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Grain Yield and Gross Return above Fertilizer Cost with Parameters Relating to the Quality of White Rice Cultivated in Rainfed Paddy Fields in Cambodia

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Abstract: This study aims to compare the grain yield, gross return above fertilizer cost (GRAFC: (paddy sales)–(fertilizer cost)), and several parameters relating to the quality of white rice cultivated with different soil-specific nutrient management in 14 provinces where different soil types are distributed. The grain yield tended to increase with increased fertilizer application; however, the relationship between the fertilization rate and the yield was not linear in areas where clay soil dominates. In cases of popular varieties cultivated from the northern to southern province, the amount of fertilizer applied was up to 163 kg ha^{-1} (sum of N-P_2O_5-K_2O), and the GRAFC and the fertilization rate showed a nonlinear relationship, with a peak of around 120 kg ha^{-1} fertilization. The nitrogen concentration recognized as a negative factor for the quality of rice tended to increase with an increasing fertilization rate, and the carbohydrate concentration and carbohydrate/protein ratio that are a positive factor for the quality were related negatively with the fertilizer rate. The amylopectin concentration in white rice was positively related with the carbohydrate concentration, which decreased with an increasing fertilization rate. The levels of fertilizer application required to achieve a higher yield, GRAFC, and the maintenance and improvement of parameters relating to grain quality were different.

Keywords: carbohydrate; fertilizer; grain yield; gross return above fertilizer cost; protein; production cost

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1. Introduction

Cambodia produced 10.96 million tons of paddy rice, and exported 502,373 tons of milled rice in 2020, the 10th and 9th highest in the world, respectively, according to the Food and Agricultural Organization of the United Nations statistical data (FAOSTAT, 2022) [1]. In Cambodia, rice is grown on 3.1 million ha, of which, 75.6% is rainfed (Ministry of Agriculture, Forestry and Fishery, Phnom Penh, Cambodia, 2017) [2]. Recently, in response to local and international demand [3], the Royal Government of Cambodia (RGC) has been promoting the production of rice with good quality by sustainable agriculture methods. The RGC has an ambition to turn Cambodia into a key "rice—white gold" exporting country in the international market [4]. For promoting Cambodian rice exports, evidence-based information about rice quality is very important [5].

Most soils in the rainfed lowlands of the Mekong region are infertile, and the rice yield is limited by this poor fertility (Bell and Seng, 2004) [6]. During the 1990s, 82% of Cambodian rice farmers applied fertilizer (Ouk et al., 2001) [7]. Potash fertilizer is not popular, and most farmers used N and phosphate fertilizers in Cambodia according to Mutert and Fairhurst (2002) [8], and Ouk et al. (2001) [7]. Although P and K application rates for wet-season rice in Cambodia are usually still low, Kong et al. (2019) [9] demonstrated the importance of these nutrients for improving the country's rice production. On the other hand, Kong et al. (2019) [10] reported that the amount of fertilizer applied to achieve a higher gross return above fertilizer cost (GRAFC) will be much less than that for maximizing the grain yield in Cambodia's wet-season rice (rainfed rice).

The authors previously aimed to compare the quality of rice among the eight samples of six different indica lowland rice varieties from different producers/suppliers in Cambodia using some sensing equipment—such as a grain scanner (image processing device), a rice taste analyzer for white rice, and a taste analyzer for cooked rice—that measures freshness, hardness, stickiness, and visual taste value, and a near-infrared transmission sensor was used to measure the taste value with conventional chemical analysis [4]. Although the taste values used for white rice and cooked rice were developed using equipment originally intended for temperate japonica, a short-grain rice variety, the taste value showed a negative relationship with protein and amylose concentrations in white rice of indica varieties in the previous study [5]. The taste values determined by the analyzer unit for cooked rice showed a positive relationship with the visual taste value and stickiness, and a negative relationship with hardness [5]. The authors [5] also reported that the C/N ratio in the white rice also showed a positive relationship with the taste value of cooked rice. A large national soil survey classified Cambodia's soils into 11 groups according to their nutrient management requirements, and these groups are easily distinguishable by local people without requiring any equipment [11]. Depending on the province where different soil types dominate, the appropriate amount of fertilizer to achieve greater benefits for farmers may vary. Thus, this study aims to compare the grain yield, GRAFC, and several parameters relating to the quality of white rice cultivated in farmers' rainfed paddy field with different nutrient managements during the wet season in 14 provinces where nine different soil types are distributed in northern to southern Cambodia to investigate the economic efficiency in fertilizer management focused on qualitative traits, as well as quantitative traits, with the intention of sustainable crop production.

2. Materials and Methods

2.1. Research Sites and Plant Materials

We selected 14 provinces where rainfed rice cultivation is widely observed among 24 provinces in Cambodia, considering suggestions from the Provincial Department of Agriculture, Forestry and Fisheries (PDAFF) as follows: Banteay Meanchey, Battambang, Kampong Thom, Pursat (Posat), Siem Reap, Kampong Chhnang, Kampong Speu, Kampot, Kampong Cham, Tboung Khum, Kandal, Takeo, Prey Veng, and Svay Rieng. Nine different soil types (clay: Toul Samroung (TS), Krakor (Kr), Kampong Siem (KaS), Kein Svay (KSv), Kbar Po (KP); silt: Bakan (Ba), Koktrap (Ko); and sandy: Prateah Lang (PL), Prey Khmer (PK)) are distributed in the selected 14 provinces. Our research sites consist of 100 rainfed lowland fields managed by core farmers, and 37 lowland rice varieties in total were cultivated. The maturity and the date of flowering of the varieties, including cited information [12], are shown in Table 1.

Table 2 shows the characteristics of 9 soil types collected from the PDAFF in the provinces and our previous papers [9,10] with the other references [6,13–16]. Depending on the variety and soil type in each area, the amount of fertilizer (using urea, DAP, and KCl) applied varied (0–96 kg N, 0–114 kg P_2O_5, 0–90 kg K_2O ha^{-1}) (Table 3). There were various cases in the proportion of fertilization application, such as 100% basal dressing, divided application into basal and top dressing, 100% top dressing given once or a few divided doses, and so on (see Supplementary Table S1). As above, depending on the site and the variety, there were large variations in the amount of fertilizer and combinations of nitrogen, phosphorus, and potassium application with their proportion as basal and top dressing. Although low soil fertility is a major constraint on rainfed lowland rice yields, nutrient management under fluctuating hydrological conditions is also challenging (Kato and Katsura, 2010) [17]. We followed core farmers' practices in each province and sought to grasp the actual situation at the real production sites with the PDAFF.

Table 1. Variety used.

Variety	Maturity/Date of Flowering (1)	Days from Sowing to Harvesting (2)	Remark (Year Released/Registered, Origin)
Early maturing			
CAR15	95–105	93–107	2015, IRRI origin
Chulasa	95–110	99	1999, IRRI origin
IR66	105–115	94	1990, IRRI origin
IR504	110–115	105–138	1992 (4), IRRI origin
Jasmine 85	95–110	107	2020 (3), IRRI origin
OM5451	95–105	95–102	2011 (4), IRRI origin
Sen Kra Ob	105–115	102–112	2019, Cambodian improved
Sen Pidao	110–120	105–111	2002, IRRI origin
Srop Ngar	120–130	129	2006, Cambodian improved
Thmor Krim	10–17 October	128	Cambodian traditional
Medium maturing			
Ka Ngork Pong	10–20 November	125–152	Cambodian traditional
Krasang Teap	10–25 October	154–158	Cambodian traditional
Malis Chin	10–20 November	123	Cambodian traditional
Neang Krim	10–27 October	130	Cambodian traditional
Phka Ampil	10–20 November	128	Cambodian traditional
Phka Chan Sen Sar	25 October–5 November	152–157	2010, Cambodian improved
Phka Doung	10–26 October	154	Cambodian traditional
Phka Malis	10–20 November	123–128	Cambodian traditional
Phka Mealtey	10–15 October	118	2017, Cambodian improved
Phka Romeat	10–25 October	155	2007, Cambodian improved
Phka Rumdeng	10–25 October	156	2007, Cambodian improved
Phka Rumduol	10–25 October	125–153	1999, Cambodian improved
Somaly	10–20 November	125	1978, Cambodian improved
Late Maturing			
Angkareach	10–15 November	181	Cambodian traditional
CAR4	8–15 November	185	1995, Cambodian improved
CAR6	9–16 November	193	1995, Cambodian improved
CAR8	19–26 November	193	1996, Cambodian improved
CAR9	10–17 November	191	1996, Cambodian improved
Kong Chheng	11–15 November	159	Cambodian traditional
Krochork Chab	10–20 November	181	Cambodian traditional
Neang Ek	10–26 November	176	Cambodian traditional
Neang Khon	10–23 November	154–169	Cambodian traditional
Phka Knhy	10–15 November	164	Cambodian traditional
Pong Rolork	15–20 December	188	Cambodian traditional
Raing Chey	5–11 November	143–186	1999, Cambodian improved
Smar Prum	5–11 November	158	1999, Cambodian improved
Tror Norng	5–10 December	178	Cambodian traditional

(1) Information about maturity or date of flowering from CARDI (2017) [12] and the PDAFF. (2) Data from each site in this study. (3) Year registered in Cambodia. (4) Cultivation year started in Mekong Delta.

Table 2. Characteristics of 9 soil types. The numerals in the parentheses are the serial numbers of references, and indicate the source of data.

Soil Type	Depth (cm)	pH (H_2O)	Total C (g kg^{-1})	Total N (g kg^{-1})	Avail. P (cmol$_c$ kg^{-1})	Avail. K (cmol$_c$ kg^{-1})	CEC (cmol$_c$ kg^{-1})	Clay (%)	Silt (%)	Sand (%)
Clay										
Toul Samroung	0–20 [9]	5.4 [9]	8.33 [9]	0.73 [9]	5.97 [9]	0.16 [9]	18.77 [9]	49.3 [9]	29.0 [6]	14.3 [6]
Krakor	5–20 [6]	5.9 [6]	9.10 [6]	1.00 [6]	4.60 [6]	0.24 [6]	15.10 [6]	48.0 [6]	18.0 [6]	28.0 [6]
Kampong Siem	10–25 [13]	6.5 [13]	0.91 [13]	0.07 [13]	11.00 [13]	0.03 [13]	6.35 [14]	41.0	31.0	29.0
Kein Svay	18–60 [15]	6.5 [15]	0.52 [15]	0.04 [15]	20.00 [15]	0.30 [15]	10.36 [14]	45.0	32.0	18.0
Kbar Po	0–20 [6]	5.9 [6]	9.10 [6]	1.00 [6]	4.60 [6]	0.24 [6]	15.10 [6]	48.0 [6]	18.0 [6]	28.0 [6]
Silt										
Bakan	0–20 [16]	5.2 [16]	0.40 [16]	0.02 [16]	4.00 [16]	0.03 [16]	4.84 [14]	16.0	49.0	35.0
Koktrap	0–25 [6]	4.0 [6]	10.90 [6]	1.10 [6]	2.60 [6]	0.10 [6]	8.09 [6]	23.0 [6]	41.0 [6]	36.0 [6]
Sandy										
Prateah Lang	0–20 [9,10]	5.3 [9,10]	7.1 [9,10]	0.67 [9,10]	4.20 [9]	0.11 [9,10]	5.27 [9,10]	8.0 [9,10]	37.0 [6]	71.0 [9]
Prey Khmer	0–20 [9]	4.6 [9]	9.30 [9]	0.90 [9]	8.10 [9]	0.02 [9]	0.70 [9]	6.0 [9]	22.0 [6]	81.0 [9]

2.2. Data Collection

The authors cooperated with the PDAFF in 14 provinces to collect paddy samples during the harvesting period in November and December 2019. The grain yield (t ha^{-1}) was calculated from the weight of filled grains at about 14% moisture content harvested from all hills in each field using a combine harvester. The drying process was performed by rice millers or sellers. The precipitation data during the rice cultivation season from June to December 2019 with that in 2016 to 2018 were collected from the meteorological station in each province. The cropping pattern, seeding rate in the paddy field for broadcasting (B) and drum seeding (D) or in the nursery for transplanting (T), planting space for drum seeding (D) and transplanting (T), sowing date, transplanting date, and harvesting date are shown in Table 1 and Supplementary Table S1. The maturity days from the sowing to harvesting of each variety at each site was from the PDAFF.

The harvested rice grains were used as white rice after milling for agronomic, chemical, and morphological measurements. The economic returns from applying the fertilizer regimes as the gross return above fertilizer cost (GRAFC) were determined in the same manner as in our previous studies [9,10]: by subtracting the total cost of the fertilizer used from the paddy sales. The specific cost for fertilizers at each site was calculated by multiplying the amount of each fertilizer by the fertilizer price during the cultivating season in 2019. The income for each site was calculated by multiplying the grain yield by the paddy price in 2020. These prices represented the local market prices at that time.

The physical properties for rice grain grading were determined by using a grain scanner (Satake RSQI 5 10B, Japan). When measuring rice, the individual image list order can be changed based on the shape. The classification of grains was conducted based on the user settings. The system imaged approximately 100 to 500 rice grains placed on the scanner. The RSQI 5 10B scanner was calibrated to the Cambodian Rice Standard [18]. This results in determining the classification of the grain quality (≥6.2 mm long).

The nitrogen concentration in white rice was measured by the Kjeldahl method, and a specific conversion factor (N × 5.95) was used to measure the protein concentration. The carbohydrate concentration in white rice was determined by the conventional procedure as a quantitative analysis of glucose using the Lane–Eynon method after HCl hydrolysis, and the starch concentration was determined as glucose multiplied by 0.9, in accordance with the method of Honma and Kawabata (1989) [19]. The amylose concentration in the white rice was measured by Juliano's method [20], and the amylopectin concentration was determined by subtracting the amylose content from the starch content.

Table 3. Soil type, soil texture (C: clay soil, Si: silt soil, Sa: sandy soil), variety used, cropping pattern (B: broadcasting. D: Drum seeding, T: transplanting), fertilization rate, grain yield, and GRAFC.

Province Soil Type	Soil Text.	Variety		N	P_2O_5	K_2O	Yield	GRAFC
				(kg ha^{-1})			(t ha^{-1})	(\$ ha^{-1})
1. Banteay Meanchey Province								
TS	C	44. Raing Chey	B	9.0	23.0	0.0	2.60	502.5
TS	C	46. Neang Khon	B	9.0	23.0	0.0	3.50	682.5
TS	C	49. Phka Knhy	B	10.0	10.0	7.5	2.80	546.2
TS	C	50. Srop Ngar	B	67.0	42.0	7.5	3.50	643.6
TS	C	51. Malis Chin	B	67.0	42.0	7.5	3.80	798.6
PL	Sa	45. Sen Kra Ob	B	87.0	46.0	30.0	3.70	754.2
PL	Sa	47. Phka Rumduol	B	55.0	0.0	0.0	3.00	652.5
PL	Sa	48. IR504	B	58.6	32.2	30.0	4.20	781.7
2. Battambang Province								
TS	C	15. Phka Rumduol	B	39.5	30.5	7.5	2.70	823.1
TS	C	16. Sen Kra Ob	B	52.8	64.4	30.0	4.00	1200.7
TS	C	17. Malis Chin	B	62.5	30.5	7.5	3.85	1180.5
TS	C	18. Srop Ngar	B	43.3	46.0	15.0	4.30	845.8
TS	C	19. CAR15	B	71.1	23.0	15.0	5.50	1099.0
TS	C	21. Neang Khon	B	36.5	34.5	0.0	3.00	591.3
TS	C	22. OM5451	B	48.5	53.5	7.5	4.23	828.3
TS	C	20. Raing Chey	T	32.0	23.0	30.0	3.80	752.3
3. Kampong Thom Province								
Kr	C	8. OM5451	B	96.0	69.0	30.0	3.00	555.2
Kr	C	13. CAR8	T	0.0	0.0	0.0	3.00	651.0
TS	C	9. Phka Mealtey	T	55.0	23.0	0.0	3.50	971.7
TS	C	10. Raing Chey	T	41.2	23.0	0.0	3.50	728.8
TS	C	12. Phka Rumduol	T	32.0	23.0	0.0	3.00	837.1
TS	C	14. Phka Chan Sen Sar	T	55.0	23.0	0.0	2.50	683.7
PL	Sa	11. Sen Kra Ob	B	55.0	23.0	0.0	4.00	1115.7
4. Pursat Province								
Ba	Si	37. Somaly	B	36.6	23.0	0.0	3.20	784.0
Ba	Si	38. Phka Rumduol	B	41.2	23.0	30.0	3.50	843.3
Ba	Si	40. Sen Kra Ob	B	78.0	23.0	0.0	3.40	817.8
Ba	Si	42. Phka Doung	T	32.0	23.0	0.0	2.50	608.1
Ba	Si	43. Neang Ek	T	32.0	23.0	0.0	2.40	582.7
PK	Sa	39. Krasang Teap	B	36.6	23.0	0.0	2.60	460.0
8. Kampot Province								
PL	Sa	1. Phka Rumduol	B	62.5	56.0	7.5	2.30	615.5
PL	Sa	2. Phka Malis	B	62.5	56.0	7.5	2.50	674.5
PL	Sa	3. Sen Pidao	B	40.0	40.0	30.0	2.30	623.1
PL	Sa	4. Krochork Chab	B	47.0	24.0	18.0	2.20	423.7
PL	Sa	5. Phka Romeat	B	47.0	24.0	18.0	2.30	635.8
PL	Sa	6. Pong Rolork	B	47.0	24.0	18.0	2.20	423.7
PL	Sa	7. Malis Chin	B	47.0	24.0	18.0	2.30	635.8
9. Kampong Cham Province								
KaS	C	91. Raing Chey	B	46.0	0.0	0.0	2.00	399.1
KaS	C	93. CAR6	B	46.0	0.0	0.0	2.00	399.1
KaS	C	94. Phka Rumduol	B	23.0	0.0	0.0	2.00	572.6
KSv	C	89. IR66	B	23.0	0.0	0.0	2.00	408.6
KSv	C	90. Sen Kra Ob	T	23.0	0.0	0.0	2.00	572.6
PL	Sa	92. OM5451	B	46.0	0.0	0.0	2.00	399.1
10. Tboung Khmum Province								
KaS	C	75. IR504	B	27.6	0.0	0.0	3.00	612.7
KaS	C	77. CAR9	B	40.2	0.0	0.0	2.30	461.9
KaS	C	80. CAR15	B	32.0	23.0	0.0	2.40	472.3
KaS	C	76. Thmor Krim	T	23.0	0.0	0.0	2.30	469.0
KaS	C	78. Phka Rumduol	T	38.9	23.0	0.0	3.00	840.3
KaS	C	79. Raing Chey	T	27.6	0.0	0.0	2.30	467.1
KaS	C	81. Sen Kra Ob	T	32.0	23.0	0.0	3.00	843.1
11. Kandal Province								
Ba	Si	32. CAR4	B	16.0	11.5	0.0	2.80	577.3
Ba	Si	33. Angkareach	B	0.0	0.0	0.0	2.70	569.7
Ba	Si	34. Phka Rumduol	B	23.0	0.0	0.0	2.20	648.4
Ko	Si	35. Raing Chey	T	23.0	0.0	0.0	1.80	370.4
KSv	C	31. OM5451	B	72.4	32.2	0.0	6.00	1217.0
KSv	C	36. IR504	B	55.0	23.0	0.0	6.00	1229.7
12. Takeo Province								
PL	Sa	95. IR504	B	15.0	15.0	15.0	4.30	966.4
PL	Sa	97. Sen Kra Ob	B	53.5	7.5	7.5	4.80	1270.6

Table 3. *Cont.*

Province Soil Type	Soil Text.	Variety		N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	Yield (t ha^{-1})	GRAFC ($ ha^{-1})	Province Soil Type	Soil Text.	Variety		N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	Yield (t ha^{-1})	GRAFC ($ ha^{-1})
PK	Sa	41. CAR9	B	0.0	0.0	0.0	2.70	507.6	PL	Sa	98. Raing Chey	B	33.0	10.0	7.5	4.00	1060.7
5. Siem Reap Province									PL	Sa	99. Tror Norng	B	78.0	23.0	60.0	4.30	913.2
PK	Sa	85. Phka Malis	B	0.0	0.0	0.0	3.00	846.0	PL	Sa	96. Phka Rumduol	T	55.0	0.0	0.0	4.20	1115.7
PK	Sa	86. Phka Rumdeng	B	19.0	33.0	7.5	2.90	786.5	KP	C	100. OM5451	B	33.0	10.0	7.5	5.40	1218.7
PK	Sa	87. Somaly	B	19.0	37.5	7.5	2.80	755.6	13. Prey Veng Province								
PK	Sa	88. Phka Rumduol	B	0.0	0.0	0.0	2.00	564.0	PL	Sa	23. IR504	B	60.0	60.0	45.0	3.50	707.9
PL	Sa	83. OM5451	B	45.0	115.0	0.0	2.90	565.1	PL	Sa	24. Krasang Teap	B	39.0	16.0	8.0	3.00	648.4
PL	Sa	82. Sen Pidao	T	10.0	10.0	7.5	2.00	550.2	PL	Sa	25. OM5451	B	39.0	16.0	8.0	3.40	738.8
PL	Sa	84. Sen Kra Ob	T	45.0	115.0	0.0	2.90	730.4	PL	Sa	26. Sen Kra Ob	B	48.2	16.0	8.0	3.20	888.2
6. Kampong Chhnang Province									PL	Sa	28. Raing Chey	B	25.3	0.0	42.0	2.30	488.4
PK	Sa	53. OM5451	B	41.0	46.0	0.0	3.20	611.6	PL	Sa	29. Ka Ngork Pong	B	41.0	18.0	11.5	2.30	486.4
PK	Sa	58. IR504	B	46.0	0.0	0.0	3.20	637.1	PL	Sa	27. Phka Rumduol	D	87.0	46.0	30.0	3.10	814.5
PK	Sa	52. Phka Rumduol	T	41.0	46.0	0.0	3.00	810.6	PL	Sa	30. CAR 15	D	87.0	46.0	30.0	3.50	712.7
PK	Sa	54. Sen Kra Ob	T	41.0	46.0	0.0	3.40	924.6	14. Svay Rieng Province								
PK	Sa	57. Phka Chan Sen Sar	T	20.0	20.0	15.0	2.30	627.8	PL	Sa	60. Raing Chey	B	54.5	20.0	15.0	3.15	881.1
PK	Sa	59. CAR15	T	20.0	20.0	15.0	3.40	669.3	PL	Sa	61. IR504	B	58.0	86.0	60.0	5.05	1071.3
PL	Sa	56. Raing Chey	B	23.0	0.0	0.0	2.10	421.1	PL	Sa	62. Phka Ampil	B	54.5	20.0	15.0	2.95	822.5
PL	Sa	55. Neang Krim	T	32.0	9.0	0.0	2.00	391.5	PL	Sa	63. Phka Rumduol	B	40.0	20.0	15.0	2.73	764.0
7. Kampong Speu Province									PL	Sa	64. Jasmine 85	B	78.0	23.0	90.0	5.05	1085.9
PK	Sa	68. Kong Chheng	B	35.6	32.2	0.0	2.83	560.4	PL	Sa	65. Krasang Teap	B	53.0	30.0	22.5	2.85	613.1
PK	Sa	69. Chulasa	B	52.5	46.0	0.0	3.00	580.9	PL	Sa	66. OM5451	B	78.0	23.0	90.0	4.95	1062.6
PK	Sa	70. Ka Ngork Pong	B	50.2	46.0	0.0	1.86	342.4	PL	Sa	67. Sen Kra Ob	B	53.0	30.0	22.5	3.25	901.3
PK	Sa	71. Sen Kra Ob	T	41.0	46.0	0.0	3.00	870.6									
PK	Sa	72. Phka Rumduol	T	35.6	12.6	0.0	3.40	1014.8									
PL	Sa	74. Phka Malis	B	56.8	27.6	0.0	3.80	1119.2									
PL	Sa	73. Smar Prum	T	35.6	32.2	0.0	3.25	648.6									

2.3. Statistical Analysis

All data were processed using Microsoft Excel 2019, and then a statistical analysis was performed using SPSS (Ver. 28.0.1.0 (142), Chicago, IL, USA).

3. Results and Discussion

3.1. Grain Yield

In Table 1, the grain yield at each cultivation site is listed and categorized depending on the geographical distribution from the northwest and in the opposite direction while considering the major soil type in each province, such as clay-soil-dominant areas (1. Banteay Meanchey, 2. Battambang, 3. Kampong Thom, 9. Kampong Cham, and 10. Tboung Khum), silt-soil-dominant areas (4. Pursat and 11. Kandal), and sandy-soil-dominant areas (5. Siem Reap, 6. Kampong Chhnang, 7. Kampong Speu, 8. Kampot, 12. Takeo, 13. Prey Veng, and 14. Svay Rieng). Cambodian clay soils, such as Toul Samroung, Krakor, Kampong Siem, Kein Svay, and Kbar Po, consist of 41 to 49% clay; silt soils, such as Bakan and Koktrap, consist of 41% to 49% silt; and sandy soil, such as Prateah Lang and Prey Khmer, consist of over 70% sand (Table 3). In the study by Kong et al. (2019) [9], the sand content was negatively correlated with the clay content, CEC, and available K, and it was considered that a high sand content decreases the soil's ability to retain nutrients. Homma et al. (2003) [21] and Sharama et al. (2019) [22] suggested that the rice yield in the unfertilized plots reflected the inherent soil fertility or nutrient-holding capacity. According to White et al. (2000) [11], the Toul Samroung soil will be comparatively fertile. In this study, there were five unfertilized sites: 'CAR8' (sample no. 13) in Krakor soil (clay) in Kampon Thom Province, 'Angakareach' (sample no. 33) in Bakan soil (silt) in Kandal Province, 'CAR9' (sample no. 41) in Pray Khmer soil (sandy) in Pursat Province, 'Phka Malis' (sample no. 85), and 'Phka Rumduol' (sample no. 88) in Pray Khmer Soil (sandy) in Siem Reap Province. According to Fukai and Ouk (2012) [23], many rice farmers in rainfed lowlands of the Mekong region will grow old and tall cultivars, such as 'Phka Rumduol' in Cambodia, that respond less well to soil nutrients than high-yielding cultivars in the irrigated lowlands. The five varieties cultivated without fertilization in this study were medium-to-late maturing, and their days from sowing to harvesting were 193 (no. 13), 181 (no. 33), 191 (no. 41), 130 (no. 85), and 125 (no. 88).

The paddy samples in this study were collected from rainfed fields; thus, the effect of each region's rainfall on the grain yield was investigated first. The relationship between the monthly base cumulative precipitation during the cultivation period of each variety at each site and the grain yield was significantly negative ($r = -0.278$, $p = 0.005$) (Figure 1a). However, behind the relationship between the precipitation during the cultivation period and the yield, another factor, its intervention, was considered. The cumulative precipitation during the cultivation period is reflected by the length of the cultivation period. After examining the possible factors, the grain yield showed a significant negative correlation with the maturity days from sowing to harvesting ($r = -0.395$, $p < 0.001$) (Figure 1b). The negative relationship between the maturity and grain yield suggests that longer maturity cases may not easily achieve a higher yield, genetically and/or environmentally. The plant samples that have shorter maturity, around 100 days, showed large variation in the yield (Figure 1b). The grain yield at the five unfertilized sites mentioned above was 2.0 to 3.0 t ha^{-1} (Table 1), the difference of which did not show any specific relations with the maturity or soil type among the file varieties cultivated without fertilizer.

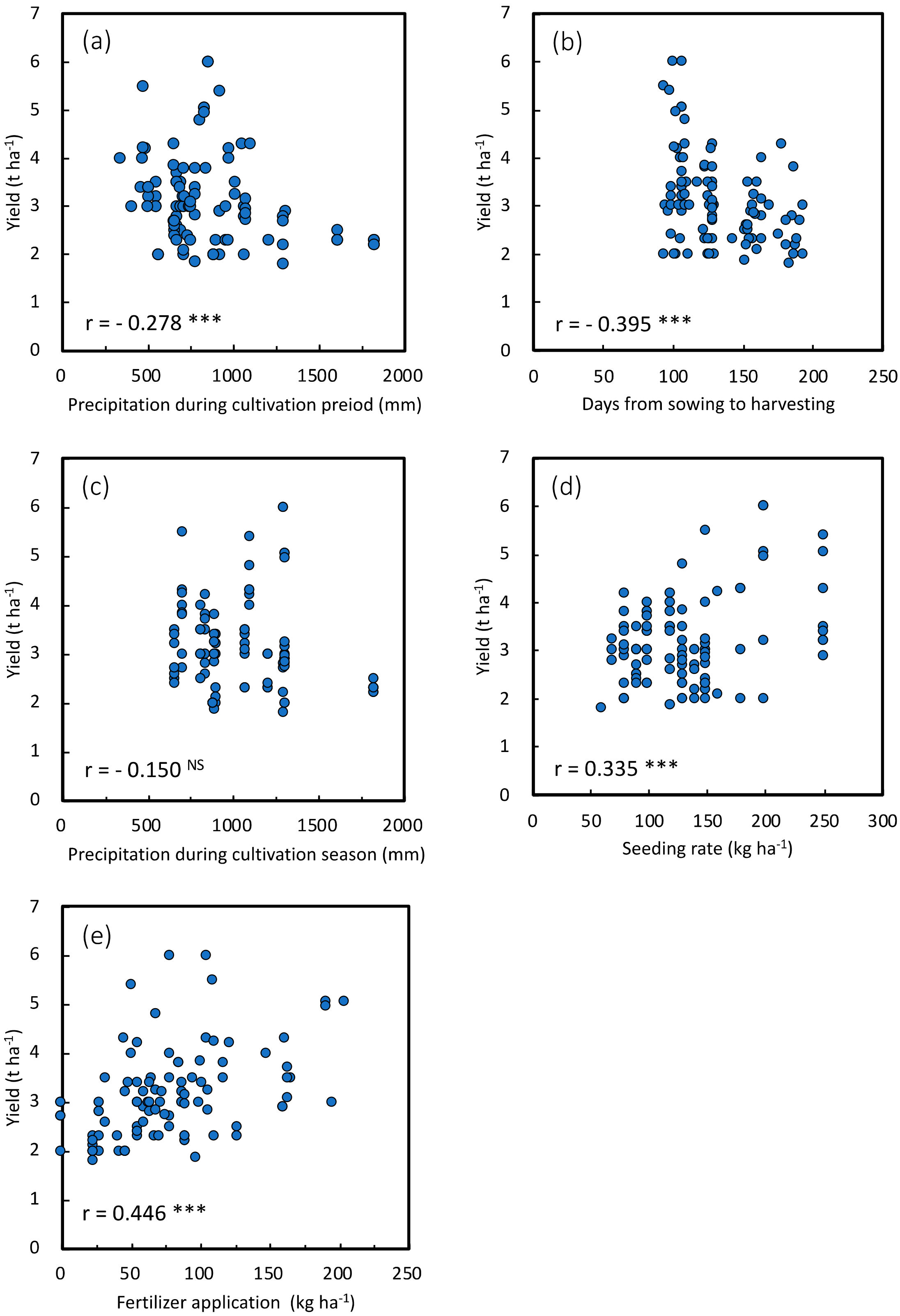

Figure 1. Relationship between precipitation during cultivation. (**a**) Days from sowing to harvesting, (**b**) precipitation during cultivation season, (**c**) direct seeding rate, (**d**) the amount of fertilizer applied, and (**e**) grain yield. ***: Significant at 0.001 probability level, NS: not significant.

To clarify the influence of precipitation on the grain yield, a partial correlation analysis when the degree of association between the cumulative precipitation during the cultivation at each site and grain yield, with the effect of days for maturity removed, was employed. The partial correlation coefficient ($r_{\text{(precipitation during cultivation period)(grain yield)(days for maturity)}}$) was -0.190, and nonsignificant ($p = 0.590$), which indicated that the effect of cumulative precipitation during the cultivation was small in 2019. Moreover, there was no specific relationship between the precipitation data in the wet rice season from June to December as the cumulative value in each province and the grain yield ($r = -0.150$, $p = 0.136$) (Figure 1c). The range of precipitation during the cultivation from June to December in 2019 was 0 mm (December in 9 provinces) to 711.4 mm (August in Kampot Province), which tended to be high at the early stage of growth, and at a low level at harvesting season in comparison with the average from 2016 to 2019, 5 mm (December in Banteay Meanchey Province) to 460.3 mm (August in Kampot Province) (see Supplementary Table S2). The climate in this region is tropical monsoonal, with a wet season (from June to November) followed by a prolonged dry season, and irregular rainfall both from year to year and within years (Kong et al., 2019) [9]. Rice is grown mostly during the wet season, but with frequent intermittent drought (Tsubo et al., 2007) [24]. However, the difference in the cumulative precipitation between 2019 (1048.4 mm, on average, in 14 provinces) and the average from 2016 to 2019 (1174.6 mm) was about 10% and not so large. It was, therefore, considered that the rice varieties adapted to the environment at each site in each province performed their usual growth at the level of an average year. In December 2019, the environment tended be dry rather than an average year, but it was in or after harvesting season, and its influence might be negligible.

From the investigations above, it was understood that other factors should be considered. As a result of another correlation analysis, the relationship between the seeding rate (the weight of seeds used in a nursery for a 1-ha paddy field in case of transplanting) and the grain yield was significantly positive ($r = 0.335$, $p < 0.001$) (Figure 1d). Contrarily, the fertilizer application amount, in total (the sum of constituents (elements) such as N, P_2O_5, and K_2O in each fertilizer applied), showed a positive relation with the grain yield, and its correlation coefficient was 0.446 ($p < 0.001$) (Figure 1e); the coefficient was much higher than the other cases mentioned above.

The grain yield showed a mostly positive relationship with the mount of fertilizer applied: with the total amount of fertilizer or nitrogen in clay- (Figure 2a,d), silt- (Figure 2b,e), and sandy-soil (Figure 2c,f) dominated areas; with phosphorus in clay- (Figure 2g) and silt-soil (Figure 2h) dominated areas; and with potassium in clay- (Figure 2j) and sandy-soil (Figure 2l) dominated areas. The relationship between the grain yield and phosphorus application in sandy-soil-dominated areas (Figure 2i) or potassium application in silt-soil-dominated areas (Figure 2k) was not clear. On the other hand, there were many sites with zero potassium application, and the grain yield there showed a comparatively large variation (Figure 2j–l). Thus, we investigated the possible factors influencing the grain yield under no potassium application. As the result, only in silt-soil dominated area, the seeding rate showed a highly positive correlation ($r = 0.816$, $p = 0.001$) with the grain yield without potassium application. In silt-soil dominated areas, potassium was mostly not applied (12 sites among 13 sites) (Figure 2k); therefore, the relationship between the seeding rate and the grain yield might be apparent under the zero-potassium condition.

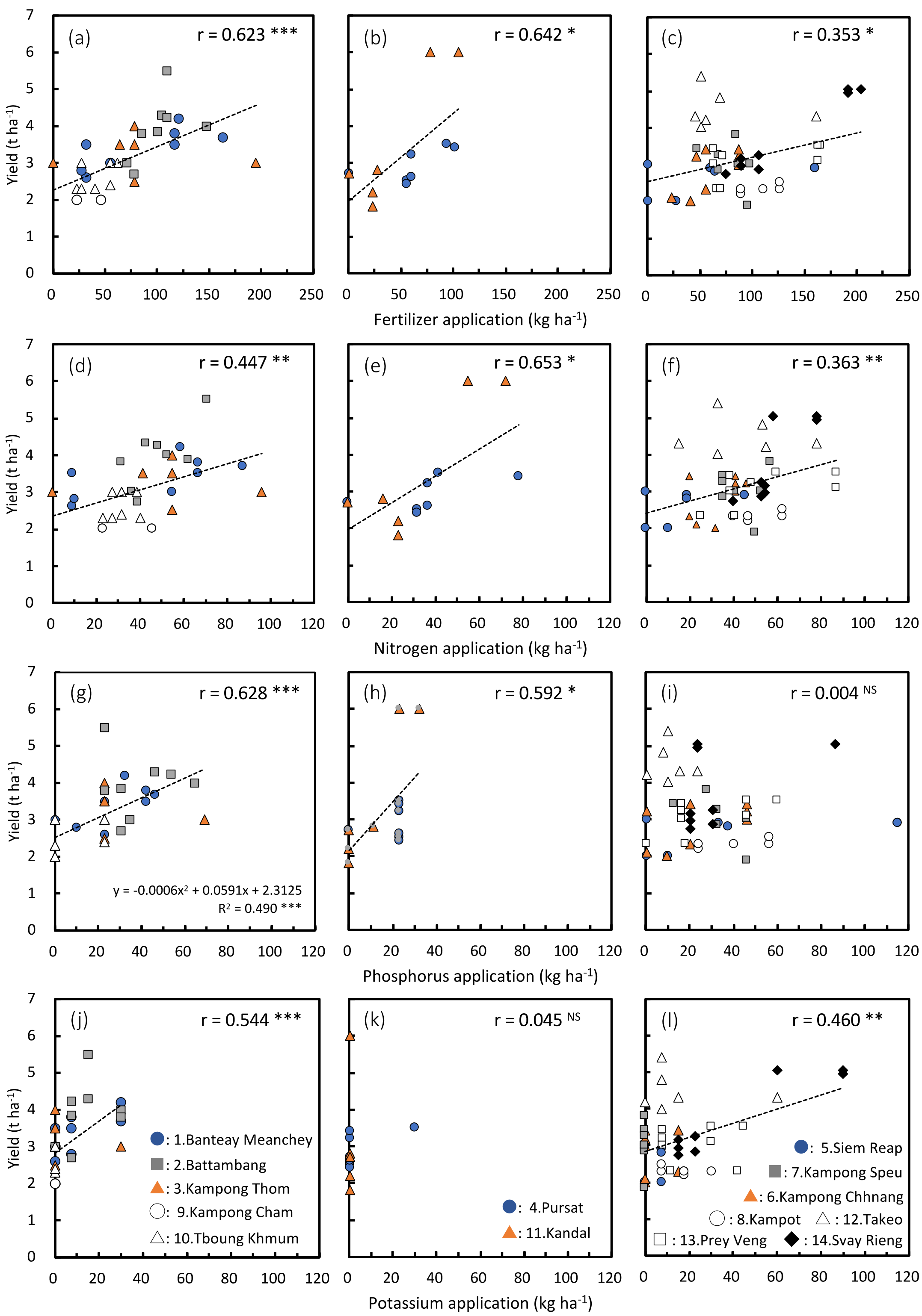

Figure 2. Relationship between the amount of all fertilizers. (**a**–**c**) Nitrogen, (**d**–**f**) phosphorus, (**g**–**i**), and potassium (**j**–**l**) applied, and the grain yield in areas where clay soil (**a**,**d**,**g**,**j**), silt soil (**b**,**e**,**h**,**k**), or sandy soil (**c**,**f**,**i**,**l**) dominates. *, **, ***: significant at 0.05, 0.01, 0.001 probability level. NS: not significant.

Depending on the province, the lineup of cultivated rice varieties varies, which may account for farmers' preferences and consumers' needs. 'Phka Rumduol', 'Sen Kra Ob', and 'Raing Chey' are popular varieties that were cultivated in areas of all three categories—

areas where clay, silt, or sandy soils are dominant—with a comparatively wide range of fertilizer quantities applied (Table 1). These three popular varieties—'Phka Rumduol', 'Sen Kra Ob', and 'Raing Chey'—were found in more than 70% of our target provinces (in 14, 12, and 10 provinces, respectively). The three varieties showed grain yield variation associated with the amount of fertilizer applied. The relationship between the total amount of fertilizer applied ($N + P_2O_5 + K_2O$) showed a significant positive linear correlation with the grain yield in one hundred samples pooled, as shown in Figure 2b. Moreover, in the case of the three popular varieties that draw attention from both farmers and consumers, the relationship between the total amount of fertilizer applied and the grain yield was positive (r = 0.455, $p = 0.005$), but the coefficient determination was higher in the quadratic regression ($R^2 = 0.371$, $p < 0.001$) than in the linear regression ($R^2 = 0.207$, $p = 0.005$). Thus, we showed the quadratic regression equation and approximation curve for the relationship between the total amount of fertilizer applied and the grain yield in Figure 3a, and from the curve, the grain yield looked saturated at over 120 kg ($N + P_2O_5 + K_2O$) ha^{-1} in the three popular varieties. More Cambodian rice farmers are beginning to apply more fertilizer to their fields [11], and the total fertilizer consumption in Cambodia has increased from 7873 t N in the period of 2002–2005 to over 63,784 t after 2012, from 12,512 t P_2O_5 in 2002–2005 to 17,112 t after 2012, and from 1033 t K_2O in 2002–2005 to 3926 t after 2012 [1]. Although much additional research is anticipated, the concept of optimizing fertilizer use efficiency, considering the importance of using a balanced NPK fertilizer (Seng et al., 2001) [25], should be emphasized for contributing to sustainable agricultural production.

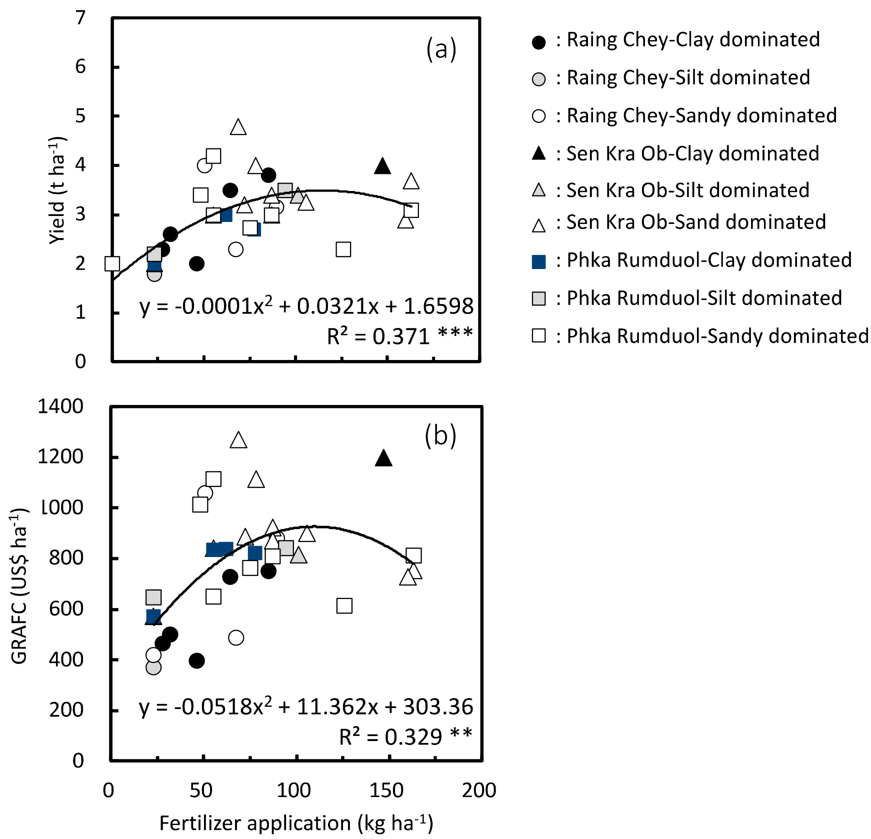

Figure 3. Relationship between the amount of fertilizer applied and the grain yield (**a**) and the gross return above fertilizer cost (GRAFC) (**b**). **, ***: significant at 0.01, 0.001 probability level.

3.2. Gross Return above Fertilizer Cost

The fertilizer cost increased as the amount of fertilizer applied increased in all cases, including different varieties and/or soil types, and the gross return above fertilizer cost (GRAFC: (paddy sales) − (fertilizer cost)) varied depending on the fertilizer cost (Table 1).

When we focused on the three popular varieties, the relationship between the total amount of fertilizer applied and the GRAFC was positive (r = 0.401, p = 0.015), but the coefficient determination was higher in the quadratic regression (R^2 = 0.320, p = 0.002) than in the linear regression (R^2 = 0.160, p = 0.016). Consequently, we show the quadratic regression equation and approximation curve for the relationship between the total amount of fertilizer applied and the GRAFC in Figure 3b; the curve peaks at around 120 kg ha^{-1} total elements applied (Figure 3b). This means that there may be an appropriate amount of fertilizer to achieve greater benefits for farmers. For one variety, 'Sen Kra Ob', the application of more than 160 kg total might be considered excessive. In a previous study [10], the N-P_2O_5-K_2O rate of 60–30–15 kg ha^{-1} was the best application rate for the GRAFC of wet-season rice in sandy soil areas of southern Cambodia. However, in various soil types, including clay- and silt-dominant areas, preferable total amounts and combinations of N-P_2O_5-K_2O application for a higher GRAFC varied, depending on soil type [9] and cultivating season [26]. The other nutrients may also influence the growth and yield of the rice plant and the quality of white rice, and additional investigations will be needed as further subjects. However, we only considered the cost of nitrogen, phosphorus, and potassium this time; therefore, we concentrated the current study on the influence of the major three nutrients. In any case, the optimal rate for maximizing farmers' incomes should be carefully considered, along with fertilizer cost.

3.3. Quality Parameters Relating to White Rice

The percentage of quality rice was 60% (≥6.2 mm) in the majority of white rice samples (83%). From examining the relationship between the percentage of quality rice and the other parameters of white rice, we found no specific relationship with parameters such as the amount of fertilizer applied (r = 0.141), yield (r = −0.036), nitrogen concentration in white rice (r = 0.047), carbohydrate concentration (r = 0.060), carbohydrate/protein ratio (r = 0.079), amylose concentration (r = −0.005), amylopectin concentration (r = 0.008), or amylopectin/amylose ratio (r = 0.051). Although the relationship between the amount of fertilizer applied and the nitrogen concentration in white rice was not clear when all samples were pooled, it was significantly positive in the three popular varieties (Figure 4a,b). On the other hand, the carbohydrate concentration showed a significantly negative correlation with the amount of fertilizer applied in all the samples, as well as in just the popular varieties (Figure 4c,d). The carbohydrate/protein ratio was negatively related to the amount of fertilizer applied in all samples used (Figure 4e,f), results that reflect the responses of nitrogen and carbohydrate concentrations mentioned above. Okadome et al. (1999) [27] reported that the protein concentration in white rice showed a significant negative correlation with taste. In our previous studies [3,5], we also found a negative relationship between the nitrogen or protein concentration in white rice and the taste of cooled rice, and another negative relationship between the ratio of total carbon to total nitrogen (C/N) in white rice and cooked rice taste as well. Former reports by Morita et al. (2005) [28] and Morita and Nakano (2011) [29] suggested the importance of the smooth accumulation of nonstructural carbohydrates for maintaining rice grain quality. Considering these results, we investigated the carbohydrate concentration and carbohydrate/protein ratio as described above. From former reports and current findings, we understood that the carbon concentration in white rice is just as important as that of nitrogen and the balance of N and C and protein and carbohydrates; in other words, when we consider the nutrient management of wet-season rice, it is, unfortunately, possible that the application of more fertilizer for attaining higher yields may also bring the continuing presence of higher nitrogen (protein) and a decrease in the carbohydrate concentration, as well as the carbohydrate/protein ratio in white rice. In our former analysis of white rice [3,5], the coefficient of variance in the C/N ratio among eight samples cultivated with conventional management was 7.1%, and the C/N ratio showed a significant positive correlation with the taste value of cooked rice (r = 0.767, p = 0.026). In this study, the coefficient of variance in the carbohydrate/protein ratio was 33.2%, 20.3%, and 23.9% in 'Raing Chey', 'Sen Kra Ob', and 'Phka Rumduol', respectively.

Considering these levels of variation in the carbohydrate/protein ration among different soil types with fertilizer management, a sensory test will be our further subject to make clear the effect of soil fertility and fertilization on the taste of cooked rice.

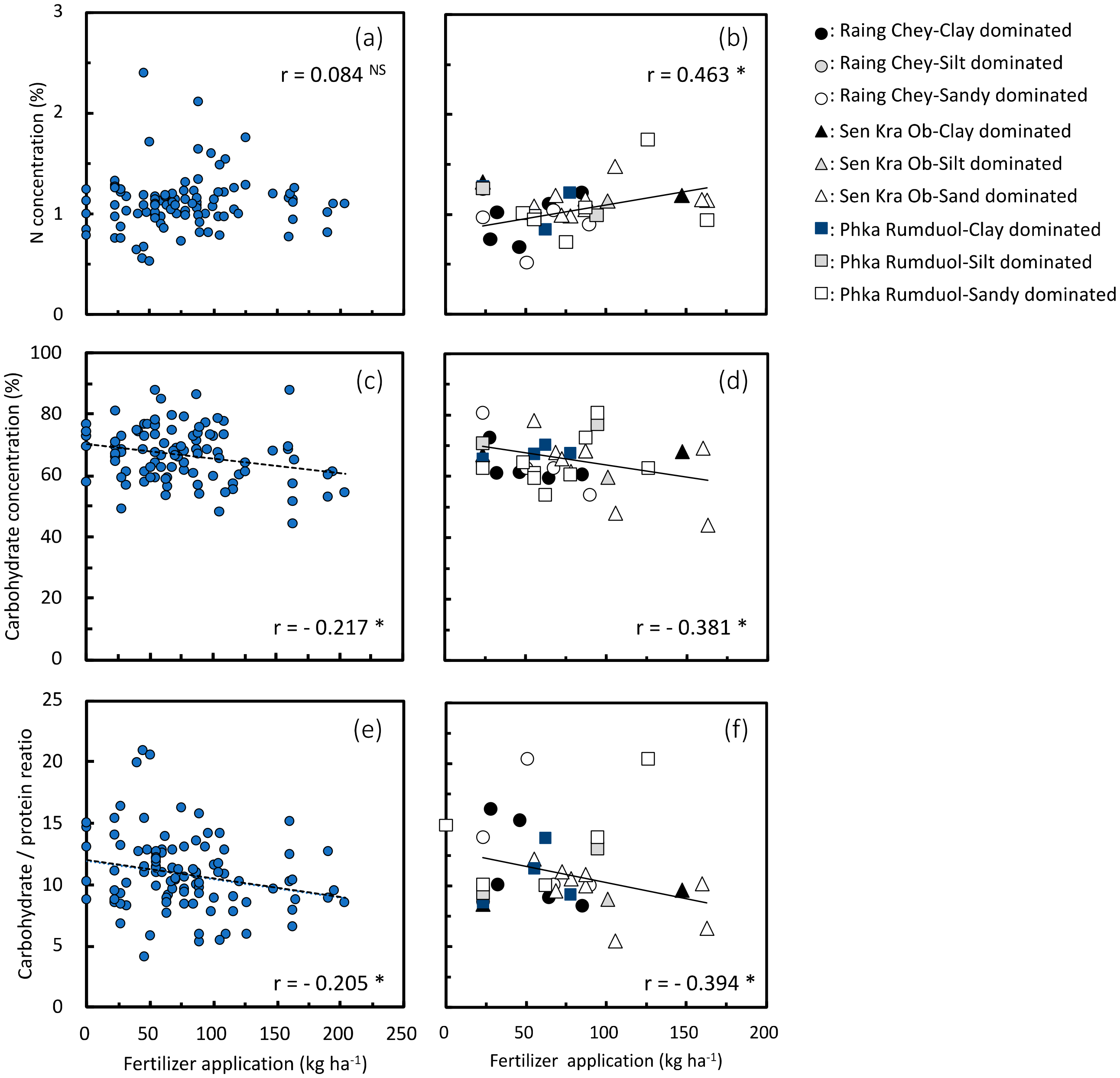

Figure 4. Relationship between the amount of fertilizer applied and the nitrogen concentration (**a**,**b**), carbohydrate concentration (**c**,**d**), and carbohydrate/protein ratio (**e**,**f**) in white rice. *: significant at 0.05 probability level. NS: not significant.

In Figure 5, the relationships between the amount of fertilizer applied and the amylopectin concentration (subtracting the amylose from the starch) in white rice are shown, but there was no specific relationship in either the case of all samples or the three varieties only. In the relationship between the amount of fertilization and the amylopectin concentration, there was no specific tendency (r = 0.167, not significant for all the samples; r= 0.125, not significant for the three varieties). In Figure 6, the relationships between the carbohydrate concentration and the amylopectin concentrations in white rice are shown. The amylopectin concentration showed a significantly positive linear correlation with the carbohydrate concentration. According to the MAFF of Japan (https:

//www.maff.go.jp/j/heya/kodomo_sodan/0304/01.html) (accessed on 16 June 2022), the amylose concentration in white rice is an index of hardness. In the report of Okadome et al. (1999) [27], the hardness of cooked rice whole grains showed a negative correlation with the taste of rice. They also stated that comprehensive taste (an overall evaluation) is closely and negatively related with the protein concentration in white rice, and is closely and positively related with the balance (stickiness/hardness) of cooked rice [27]. On the other hand, Yamashita et al. (1993) [30] suggested that the amylopectin contents or the proportion of amylose to amylopectin was considered to affect the eating quality of cooked rice among cultivars rather than the amylose contents. In our current study, we found a highly significant positive relationship between the amylopectin concentration and carbohydrate concentration, which decreased with heavier fertilization. The higher amylopectin concentration will contribute to higher stickiness, which will be important, as described above by Okadome et al. [27]. In this study, the carbohydrate concentration showed negative relationships with the amylose concentration ($r = -0.397$, $p < 0.001$) and the proportion of amylose to amylopectin ($r = -0.395$, $p < 0.001$), respectively. Yamashita et al. (1993) [30] stated that the combination of a lower protein concentration with a low/moderate amylose concentration brought a higher comprehensive evaluation result of taste, and higher protein with higher amylose was the worst. According to Matsue et al. (2002) and Igarashi and Kohara (2008) [31,32], the amylose concentration will increase as the air temperature decreases. Although the daily minimum temperature was 18.0 to 21.9 °C depending on the province in the current study (see Supplementary Table S1), the effect of temperature was not clear on the grain characteristics. Contrarily, the amylopectin concentration will be influenced by the change in carbohydrate concentration, and these two parameters will vary synchronously. As described above, the carbohydrate concentration will be affected and decrease with the increasing fertilization rate in contrast to the nitrogen concentration, which will increase with increasing fertilizer application. As the responses of those parameters to increasing fertilization rates, important parameters for maintaining and improving the taste of rice—such as carbohydrate concentration and carbohydrate/protein ratio—will decrease with heavier fertilization. According to the U.S. Department of Agriculture (2022) [33], three kinds of fertilizer have dramatically increased in price over the past year: urea, the price of which has increased 149%; liquid nitrogen, the price of which has increased 192%; and anhydrous ammonia, which now costs 235% more. The Pacific Coast Business Times (2022) [34] reported that the study above by the U.S. Department of Agriculture was completed in February 2022, before the war in Ukraine and sanctions against Russia pushed prices even higher, as fertilizers doubled and even tripled in price due to the war, pandemic, and inflation. An article in The Economist (2022) [35] discussed how the fertilizer price index has increased remarkably—by nearly four times its price in January 2006. In this sort of social situation, further emphasis on analyzing the trade-offs for inputs and returns of not only quantity, but also the quality, of products with beneficial concepts beyond fertilizer use efficiency is urgently required for maintaining and improving the sustainability of the food production system.

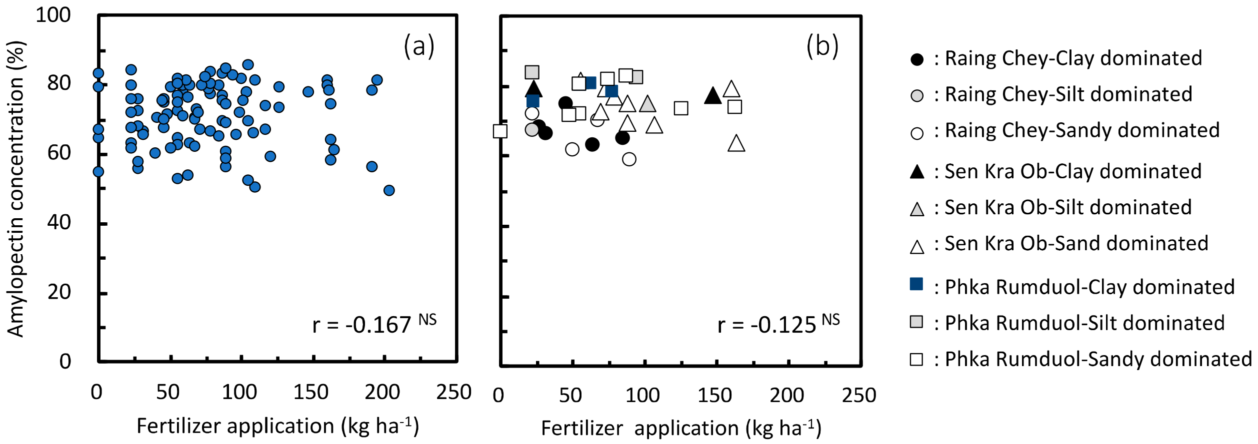

Figure 5. Relationship between the amount of fertilizer applied and the amylopectin concentration in white rice (**a**,**b**). NS: not significant.

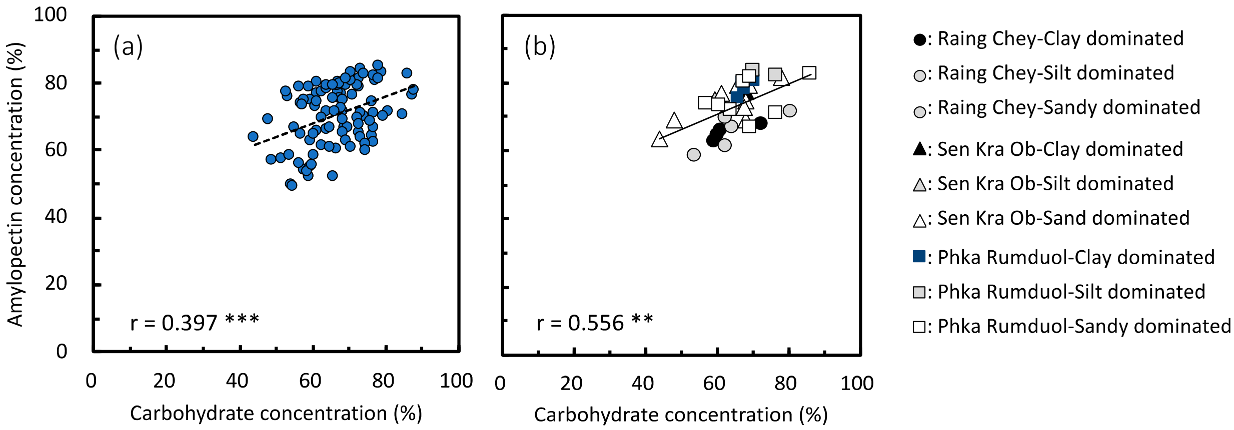

Figure 6. Relationship between the carbohydrate concentration and the amylopectin centration in white rice (**a**,**b**). **, ***: significant at 0.01, 0.001 probability level.

4. Conclusions

The gross return above fertilizer cost (GRAFC) showed a nonlinear relationship with the fertilization rate, with a peak around a moderate level of the fertilization rate. The nitrogen concentration, recognized as one of the negative factors for the quality of white rice, tended to increase with an increasing fertilization rate, and the carbohydrate concentration and carbohydrate/protein ratio, which are positive factors for the quality, were negatively related with the fertilizer rate. The amylopectin concentration in white rice was positively related with the carbohydrate concentration, which decreased with an increasing fertilization rate. From these results, the level of fertilizer application required to achieve a higher yield, the GRAFC, and the maintenance and improvement of parameters relating to grain quality were different. The most profound result in this study was the decrease in carbohydrate/protein ratio in white rice with increasing fertilizer application. The optimal rate of fertilizer application should be carefully examined by considering the soil types in cultivation areas. As a general understanding, agricultural practices responding to market-oriented production, assuming sustainable production, have been desired in recent years, and the concept of a backcasting approach relating to the quality of agricultural products is also needed in the tropics.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su141710708/s1, Table S1. Fertilizing rate in total, proportion of basal and top dressing, seeding rate or planting space, sowing date, harvesting date, precipitation, day length, temperature, fertilizer cost, paddy sales. Table S2. Precipitation (mm) during cultivation season of rainfed rice (2019).

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