271	0.023	3.134	3.012	0.132	0.039
Saravan	06/02	10/10	0.24	3.676	3.819	0.509	0.039	4.197	3.961	0.370	0.056
Savannakhet	06/10	10/20	0.26	3.917	4.074	0.355	0.040	4.233	4.181	0.324	0.012
Sekong	07/20	11/10	0.25	3.409	3.533	0.521	0.037	4.012	3.906	0.366	0.026
Vientiane	06/01	10/16	0.27	4.256	4.363	0.238	0.025	4.474	4.418	0.233	0.013
VientianeC	06/15	11/06	0.29	4.485	4.459	0.231	0.006	4.488	4.544	0.115	0.012
Xayabury	06/01	10/23	0.2	3.859	3.890	0.207	0.008	4.026	3.919	0.184	0.027
Xaysomboon	06/10	10/30	0.14	3.490	3.179	0.666	0.089	3.202	3.378	0.269	0.055
Xiengkhuang	06/15	11/06	0.18	3.615	3.755	0.196	0.039	3.760	3.656	0.218	0.027

Table 8. The rice yield of each province in Thailand (2011–2020).

Province	Plant Date	Harvest Date	*HI*	Calibration Period (2011–2015)				Validation Period (2016–2020)			
				Observation Yield (t/ha)	Simulation Yield (t/ha)	*RMSE*	*RE*	Observation Yield (t/ha)	Simulation Yield (t/ha)	*RMSE*	*RE*
Amnat Charoen	06/20	11/04	0.14	2.125	2.159	0.049	0.016	2.2	2.141	0.076	0.027
Bueng Kan	06/10	10/25	0.13	2.005	1.989	0.202	0.008	1.958	2.005	0.076	0.024
Buri Ram	06/20	10/28	0.16	2.351	2.317	0.199	0.015	2.249	2.349	0.179	0.045
Chaiyaphum	06/10	10/18	0.15	2.323	2.394	0.118	0.03	2.288	2.399	0.137	0.049
Chiang Rai	06/15	10/27	0.24	3.746	3.737	0.12	0.002	3.544	3.781	0.257	0.067
Kalasin	06/20	11/01	0.15	2.285	2.299	0.038	0.006	2.319	2.261	0.096	0.025
Khon Kaen	06/25	11/02	0.14	2.121	2.072	0.11	0.023	2.089	2.062	0.102	0.013
Loei	06/10	10/18	0.15	2.393	2.425	0.053	0.013	2.31	2.417	0.142	0.046
Maha Sarakham	06/01	10/09	0.16	2.321	2.253	0.169	0.029	2.249	2.185	0.273	0.028
Mukdahan	06/15	10/30	0.15	2.342	2.331	0.067	0.005	2.457	2.299	0.194	0.064
Nakhon Phanom	07/01	11/15	0.15	2.36	2.349	0.12	0.005	2.233	2.286	0.136	0.024
Nakhon Ratchasima	06/25	11/02	0.17	2.338	2.368	0.183	0.013	2.244	2.429	0.33	0.083
Nong Bua Lam Phu	06/20	10/28	0.25	3.8	3.815	0.114	0.004	3.828	3.692	0.264	0.035
Nong Khai	06/15	10/30	0.15	2.322	2.281	0.074	0.018	2.271	2.318	0.066	0.021
Phayao	06/20	10/28	0.2	3.44	3.28	0.239	0.047	3.076	3.244	0.187	0.055
Roi Et	06/10	10/22	0.16	2.35	2.359	0.049	0.004	2.265	2.332	0.101	0.03
Sa Kaeo	06/10	10/22	0.13	2.06	1.988	0.105	0.035	2.006	1.999	0.068	0.003
Sakon Nakhon	06/15	10/30	0.14	2.138	2.13	0.109	0.004	2.159	2.023	0.181	0.063
Si Sa Ket	06/15	10/30	0.16	2.356	2.417	0.14	0.026	2.238	2.355	0.17	0.052
Surin	06/10	10/22	0.16	2.378	2.372	0.067	0.003	2.358	2.273	0.182	0.036
Ubon Ratchathani	07/01	11/15	0.14	2.117	2.157	0.062	0.019	2.202	2.157	0.074	0.021
Udon Thani	06/10	10/22	0.16	2.343	2.405	0.098	0.026	2.31	2.427	0.127	0.051
Yasothon	06/20	11/01	0.15	2.318	2.285	0.121	0.014	2.26	2.271	0.072	0.005

Table 9. The yield and evaluation indicators of the countries in the calibration and validation periods.

Country	Calibration Period				Validation Period			
	Observation Yield (t/ha)	Simulation Yield (t/ha)	*RMSE*	*RE*	Observation Yield (t/ha)	Simulation Yield (t/ha)	*RMSE*	*RE*
Cambodia	3.047	3.052	0.230	0.002	3.276	3.131	0.213	0.044
Laos	3.797	3.866	0.233	0.018	4.034	3.920	0.236	0.028
Thailand	2.353	2.356	0.057	0.001	2.302	2.334	0.089	0.014

3.2. Changes in Rice Yield in History and in the Future

On the basis of the model calibration results, this study simulated the rice yields in the Lower Mekong River Basin for the entire historical period (HIS: 1981–2021) and two future projection periods (NF: 2021–2060 and FF: 2061–2100) for each province. Figures 6–8 show the simulated annual average rice yields for the entire simulation period for the three countries in the basin, where the historical period is the simulated historical rice yield based on the ERA5-Land climate data, and the NF and FF periods are the simulated future yield ranges for rice based on the latest CMIP6 8-model climate data. In the historical period, the simulated rice output of various countries gradually increased. From the first 10 years (1981–1990) to the last 10 years (2011–2020), the average simulated output of Cambodia, Laos, and Thailand increased from 2.678, 3.480, and 1.995 tons per hectare to 3.103, 3.877, and 2.343 tons per hectare, increases of 0.425, 0.397, and 0.348 tons per hectare respectively.

Over the future projection period, the rice yields also showed an increasing trend, with greater yield increases in the SSP5-8.5 (about 35%) scenario than in the SSP2-4.5 (about 15.8%) and SSP1-2.6 (about 9.3%) scenarios. Comparing the average simulated yields for the last 20 years of the 21st century with the average simulated yields for the first 20 years of the 21st century, Cambodia, Laos, and Thailand increased by 14.1%, 4.1%, and 11.5%, respectively, in the SSP1-2.6 scenario, by 22%, 11.7%, and 14.4%, respectively, in the SSP2-4.5 scenario, and by 43.8%, 25.6%, and 39%, respectively, in the SSP5-8.5 scenario.

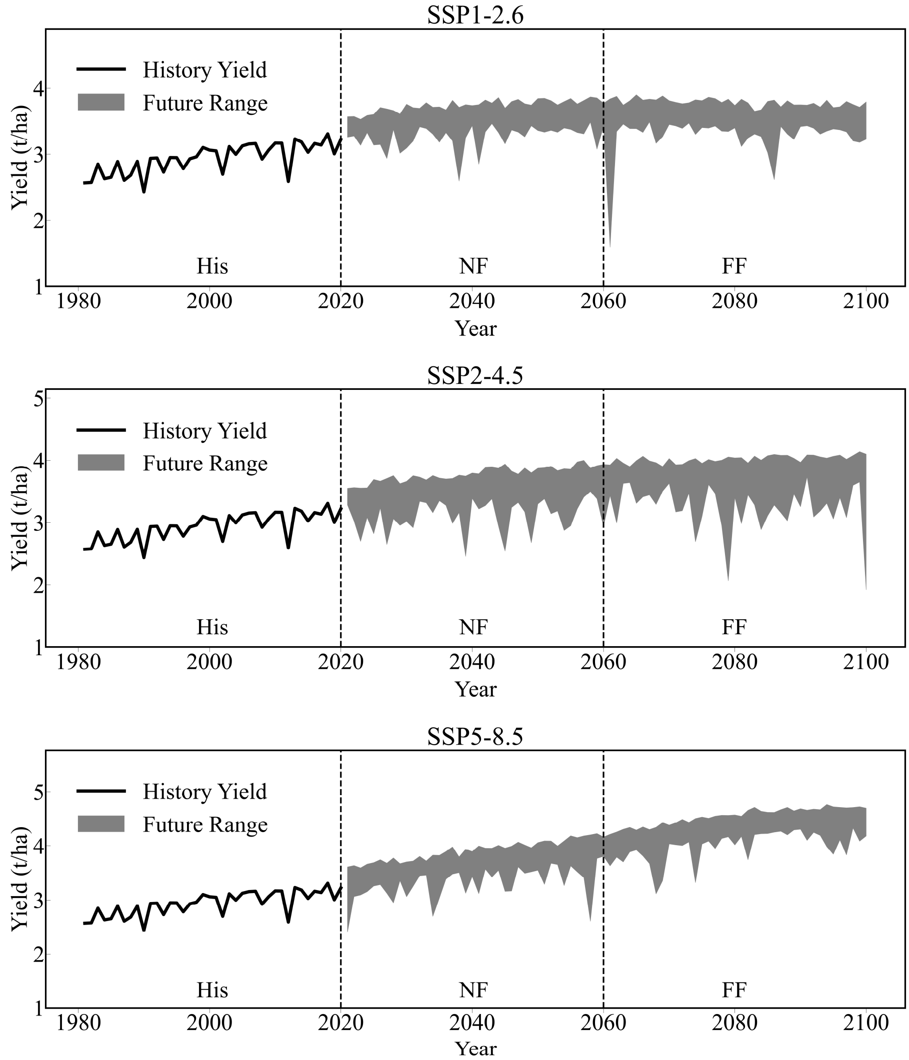

Figure 6. The yield in Cambodia in different periods under the three shared socioeconomic paths (SSP1-2.6, SSP2-4.5, and SSP5-8.5).

In addition, the average simulated rice yields in all emission scenarios increased more in the NF period than in the FF period; the SSP1-2.6 scenarios showed small decreases in rice yields at the end of the 21st century for all countries, with increases of 4.2%, 4.1%, and 4.8% for each country in the NF period and decreases in rice yields at the end of the FF period of 1.8%, 2.0%, and 0.9%, respectively. Under the SSP2-4.5 scenario, the rice growth in the NF period was 7.2%, 6.7%, and 5.8%, the rice yield in Laos and Thailand decreased by 0.3% and 2.2% at the end of the FF period, and the growth in Cambodia slowed. Under the SSP5-8.5 scenario, the largest increase in rice in the NF period was 13.1% in Cambodia, and the smallest was 9.8% in Laos. During the FF period, the growth of rice production in all countries slowed. In the NF and FF periods, the average yield of the first 10 years (2021–2030 in NF, 2061–2070 in FF) and the last 10 years (2051–2060 in NF, 2091–2100 in FF) is shown in Table 10.

Table 10. The average yields of NF and FF in the LMB.

Scene	Country	NF			FF		
		2021–2030 (t/ha)	2051–2060 (t/ha)	Growth Rate	2061–2070 (t/ha)	2091–2100 (t/ha)	Growth Rate
SSP1-2.6	Cambodia	3.428	3.573	4.2%	3.568	3.505	−1.8%
	Laos	3.890	4.049	4.1%	4.018	3.937	−2.0%
	Thailand	2.487	2.606	4.8%	2.568	2.544	−0.9%
SSP2-4.5	Cambodia	3.364	3.607	7.2%	3.708	3.743	0.9%
	Laos	3.889	4.148	6.7%	4.226	4.214	−0.3%
	Thailand	2.395	2.535	5.8%	2.633	2.576	−2.2%
SSP5-8.5	Cambodia	3.412	3.858	13.1%	4.059	4.433	9.2%
	Laos	3.908	4.291	9.8%	4.543	4.778	5.2%
	Thailand	2.486	2.798	12.6%	2.937	3.186	8.5%

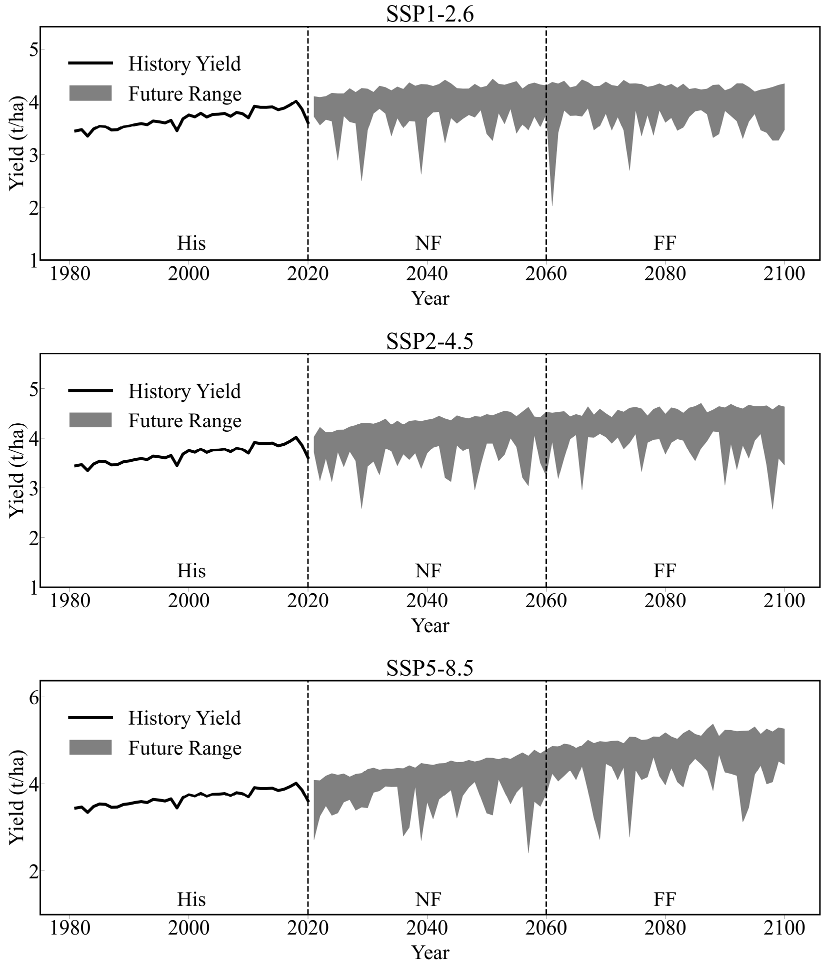

Figure 7. The yield in Laos in different periods under the three shared socioeconomic paths (SSP1-2.6, SSP2-4.5, and SSP5-8.5).

3.3. Correlation between the Yield and Temperature under Climate Change

In the future, the average temperature of the rice growth period will increase by 1.6 °C, 2.4 °C, and 3.7 °C under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively. The temperature increase from the historical period to the NF period was greater than that from the NF period to the FF period in the same emission scenario. Compared with the rice yield situation in each country during the same period, the rice yield variation had a high similarity with the temperature variation. Table 10 shows the variation in the temperature and rice yield in different countries under different emission scenarios, where HIS is the mean value of the historical period, NF − HIS is the difference between the near future and the historical period, and FF − NF is the difference between the far future and the near future.

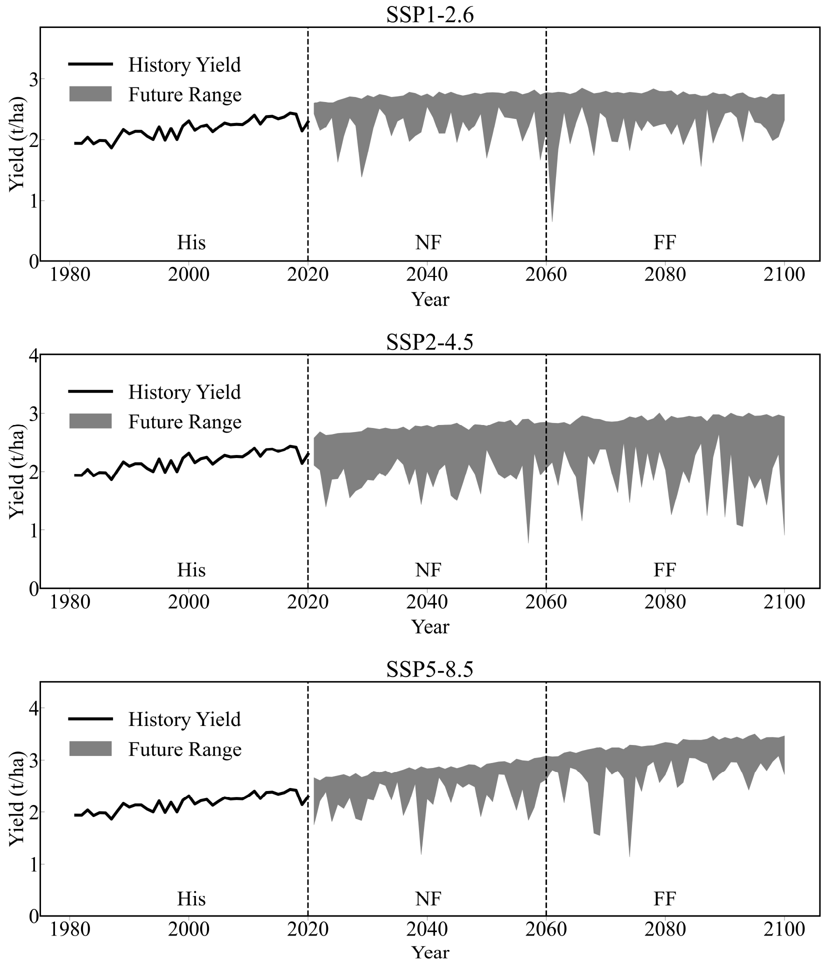

Figure 8. The yield in Thailand in different periods under the three shared socioeconomic paths (SSP1-2.6, SSP2-4.5, and SSP5-8.5).

As shown in Table 11, the average temperature of the rice growing period during the historical period in the LMB countries was 26.97 °C in Cambodia, 22.80 °C in Laos, and 25.92 °C in Thailand, with average yields of 2.94 (t/ha), 3.68 (t/ha), and 2.173 (t/ha), respectively. Under the SSP1-2.6 emission scenario, the average temperature increase during the FF was not high in each country, 0.23 °C, 0.31 °C, and 0.30 °C, respectively, and the yield did not increase much during the same period. It was 0.02 (t/ha) in Cambodia, and the increase was about zero in Laos and Thailand. Under the SSP5-8.5 scenario, there was little difference between the short-term and long-term temperature increases, and there was no obvious difference in the change in yield growth in the same period. The yield and temperature change did not follow a completely positive relationship. Under the SSP2-4.5 scenario, the yield increase in Cambodia in the NF period of 0.57 (t/ha) was larger than that in the FF period of 0.21 (t/ha), but the temperature increase of 0.35 °C was smaller than that in the FF period of 0.81 °C. Under the SSP5-8.5 scenario, the temperature rise in Laos in the NF period was 3.06 °C, which was greater than 2.07 °C in the FF period. The output increase in the NF period was only 0.42 (t/ha), which was less than 0.60 (t/ha) in the FF period.

To further explore the response of the rice yield to the temperature, the Pearson correlation coefficients (r) were calculated for the simulated rice yield and average temperature during the growing season in different countries for different periods under different emission scenarios, as shown in Figures 9–11. The results showed that there was a certain linear relationship between the rice yield and temperature. The research found that, in the NF period, the simulated rice yield in all countries was positively correlated with the temperature, and the correlation gradually increased with the increase in the greenhouse gas emissions. The yield of Cambodia had the highest correlation with temperature, and the r-value under the three emission scenarios of SSP1-2.6, SSP2-4.5, and SSP5-8.5 was 0.518, 0.659 and 0.881, respectively ($p < 0.01$). The rice yield and temperature in Laos and Thailand were not significantly correlated in the SSP1-2.6 scenario; they were generally correlated in the SSP2-4.5 scenario with r-values of 0.588 and 0.45, respectively ($p < 0.01$), and they were increased in the SSP5-8.5 scenario with r-values of 0.662 and 0.74, respectively ($p < 0.01$). In the FF period, the yield and temperature in each country were negatively correlated under the low-emission scenario SSP1-2.6, with r-values of −0.503, −0.741, and −0.747 for Cambodia, Laos, and Thailand, respectively ($p < 0.01$); the correlation weakened or was not correlated under the medium-emission scenario SSP2-4.5, with r-values (p) of −0.356 ($p < 0.05$) and −0.489 ($p < 0.01$) for Laos and Thailand, respectively; positive correlations were found under the SSP5-8.5 scenarios with r-values of 0.869, 0.568, and 0.691, respectively ($p < 0.01$).

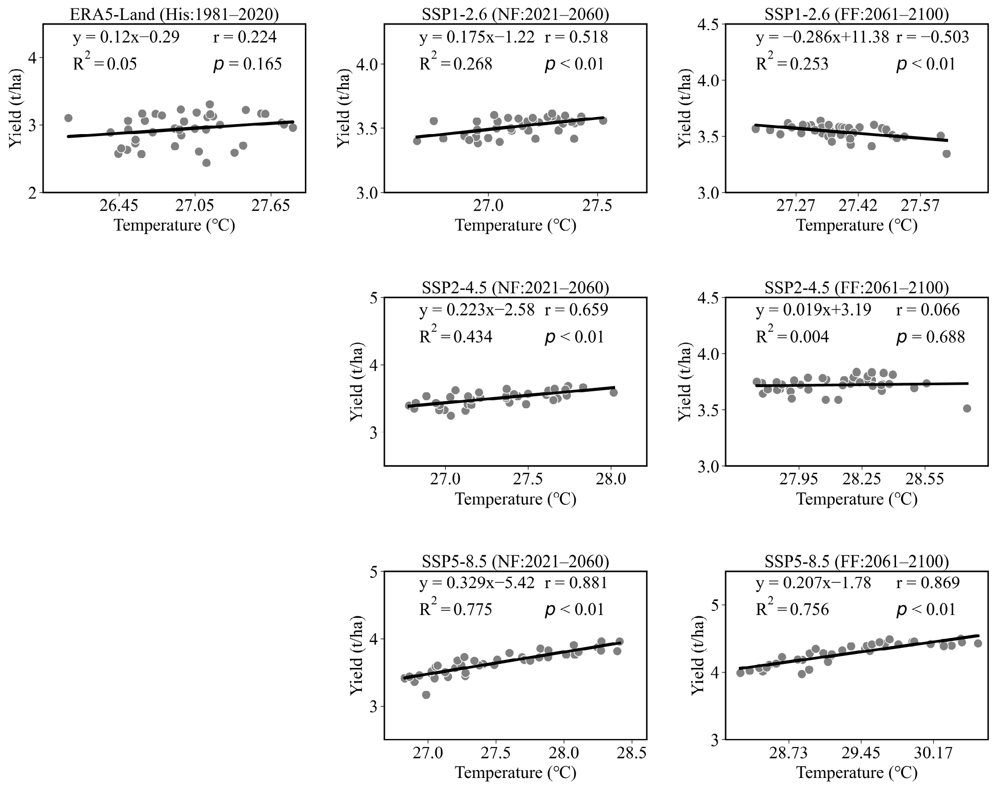

Figure 9. The correlation between the yield and temperature in Cambodia in different periods under the three shared socioeconomic paths (SSP1-2.6, SSP2-4.5, and SSP5-8.5).

Table 11. The temperature changes in the different countries in the different periods under the three scenarios.

Scene	Country	Temperature (°C)			Yield (t/ha)		
		HIS	NF − HIS	FF − NF	HIS	NF − HIS	FF − NF
SSP1-2.6	Cambodia	26.97	+0.18	+0.23	2.94	+0.58	+0.02
	Laos	22.80	+2.66	+0.31	3.68	+0.32	+0.00
	Thailand	25.92	+1.11	+0.30	2.17	+0.39	+0.00
SSP2-4.5	Cambodia	26.97	+0.35	+0.81	2.94	+0.57	+0.21
	Laos	22.80	+2.80	+0.92	3.68	+0.37	+0.20
	Thailand	25.92	+1.32	+0.90	2.17	+0.32	+0.13
SSP5-8.5	Cambodia	26.97	+0.55	+1.87	2.94	+0.70	+0.65
	Laos	22.80	+3.06	+2.07	3.68	+0.42	+0.60
	Thailand	25.92	+1.56	+2.01	2.17	+0.48	+0.44

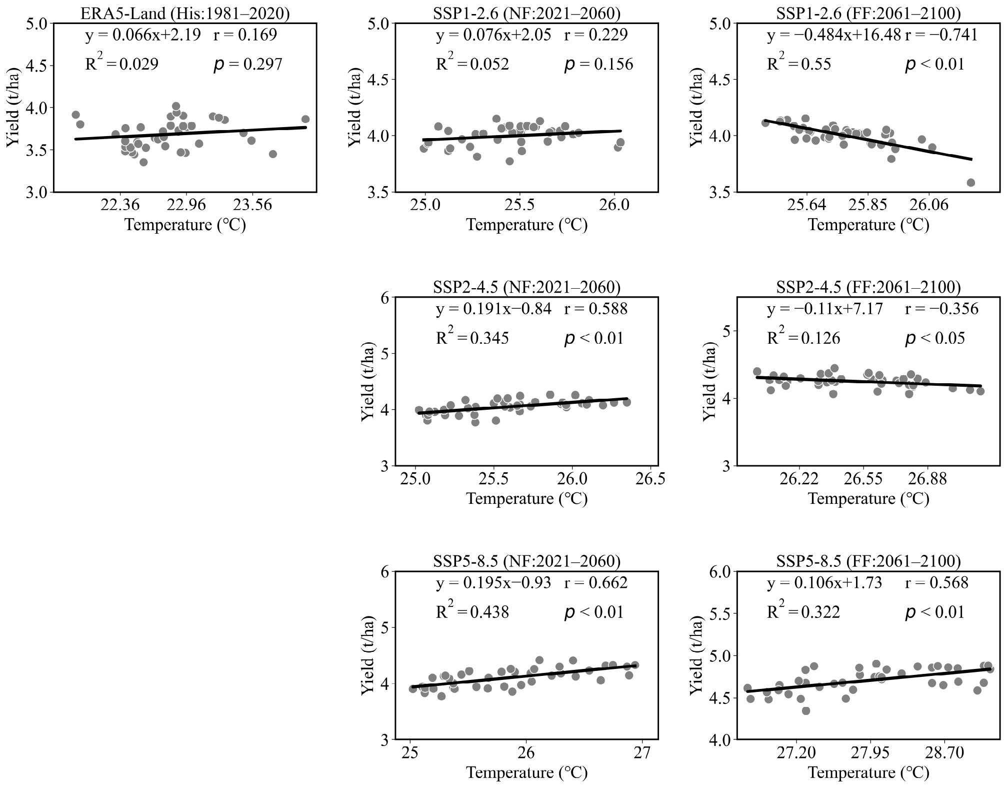

Figure 10. The correlation between the yield and temperature in Laos in different periods under the three shared socioeconomic paths (SSP1-2.6, SSP2-4.5, and SSP5-8.5).

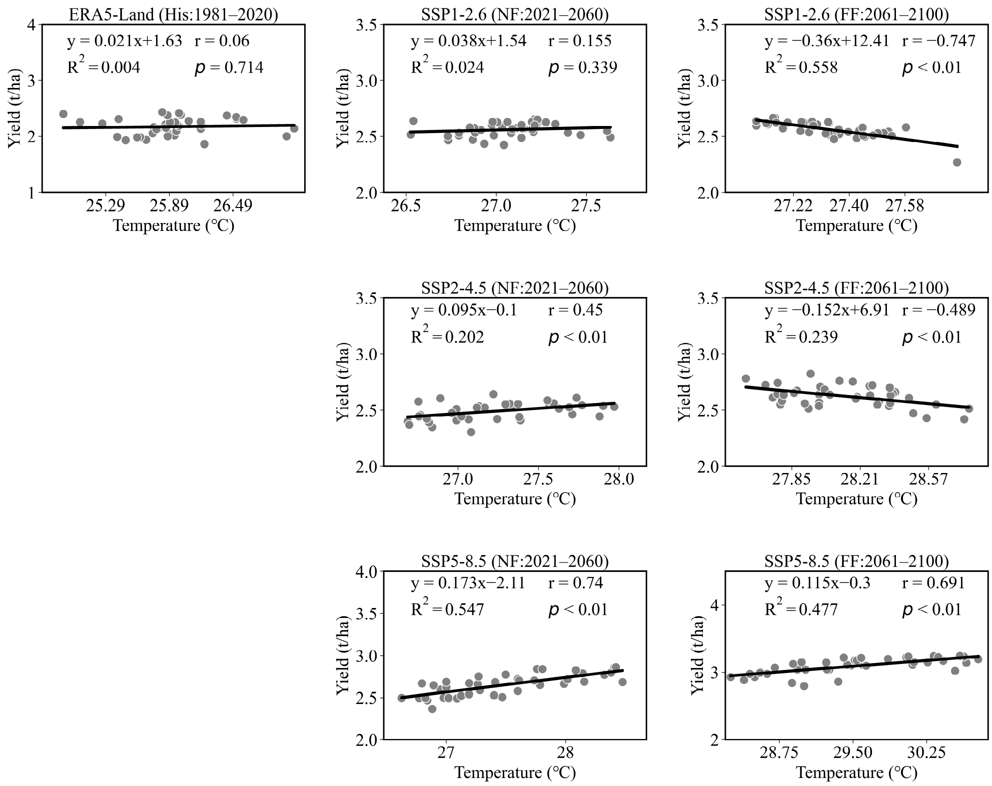

Figure 11. The correlation between the yield and temperature in Thailand in different periods under the three shared socioeconomic paths (SSP1-2.6, SSP2-4.5, and SSP5-8.5).

3.4. The Correlation between Yield and Precipitation under Climate Change

In addition to temperature, precipitation is one of the important factors influencing yield. Because there are differences in the planting systems of various countries and provinces in the study area, and the planting dates and harvest dates are different, changes in the growth period and rainy season will lead to changes in the precipitation during the growth period, thus affecting the rice yield. In the historical period, the average precipitation of Cambodia, Laos, and Thailand in the growing season was 1027 mm, 1396 mm, and 1028 mm, respectively. The simulated average yield of rice in Laos was also higher than that in Cambodia and Thailand in the same period. In addition, in the years with reduced precipitation during the growth period, the rice yield decreased significantly. Figure 12 shows the total precipitation and rice yield during the growth period in various countries in the historical period. The black dotted circle highlights the dry years [7,20,34,58]. In the future, the rainy season (rainfed rice-growing period) precipitation in the LMB will increase by 12.5%, 13.3%, and 15.3%, under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively.

To further explore the response of rice yield to precipitation, Pearson correlation coefficients ®were calculated for the simulated rice yield and average precipitation during the growing season, as shown in Figures 13–15. In the historical period, there was no significant correlation between the rice yield and precipitation in Cambodia and Laos, except for some weak correlation between the simulated average rice yield and precipitation during the growing period in Thailand (r = 0.323, $p < 0.05$). In the NF period, the correlation between the rice yield and precipitation increased in Cambodia, Laos, and Thailand. The r-values between the yield and precipitation during the growing period under the moderate emission scenario SSP2-4.5 were 0.565 ($p < 0.01$) and 0.508 ($p < 0.01$) in Cambodia and Thailand, respectively. The yield and precipitation during the growing period in Laos reached a general correlation (r = 0.6, $p < 0.01$) under the SSP1-2.6 scenario, and the r-values were higher than 0.5 under both the SSP2-4.5 and the SSP5-8.5 scenarios. In the FF period, the correlation between rice yield and precipitation weakened, and there was no obvious correlation between rice yield and precipitation in Cambodia under the three emission scenarios. In Laos, there was some correlation between the rice yield and precipitation in the SSP1-2.6 and SSP5-8.5 scenarios, with r-values of 0.389 ($p < 0.05$) and 0.552 ($p < 0.01$), respectively, but there was no significant correlation in the SSP2-4.5 scenario. The rice yield and precipitation in Thailand were significantly weakly correlated in the SSP2-4.5 and SSP5-8.5 scenarios, with r-values of 0.352 ($p < 0.01$) and 0.56 ($p < 0.01$), respectively, but not in the SSP1-2.6 scenario. In general, the rice yield in Laos was more strongly correlated with precipitation than in Cambodia and Thailand; under the same scenario, the correlation between the rice yield and precipitation in the NF period was stronger than that in the FF period, and the correlation in the historical period was the weakest or had no obvious correlation.

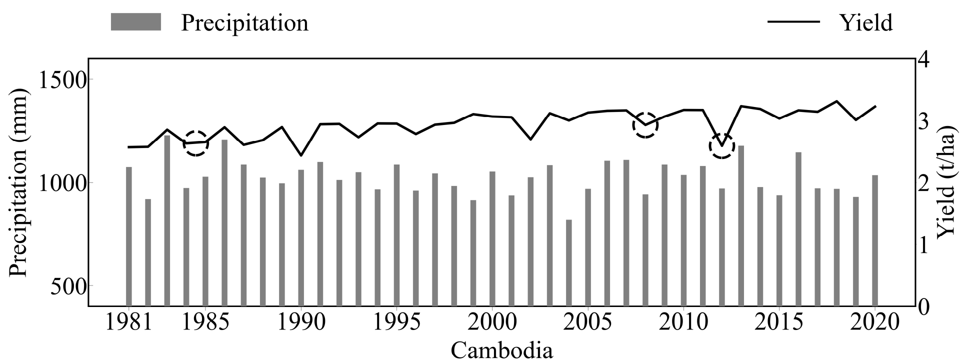

Figure 12. *Cont.*

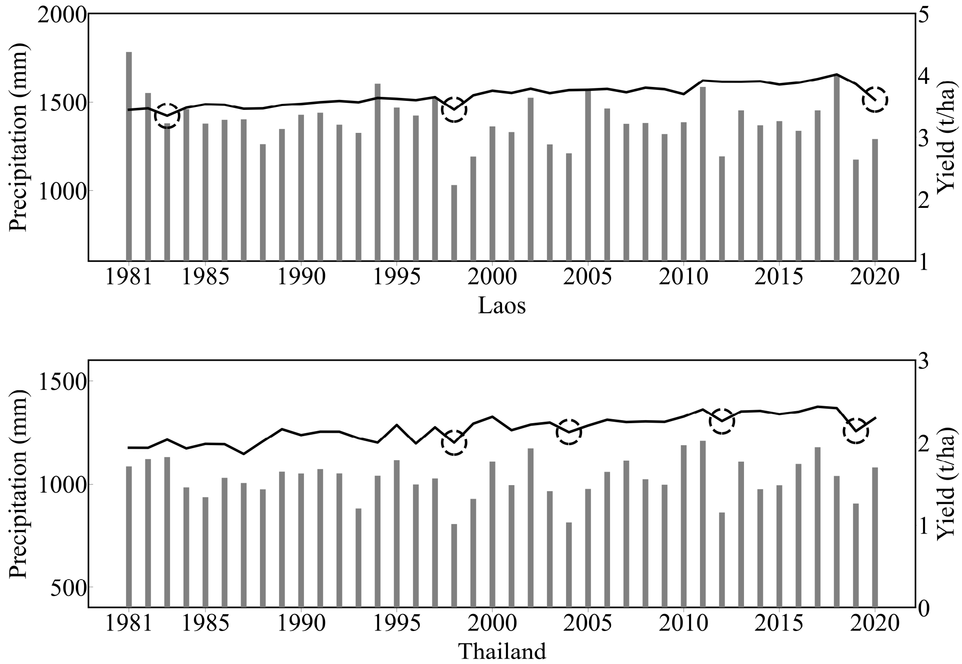

Figure 12. The rice yield in the historical period and the precipitation in the growth period.

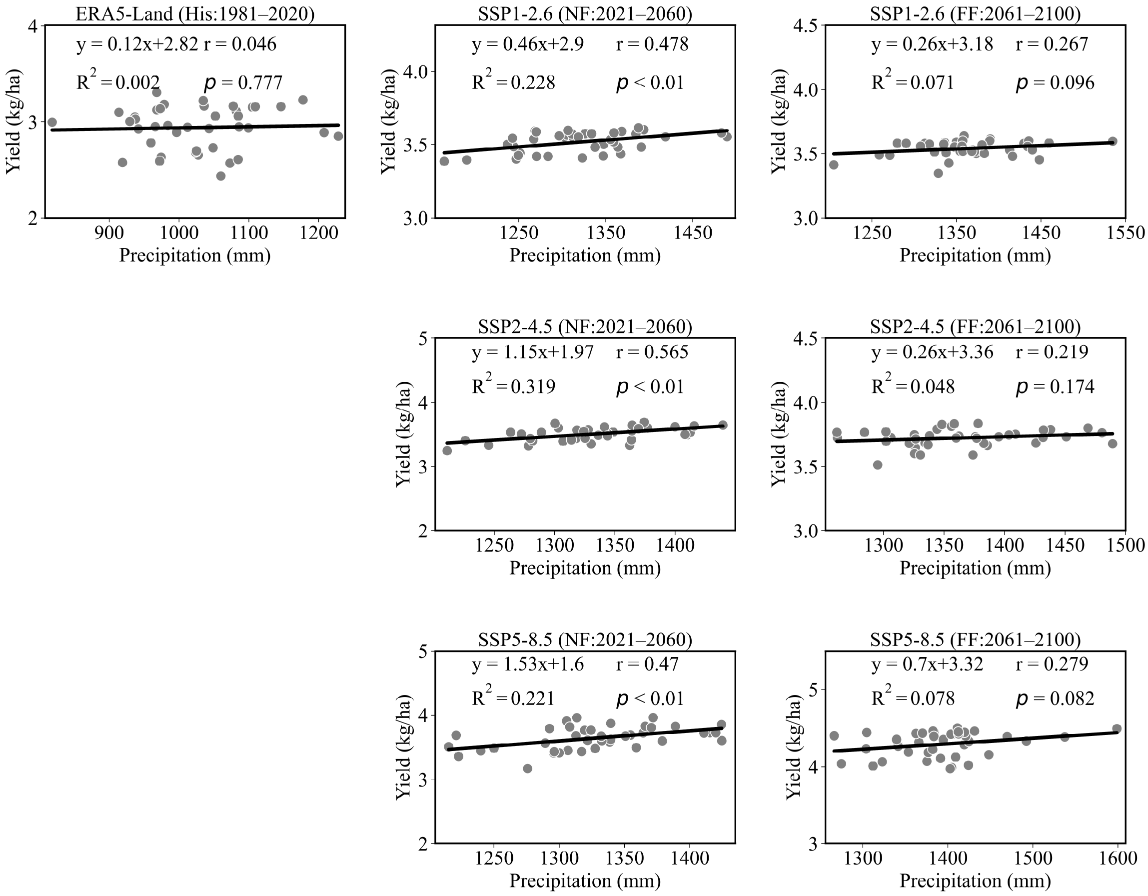

Figure 13. The correlation between the yield and precipitation in Cambodia in different periods under the three shared socioeconomic paths (SSP1-2.6, SSP2-4.5, and SSP5-8.5).

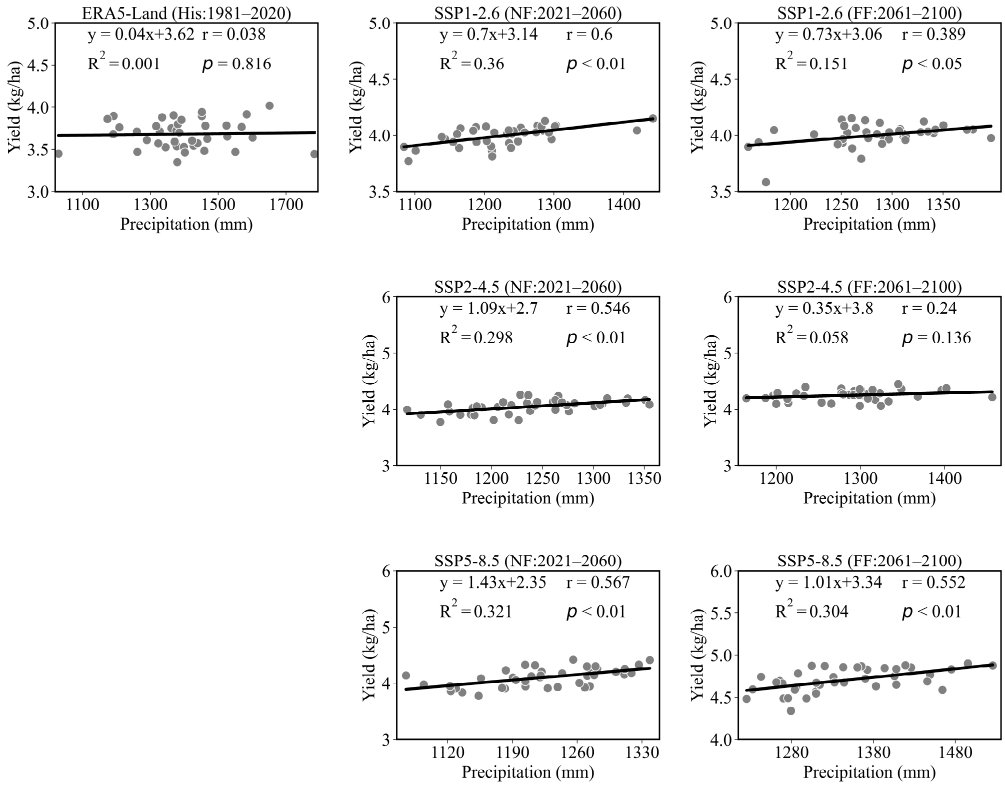

Figure 14. The correlation between the yield and precipitation in Laos in different periods under the three shared socioeconomic paths (SSP1-2.6, SSP2-4.5, and SSP5-8.5).

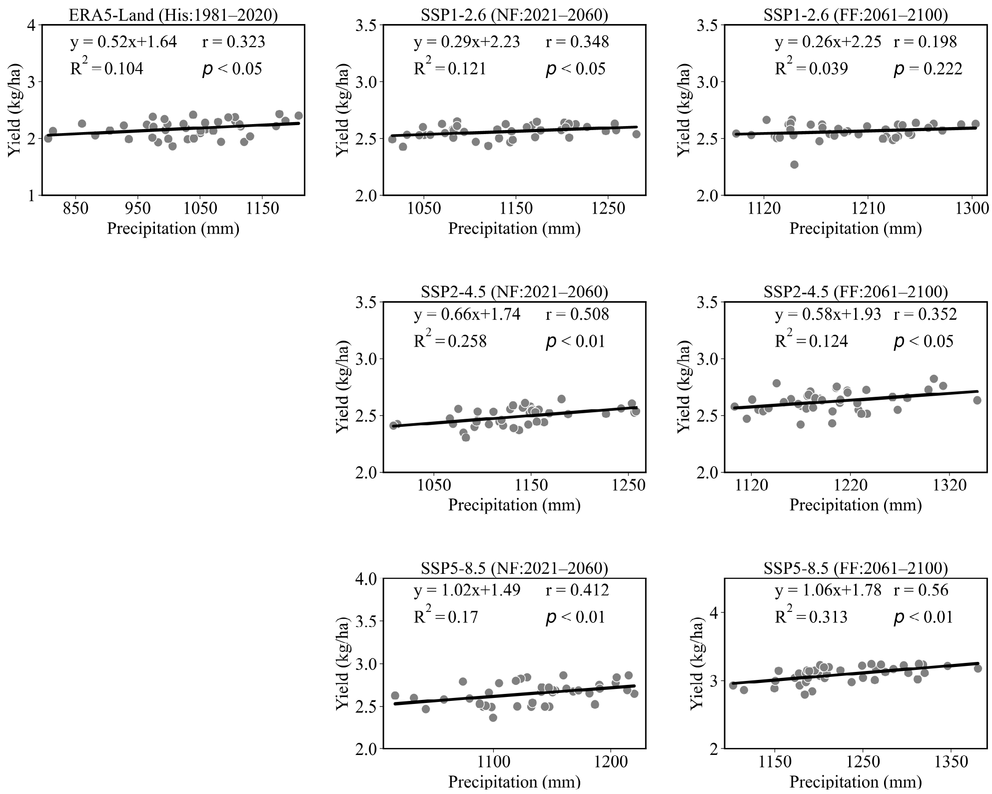

Figure 15. The correlation between the yield and precipitation in Thailand in different periods under three shared socioeconomic paths (SSP1-2.6, SSP2-4.5, and SSP5-8.5).

4. Discussion

This study was based on AquaCrop-OSPy, an open-source version in Python of the AquaCrop model, to simulate rice yield in the Lower Lancang–Mekong River Basin. AquaCrop-OSPy is mainly aimed at exploring the impact of climate change on crop yield, without considering soil fertility and salt stress modules for the time being. However, due to the further increase in the global temperature, the accelerated melting of ice sheets and glaciers has further increased the sea level [59–63]. It is predicted that, by 2050, the sea level in southern Vietnam may rise by 30 cm [64,65], which will lead to salt intrusion in the Lancang–Mekong Delta region, affecting about 1.8 million hectares of land and threatening rice production [64–66]. The effects of soil fertility stress and salinity stress were not considered in this study, and further research is needed to explore the potential influences. The AquaCrop model requires that the input temperature data include minimum and maximum temperatures; however, in this paper, the average temperature during the growth period was used to analyze the effect of temperature on rice yield, which may lead to the relationship between temperature and rice yield being blurred. In addition, this paper did not analyze the correlation between CO_2 concentration and rice yield, but many previous studies found that the fertilization effect that will be increased by the increase in the CO_2 concentration will compensate for the rice yield reduction caused by the heat stress from the continuous increase in the temperature and the irregular change in the precipitation [67,68]. This finding happens to be consistent with the results of this study. In the near future, rice yield and temperature will show a significant positive correlation in both the low-emission scenario (SSP1-2.6) and the high-emission scenario (SSP5-8.5). In the far future, rice yield and temperature will be negatively correlated in the low-emission scenario (SSP1-2.6) and positively correlated in the high-emission scenario (SSP5-8.5).

5. Conclusions

On the basis of the climate data of the historical and future periods, rice yields in the Lower Lancang–Mekong River Basin (LMB) under various scenarios were simulated using the AquaCrop model. The correlation between the temperature and precipitation and the rice yield during the growing period was analyzed. The study drew the below conclusions.

The AquaCrop model had a good capacity for rice yield simulation in the LMB. From 1981 to 2100, the LMB rice yields will increase significantly. The range in the rice yield increase in the future projection period depends on different emission scenarios. The increase in the rice yield under the SSP5-8.5 scenario was the largest (about 35%), followed by the SSP2-4.5 (about 15.8%) and the SSP1-2.6 (about 9.3%) scenarios. The increasing trend in the rice yield in the near future will be stable, and the trend in the far future will slow or decline.

The average temperature of the LMB rice planting period will increase. In the near future, rice yield will be positively correlated with temperature. In the far future, the continued increase in temperature will limit rice production.

In the future, the rainy season (rainfed rice-growing period) precipitation in the LMB will increase, but the effect of increased precipitation on rice yield will be insignificant. The correlation between the two was weak or showed no obvious correlation, and the response of rice yield to precipitation was more uncertain.

The result is valuable for the management of the rice cultivation and irrigation system in the LMB, and it will help the government to adapt the impact of climate change on the rice production. Given that the impact of climate change on the production of LMB rice and other crops is multifaceted and complex, although our results imply a bright future for rice yield increase in general, it is noteworthy that extreme climate events may result in tremendous agricultural losses, and water safety measures should be enhanced to meet the food demand of the increasing population. We suggest carrying out further research to construct a running platform for forecasting the impact of climate change and human activities on rice to propose reasonable and efficient measures to ensure food security.

Author Contributions: D.L. and H.L. contributed to writing and editing, gave some supervision, and provided funding; S.X. came up with the idea, supervised the research, and performed the simulation; H.H. provided the methodology; Z.D. provided the resources and data curation; T.W. performed some validation; G.M. provided funding. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The climate data used in this study are from the ERA5-Land Dataset (https://cds.climate.copernicus.eu, accessed on 10 May 2022.) and the CMIP6 Simulation Dataset (https://esgf-node.llnl.gov/projects/cmip6/, accessed on 30 May 2022.).

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

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