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Environmental Impact Assessment of Rice–Wheat Rotation Considering Annual Nitrogen Application Rate

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Abstract: Rice–wheat rotation is a widely adopted multiple-cropping system in the Yangtze River Basin, China. Nitrogen (N) fertilizer is a key factor in regulating crop yield; however, only a few studies have considered the impact of annual N application on the yield, environmental impacts, and economic profits of rice–wheat rotation systems. In this study, a field experiment was conducted in the Jiangsu Province from 2020 to 2022. The rice and wheat seasons included six and five N fertilizer application rates, respectively (Rice: 0, 180, 240, 300, 360, and 420 kg N ha^{-1}; Wheat: 0, 180, 240, 300, and 360 kg N ha^{-1}), combined to form a total of 30 treatments. Life-cycle assessment was used to evaluate the environmental impacts of rice–wheat rotation under different N application treatments, using area, yield, and economic profit as functional units. Ten environmental impact categories were selected, including global warming. The results showed that grain yield did not consistently increase with an increase in N application, and the annual yield was the highest when 300 and 240 kg N ha^{-1} (R300W240 treatment) was applied in the rice and wheat seasons, respectively. The area-based weighting index of the R300W240 treatment ranked 20th among the 30 treatments, while the yield- and profit-based weighting indices were the lowest among the 30 treatments, decreasing by 14.9% and 28.7%, respectively, compared to the other treatments. The R300W240 treatment was the optimal annual N application strategy for rice–wheat rotation. Among the 10 environmental impacts considered, urea production contributed significantly to over eight environmental impacts, whereas the pollutant losses caused by its application contributed significantly to six environmental impacts. These findings reveal the dependence of the rice–wheat rotation system on the unsustainable use of N fertilizer and indicate that N fertilizer management practices should be further optimized to improve the environmental sustainability of grain production in the future.

Keywords: rice–wheat rotation; annual nitrogen management; global warming; environmental impact; life cycle assessment

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1. Introduction

Rice–wheat rotation is one of the main grain production modes in East Asia and is widely distributed in countries such as China and India [1,2]. In China, the area of rice–wheat rotation remains above 4.67 million ha and is mainly concentrated in the Yangtze River Basin. At present, in the context of rising global temperatures, population growth, and COVID-19, achieving sustainable food production at a minimum environmental cost and ensuring food security are still the main tasks facing China's agricultural production industry [3].

The application of nitrogen (N) fertilizers plays an important role in rice and wheat yield. The national N fertilizer application rate in 2021 is 17.4 million tons [4]. Although the amount of N fertilizer applied nationwide has decreased annually over the past decade, the total amount is still relatively large. Compared to developed countries, the utilization efficiency of N fertilizers still needs to be improved [5,6]. Long-term cultivation and extensive N fertilizer application not only lead to a decrease in the N utilization efficiency of crops but also damage the ecological environment [7]. Under the rice–wheat rotation mode, a portion of N enters the atmosphere in gas form, causing global warming, environmental acidification, and fine particulate matter formation [8,9]; however, parts of N are lost through runoff, leaching, and other pathways, leading to eutrophication of water [10]. At the same time, the heavy metal residues from fertilizer application in the soil can also threaten human health [11]. Currently, it is necessary to evaluate the environmental impact of the rice–wheat rotation mode from the perspective of the entire production system, which is beneficial for guiding the sustainable development of this mode of production [12].

Life cycle assessment is a product-oriented whole-process evaluation method that provides a standard method for systematically evaluating the environmental impact of products from a system perspective [13,14]. Previous studies on the environmental impact evaluation of rice–wheat rotation have mainly focused on screening suitable rotation modes, irrigation methods, and straw-returning methods to coordinate economic and environmental benefits. For example, Cai et al. (2018) quantitatively analyzed the carbon and reactive nitrogen emissions of rice wheat, rice rape, rice fava bean, and rice milk vetch in Yixing, Jiangsu Province, China. They showed that winter legume–rice rotations can reduce nitrogen pollution and the carbon footprint while maintaining net ecosystem economic benefits [15]. Chen et al. (2021) evaluated the environmental and economic benefits of the rice–wheat rotation system using four irrigation methods (conventional flooding irrigation, intermittent irrigation, transplanting rain-fed, and dry rice cultivation), and the results showed that dry rice cultivation with high-yield rice varieties could provide more comprehensive benefits throughout the whole rotation system [16]. Ghosh et al. (2022) evaluated the energy and carbon relationships in rice–wheat rotation in India under contrasting tillage and residue management scenarios, and the results showed that the selection of high-yield, biotic, and abiotic stress-tolerant rice varieties will help narrow the yield gap with puddled transplanted rice and further improve the crop and biomass yield and energy productivity of the rice–wheat cropping system [17]. Xu et al. (2022) compared the ecological, environmental, and economic benefits of the rice–wheat rotation system with traditional fertilization and controlled-release fertilizer application, and the results showed that twice-split application of bulk blending urea was the most effective fertilization strategy to balance the economic benefit and ecological and environmental impacts in the rice–wheat rotation system [18]. However, they only considered the amount of N in a single-season crop and did not optimize the annual N fertilizer management. In addition, the aforementioned studies focused only on one environmental impact, such as global warming or energy consumption, and did not comprehensively assess multiple environmental impacts.

An annual rice–wheat rotation field experiment was conducted in Yangzhou City in the lower reaches of the Yangtze River from 2020 to 2022, and five and six N fertilizer gradients were set in the rice and wheat seasons, respectively, to form 30 different N fertilizer application treatments. The main objective of this study was to quantitatively evaluate the environmental impact of different N-treated rice–wheat rotation systems to screen suitable combinations of annual N doses that can both meet crop yields and accommodate environmental benefits.

2. Materials and Methods

2.1. Study Area

The study area is located in Shatou Town, Yangzhou City, Jiangsu Province, China (119°56′ E, 32°32′ N) (Figure 1). The region belongs to the transitional zone from a subtropical monsoon humid climate to a temperate monsoon climate with four distinct seasons, abundant sunshine, and abundant rainfall. The multi-annual average temperature is 16.5 °C, and the average annual rainfall is 1139 mm. The meteorological conditions used in the experiments are shown in Figure 2. The soil was sandy loam with a pH of 7.78. The average organic matter content of the topsoil (0–20 cm) is 22.33 g kg^{-1}, and the total N and alkaline N contents are 2.87 g kg^{-1} and 106.73 mg kg^{-1}, respectively.

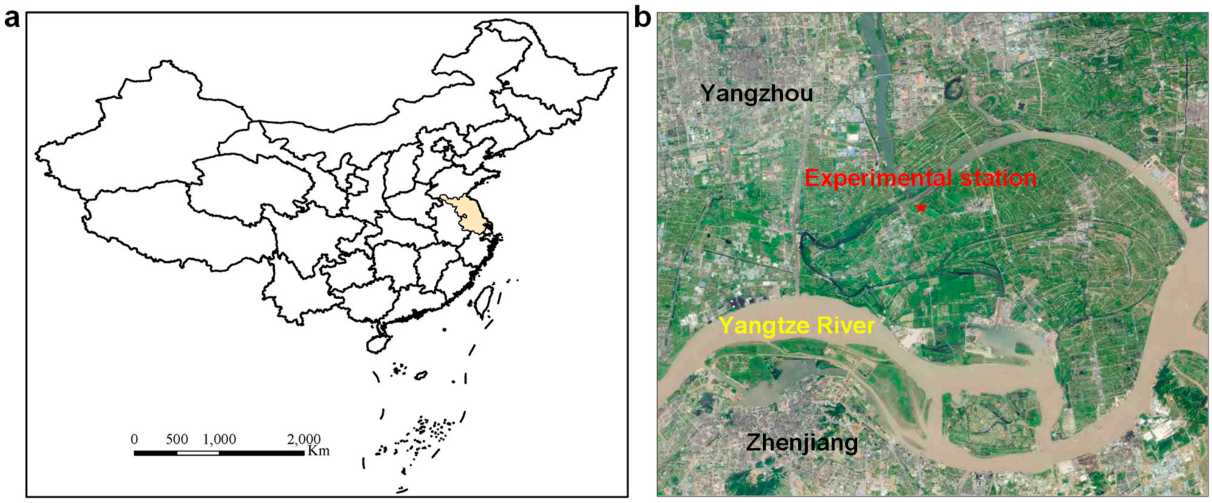

Figure 1. Location of the research area. (**a**) Jiangsu Province in China; (**b**) the experimental station in Yangzhou City, Jiangsu Province.

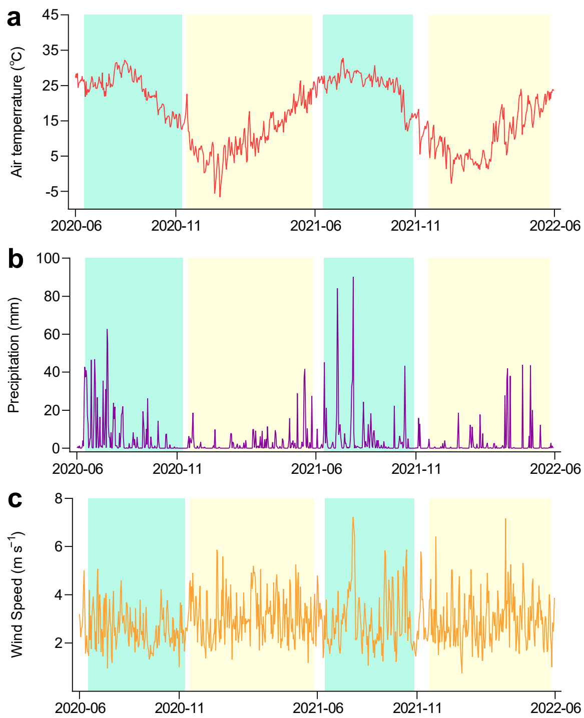

Figure 2. Meteorological conditions during the experiment (2020–2022). (**a**) air temperature; (**b**) precipitation; (**c**) wind speed.

2.2. Experimental Design and Yield Measurement

This experiment adopted a rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) rotation system and considered two complete annual events from 2020 to 2022 as a paradigm. Rice was transplanted on 14 June 2020 and 13 June 2021, and harvested on 10 November 2020 and 28 October 2021. Wheat was sown on 17 November 2020 and 20 November 2021, and harvested on 27 May 2021 and 25 May 2022. The rice and wheat varieties used in this study were Nanjing 5055 and Yangmai 25, respectively. The rice cultivation method involved manual transplanting, whereas the wheat was sown using a drill machine. During the rice season, six N application rates (pure N) were set, namely 0 (R0), 180 (R180), 240 (R240), 300 (R300), 360 (R360), and 420 (R420) kg ha^{-1}. After rice harvesting, five N application rates were set for each N fertilization gradient of rice for wheat production, namely 0 (W0), 180 (W180), 240 (W240), 300 (W300), and 360 (W360) kg ha^{-1}. A total of 30 treatments were formed through cross combinations (Tables S1 and S2). Each treatment had three replicates, totaling 90 experimental plots, each with an area of 47.5 m^2 (9.5 m $\times$ 5 m). The N fertilizer used was urea, with base fertilizer: tillering fertilizer: spikelet-promoting fertilizer: flower-protecting fertilizer = 4:2:2:2. Phosphate fertilizer (superphosphate) and potassium fertilizer (potassium chloride) were applied as base fertilizers at application rates of 47 kg P_2O_5 ha^{-1} and 158 kg K_2O ha^{-1} in the rice season and 90 kg P_2O_5 ha^{-1} and 144 kg K_2O ha^{-1} in the wheat season, respectively. After harvesting, the straw was crushed using agricultural machinery and returned to the field, with annual average values of 4.5 t ha^{-1} wheat straw and 7.5 t ha^{-1} rice straw returning to the field. The rice irrigation mode followed the high-yield rice cultivation mode [19], and no artificial irrigation was performed during the wheat season. Chemical pesticides were used for pest control and other field management practices were implemented according to the requirements of high-yield cultivation.

During the rice maturity period, three quadrats were selected in each plot and 100 hills were harvested from each quadrat. After threshing and removing impurities, the moisture content of the grains was measured using a portable grain moisture meter (PM-8188-A; Kett, Tokyo, Japan) to calculate the actual yield. Similarly, during the wheat maturity period, three 10 m^2 plots were chosen from each plot for actual yield measurements.

2.3. Life Cycle Assessment

According to ISO 14044 [20], life cycle assessment consists of four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation of results. The description of each step is as follows.

2.3.1. Goal and Scope Definition

The goal of this study was to quantitatively evaluate the environmental impact of rice–wheat rotation with different fertilization modes and to identify key regulatory points for energy conservation and emission reduction. The system boundary in this study was from the cradle to the farm gate and included agricultural material production and transportation, grain production, and direct/indirect field emissions. This study excluded stages such as infrastructure construction and agricultural machinery production because their contributions to environmental impacts are usually small [21]. To avoid biased results, we selected three functional units for the comprehensive environmental impact assessment: per hectare, per ton of grain, and per output value. To calculate the environmental impact per output value, we conducted an economic benefit analysis based on data from 2021 to 2022 (Table S7 and Figure S1 in the Supplementary Materials).

2.3.2. Inventory Analysis

The life-cycle inventory includes all input–output items of the evaluation system. The agricultural inputs for the annual production system of rice–wheat rotation in this study included seeds, fertilizers, pesticides, irrigation water, electricity, and diesel (Tables S1 and S2), and the system outputs included measured grain yields in the field as well as environmental pollutants emitted into the atmosphere, soil, and water (Tables S3 and S4). For the emissions and losses of environmental pollutants, the CH_4 generated by rice cultivation was estimated using the IPCC Tier 1 method [22]; the CH_4 emissions generated by wheat cultivation were not considered. The N_2O emissions generated by rice and wheat cultivation included both direct and indirect emissions. Direct N_2O emissions were estimated by multiplying the total N input and the emission coefficient recommended by the IPCC, with emission coefficients of 0.005 and 0.01 for rice and wheat, respectively. Indirect N_2O emissions refer to the sum of N_2O emissions caused by NH_3 volatilization and N leaching. Based on previous studies on rice–wheat rotation in the lower reaches of the Yangtze River in eastern China, nitrogen oxides, NH_3 volatilization, N leaching, and runoff of rice–wheat rotation were estimated using the coefficient method [23–25]. The emission factors of P runoff and leaching are shown in the Table S5 [26–28]. For more details on the P runoff and leaching, refer to study [29]. Because of the weak mobility of K, its loss was not considered. The heavy metal residues (Cd, Pb, Cu, and Zn) produced by fertilizer application are shown in Tables S3 and S4. Pesticides entering the soil, atmosphere, and water account for 43%, 10%, and 1% of their effective component inputs, respectively [30].

2.3.3. Impact Assessment

The ReCiPe 2016 midpoint method [31] is widely used for environmental impact assessment of agricultural ecosystems [13,32]. Among the 18 environmental impact categories, we selected 10 indicators that were closely related to food crop production: global warming (GW), fine particulate matter formation (FPMF), territorial discrimination (TA), freshwater eutrophication (FE), territorial ecotoxicity (TET), freshwater ecotoxicity (FET), human carcinogenic toxicity (HTc), human non-carcinogenic toxicity (HTnc), fossil resource scale (FRS), and water demand (WD). Environmental impact assessment consists of three steps: characterization, normalization, and weighting. The normalization process of the characterized values refers to the global per capita environmental impact benchmark value [33,34], and the weighting coefficients (relative importance) of each environmental indicator were obtained based on expert opinions (Table S6).

2.4. Statistical Analysis

The yield of rice–wheat rotation in this study covers two complete anniversaries from 2020 to 2022, and the data are presented in the form of mean ± standard deviation. The Shapiro–Wilk test was used to analyze the normal distribution of the data, and one-way analysis of variance (Tukey's test) was performed on the annual total crop yield. All statistical analyses were performed using IBM SPSS Statistics for Windows version 28. Due to the lack of obvious differences in input and output data of the production system between years, the life cycle assessment was performed using the data from 2021 to 2022 using SimPro 9.0 software (Amsterdam, The Netherlands).

3. Results

3.1. Grain Yield of Rice–Wheat Rotation under Different N-Application Treatments

The crop yield was not only affected by the amount of N applied in the current season, but also by the amount of N applied in the previous crop (Figure 3). Overall, the annual yields of rice and wheat from 2021 to 2022 were higher than those from 2021 to 2021. Among the 30 treatments, the annual yield of the R0W0 treatment was the lowest at 6776 kg ha^{-1} and 6813 kg ha^{-1} over the two years, respectively. With an increase in the N application rate, the annual rice and wheat yields increased accordingly. The annual yield of the R300W240 treatment was the highest, at 15,741 kg ha^{-1} and 17,541 kg ha^{-1} for the two years, respectively. However, as the N application rate continued to increase, the annual yields of rice and wheat showed a gradually decreasing trend. When the annual N application rate reached the highest value, the annual yield of treatment R420W360 significantly decreased by 18.3–20.9% compared to that of the R300W240 treatment ($p < 0.01$). When the annual N application rate reached the highest value, the annual yield of the R420W360 treatment decreased significantly (by 18.3–20.9%) compared to the R300W240 treatment ($p < 0.01$).

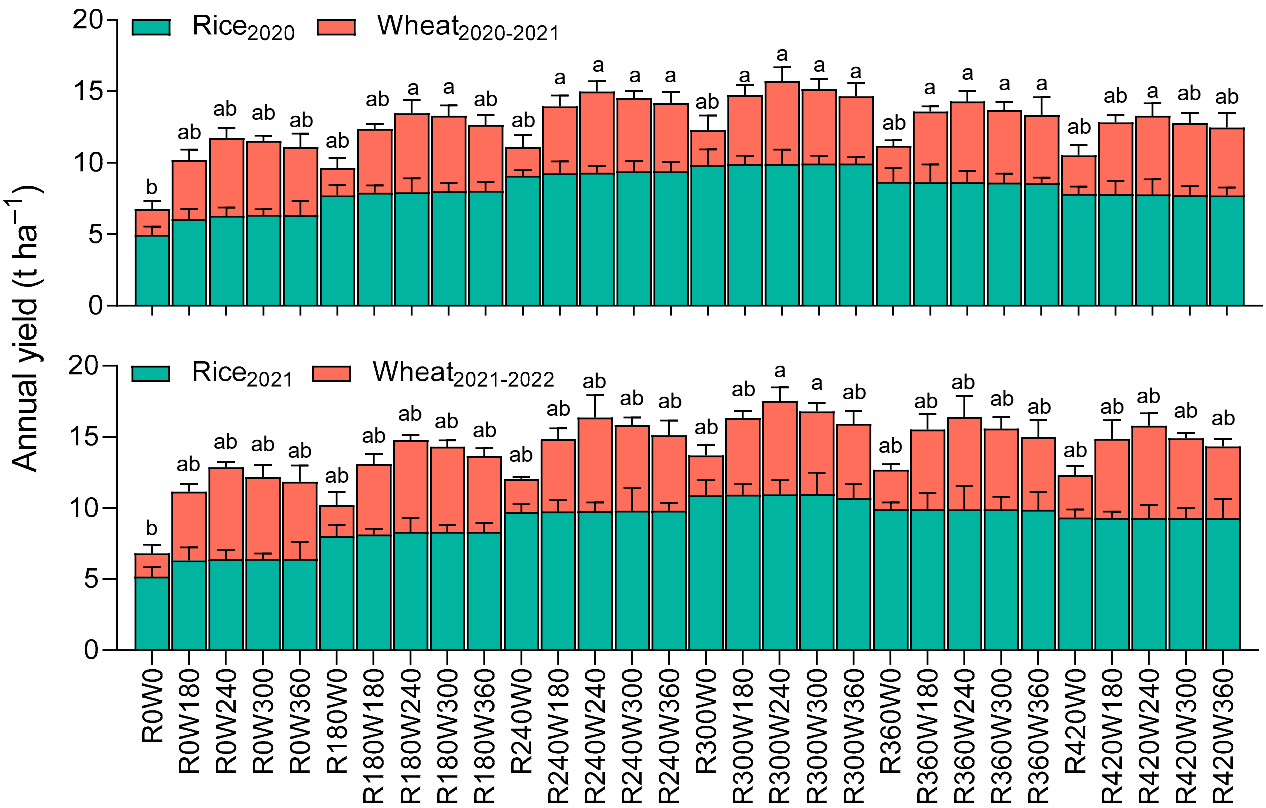

Figure 3. Crop yield of rice–wheat rotation system with different fertilization modes. Different lower-case letters represent significant differences at the 0.01 level.

3.2. Environmental Impact of Rice–Wheat Rotation under Different N-Application Treatments

3.2.1. Area-Based Environmental Impact and Hotspot Analysis

In the rice–wheat rotation system, crop growth, fertilization, and the application of pesticides and diesel all affect the environment (Figure 4). The GW per unit area under different fertilization treatments increased with the increase in annual N application, ranging from 7472 to 19,465 kg CO_2 eq ha^{-1}. Owing to the high emissions of CH_4 from rice cultivation, its contribution to the total GW was the highest (51.6–80.4%). The contribution of urea application to GW was also high (0–29.8%), followed by wheat cultivation (2.5–14.6%). The contributions of other inputs (seeds, P and K fertilizers, pesticides, diesel, and electricity) to the GW were relatively small. The FPMF of different treatments ranged from 4.8 to 41.8 kg PM2.5 eq ha^{-1}. Rice cultivation contributed the most to FPMF, accounting for 36.3–69.9%, followed by wheat cultivation (0–39.3%). The contributions of urea application (0–28.1%) and electricity use (7.8–68.0%) were also large, whereas the contributions of other inputs were relatively small. The TA of different treatments ranged from 16.8 to 273.0 kg SO_2 eq ha^{-1}. The contribution of each input to TA was as follows: rice cultivation (0–85.3%), electricity use (4.1–66.7%), wheat cultivation (0–61.7%), and urea application (0–16.4%), with small contributions from other inputs. The FE of different treatments ranged from 1.1 to 2.2 kg P eq ha^{-1}. The contribution of wheat cultivation to FE was as high as 30.3–59.8%, followed by urea application (0–49.3%), rice cultivation (12.0–23.7%), and pesticide application (5.1–10.0%); the impacts of other inputs were relatively small.

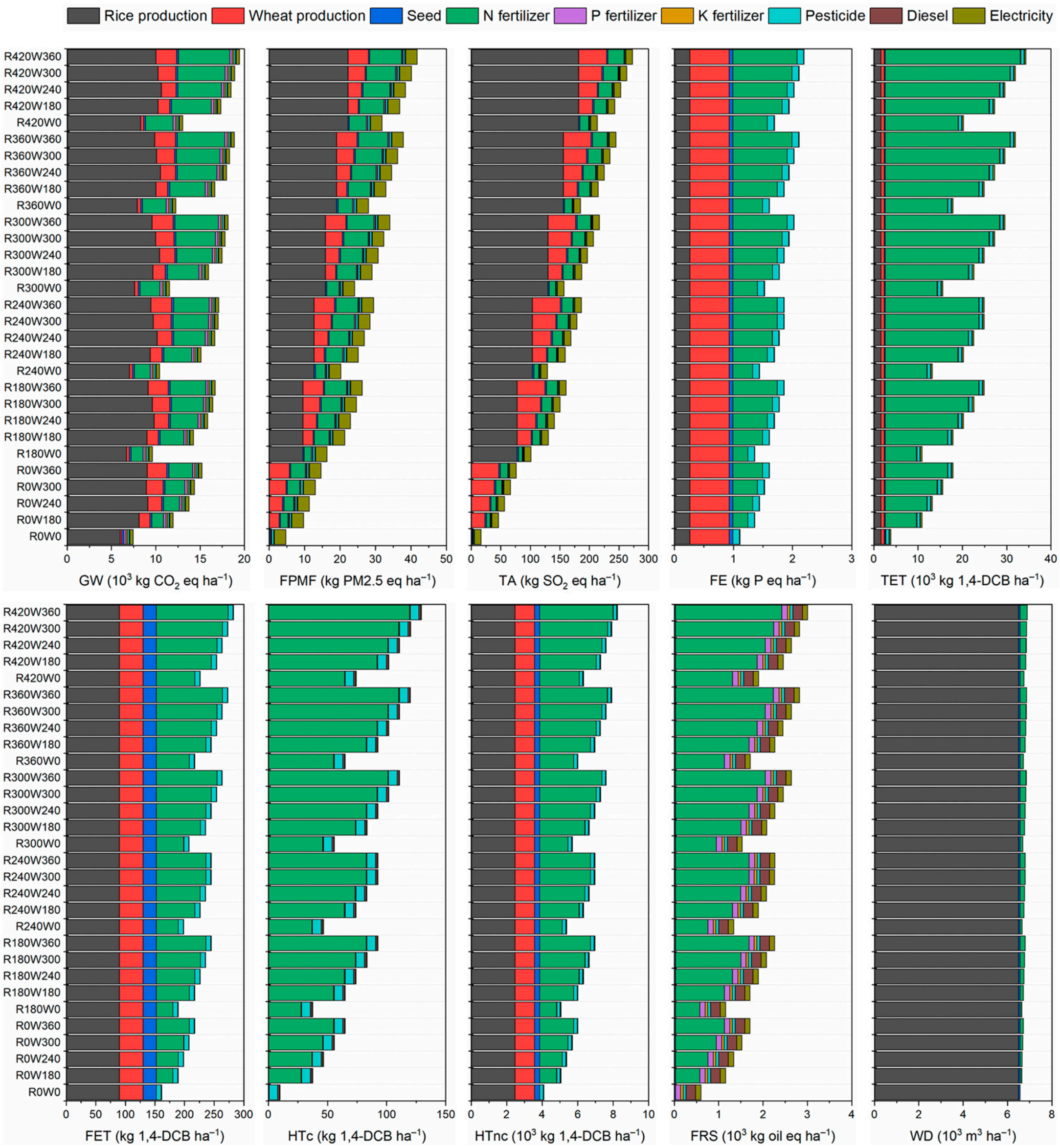

Figure 4. Environmental impacts per hectare of rice–wheat rotation system with different fertilization modes.

For environmental and human toxicity, the TET of the different treatments ranged from 3865 to 34,341 kg of 1,4-DCB ha^{-1}. The contribution of N fertilizer application was high, ranging from 0% to 88.7%. Rice cultivation (4.9–43.2%), wheat cultivation (2.2–19.1%), and pesticide application (2.1–19.0%) also contributed significantly, whereas the contribution of other inputs was relatively small. The FET values of the different treatments ranged from 161.5 to 282.7 kg 1,4-DCB ha^{-1}. Rice cultivation (31.9–55.8%) and N fertilizer application (0–42.9%) were dominant, followed by wheat cultivation (14.2–24.9%), seed input (7.8–13.7%), and pesticide application (3.0–5.2%). The HTc of different treatments ranged from 10.1 to 129.5 kg of 1,4-DCB ha^{-1}. HTc was mainly caused by the application of urea (0–92.2%) and pesticide (5.6–72.0%), with little contribution from other inputs. The HTnc values of the different treatments ranged from 4111 to 8251 kg 1,4-DCB ha^{-1}. Rice cultivation (30.0–60.2%), urea application (0–50.2%), and wheat cultivation (13.4–26.9%) contributed the most, followed by seeds (3.5–6.9%) and pesticides (2.4–4.8%), with little contribution from P fertilizer, K fertilizer, and electricity use.

For resource consumption, the FRS of the different treatments ranged from 604 to 3011 kg oil eq ha^{-1}, all of which were caused by agricultural inputs and energy consumption. The contributions of various items in descending order were urea (0–79.7%) > diesel (7.2–35.9%) > P fertilizer (4.2–19.9%)> electricity (3.9–19.6%) > pesticides (2.2–11.1%) > K fertilizer (1.8–9.2%). The WD of the different treatments ranged from 6574 to 6903 m^3 ha^{-1}, mainly from the irrigation water used in rice cultivation. Wheat cultivation in the lower reaches of the Yangtze River relies primarily on rainwater and requires very little irrigation. Moreover, N fertilizer production accounted for a small proportion of water resources (0–4.8%).

3.2.2. Yield-Based Environmental Impact

The environmental impacts per unit yield for different treatments are shown in Figure 5. The GW of the R300W0 treatment was the lowest (844 kg CO_2 eq t^{-1}), whereas that of the R420W360 treatment was the highest (1358 kg CO_2 eq t^{-1}). The R0W0 treatment had the lowest FPMF (0.7 kg PM2.5 eq t^{-1}), TA (2.46 kg SO_2 eq t^{-1}), TET (567 kg 1,4-DCB t^{-1}), HTc (1.48 kg 1,4-DCB t^{-1}), and FRS (88.7 kg oil eq t^{-1}), while the R420W360 treatment had the highest impacts, namely FPMF of 2.91 kg PM2.5 eq t^{-1}, TA of 19.05 kg SO_2 eq t^{-1}, TET of 2396 kg 1,4-DCB t^{-1}, HTc of 9.04 kg 1,4-DCB t^{-1}, and FRS of 210.1 kg oil eq t^{-1}. Owing to the extremely low annual yield of the R0W0 treatment, it had the highest FE (0.163 kg P eq t^{-1}), FET (23.7 kg 1,4-DCB t^{-1}), HTnc (603 kg 1,4-DCB t^{-1}), and WD (965 m^3 t^{-1}); however, due to the relatively high yield of the R300W240 treatment, these environmental impacts were small, namely FE (0.106 kg P eq t^{-1}), FET (14.0 kg 1,4-DCB t^{-1}), HTnc (398 kg 1,4-DCB t^{-1}), and WD (388 m^3 t^{-1}).

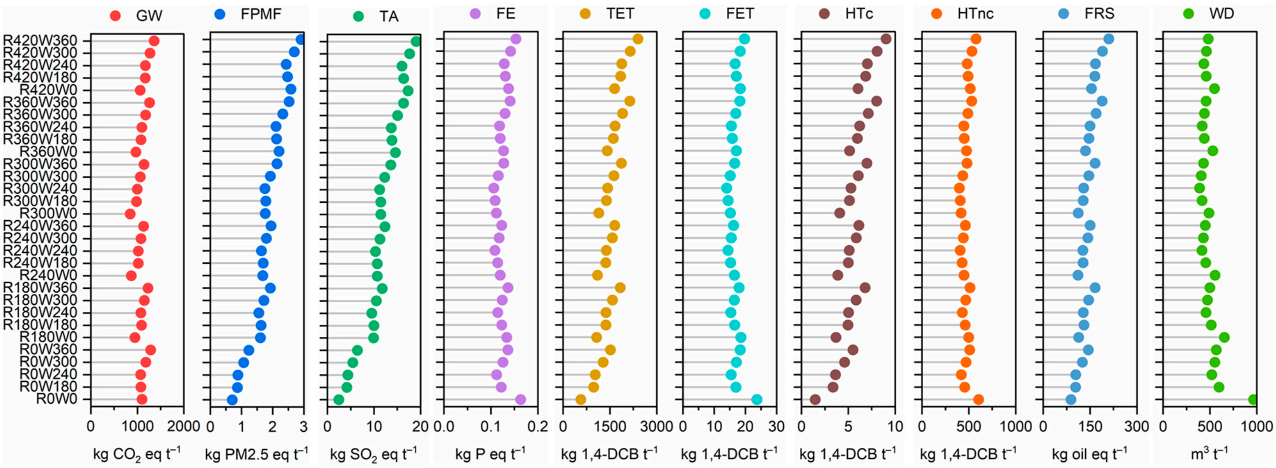

Figure 5. Environmental impacts per ton grain of rice–wheat rotation system with different fertilization modes.

3.2.3. Profit-Based Environmental Impact

The environmental impacts of the different treatments per output value are shown in Figure S1. Owing to the extremely low output value of the R0W0 treatment, it had the highest GW of 2966 kg CO_2 eq (CNY $10^3)^{-1}$, FE of 0.44 kg P eq (CNY $10^3)^{-1}$, FET of 64.1 kg 1,4-DCB (CNY $10^3)^{-1}$, HTnc of 1632 kg 1,4-DCB (CNY $10^3)^{-1}$, FRS of 239.9 kg oil eq (CNY $10^3)^{-1}$, and WD of 2609 m^3 (CNY $10^3)^{-1}$. R300W0 treatment had the lowest GW and FRS, with the value of 629 kg CO_2 eq (CNY $10^3)^{-1}$ and 83.5 kg oil eq (CNY $10^3)^{-1}$. R300W240 treatment had the lowest FE, FET, HTnc, and WD, with the values of 0.07 kg P eq (CNY $10^3)^{-1}$, 9.5 kg 1,4-DCB (CNY $10^3)^{-1}$, 270 kg 1,4-DCB (CNY $10^3)^{-1}$, and 263 m^3 (CNY $10^3)^{-1}$, respectively. The ranges of FPMF, TA, TET, and HTc were 0.74–2.51 kg PM2.5 eq (CNY $10^3)^{-1}$, 3.66–16.43 kg SO_2 eq (CNY $10^3)^{-1}$, 848–2067 kg 1,4-DCB (CNY $10^3)^{-1}$, and 3.03–7.79 kg 1,4-DCB (CNY $10^3)^{-1}$, respectively, all showing an increasing trend with the increase in N application rate.

3.2.4. Weighting Index

The area-based weighting index of the environmental impact for each treatment increased with the increase in N application, ranging from 3.54 to 7.07 (Figure 6a). WD had the greatest contribution to the area-based weighting index, ranging from 30.8% to 58.5%, followed by FET and HTc, which accounted for 21.3–24.3% and 3.0–19.4%, respectively. The R0W0 treatment had the highest yield-based weighting index of 0.52, whereas the R300W240 treatment had the lowest yield-based weighting index of 0.34; the latter was 34.6% lower than the former (Figure 6b). Owing to the extremely low economic benefits of the R0W0 treatment, its profit-based weighting index was 1.40, which was 222–502% higher than that of the other treatments. The profit-based weighting index for the R300W240 treatment was the smallest, with a value of 0.23 (Figure 6c). R300W240 was found to be the optimal fertilization treatment.

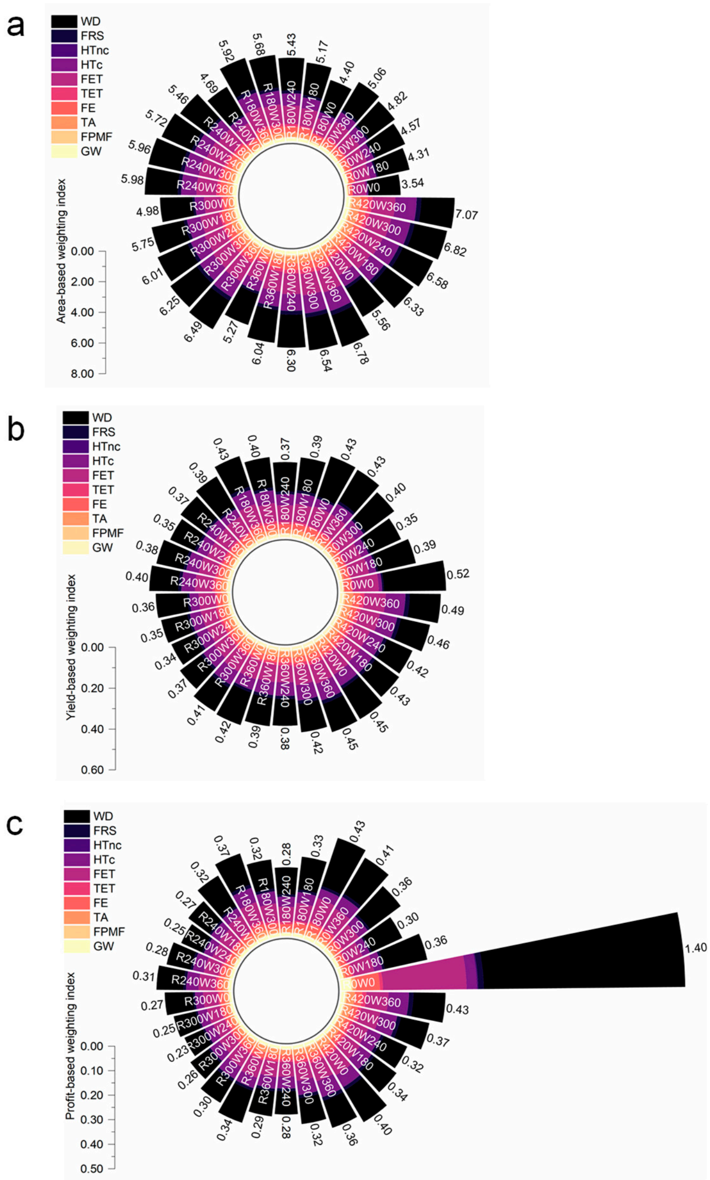

Figure 6. Weighting index of environmental impact based on (**a**) area, (**b**) yield, and (**c**) profit.

4. Discussion

Previous studies on the appropriate N application rate for rice–wheat rotation have often only considered fertilizer management for single-season crops without considering the impact of the annual N application rate on yield and environmental effects. In rice–wheat rotation as a whole production system, the residual N in the soil during the rice season not only continues to provide N for the growth of the next wheat season but also causes environmental pollution due to the loss of N to the environment [35]. As shown in Figure 3, high N application leads to higher yields, whereas higher N application leads to ineffective tillering and even lodging, thus decreasing crop yields. When excessive nutrients are present in surplus in the soil, they put pressure on the ecological environment [36]. This study found that a relatively high annual yield could be achieved at 300 and 240 kg N ha^{-1} for rice and wheat, respectively, with relatively high economic benefits and low environmental impact; thus, R300W240 was the best annual nitrogen application strategy.

Global warming triggered by crop production has attracted widespread attention as the single most important environmental indicator threatening human health and ecosystems. The GW of the field-scale rice–wheat rotation production system is listed in Table 1. Owing to the different calculation models and emission factors, the results of different studies exhibit some variability. The GW_{Area} of rice–wheat rotation systems in different regions of China ranged from 7.1 to 45.1 t CO_2 eq ha^{-1}, and the results of this study are within this range. Several studies in India have shown lower GWs (3.2–10.7 t CO_2 eq ha^{-1}), mainly due to lower fertilization rates and GHG emissions from the fields. Xu et al. (2022) reported the impact of different fertilization modes on the GW of rice–wheat rotation [18]. Under conventional fertilization modes, the GW of rice–wheat rotation reached 45.1 t CO_2 eq ha^{-1}, mainly due to the large amount of GHG caused by N fertilizer application. Their research further indicated that the application of controlled-release fertilizers could reduce the GW of the rice–wheat rotation system by 42.3%. To increase the robustness of the evaluation results, we conducted an uncertainty analysis of the GW for the rice–wheat rotation system using the R300W240 treatment as an example (Table S8). This study assumed that the activity data and emission losses followed a triangular distribution [37], with a coefficient of variation of 10% [38,39]. Monte Carlo simulation was used to estimate the uncertainty generated by 10,000 random samples. The average GW of the R300W240 treatment was 17,494 ± 840 kg CO_2 eq ha^{-1}, and the 2.5% and 97.5% quantiles were 16,017 and 19,313 kg CO_2 eq ha^{-1}, respectively. The median and coefficient of variation were 17,439 kg CO_2 eq ha^{-1} and 4.8%, respectively, indicating weak uncertainty in the evaluation results.

Table 1. Comparison between published global warming (GW) of rice–wheat rotation with current study.

Reference	Site	GW_{Area} (t CO_2 eq ha^{-1})	GW_{Yield} (t CO_2 eq t^{-1})
[14]	Jiangsu, China	11.3–13.3	1.5–1.8
[40]	Hubei, China	15.3–22.6	1.0–1.3
[41]	Anhui, China	9.1	–
[15]	Hubei, China	7.1	–
[42]	Hubei, China	26.9	–
[16]	New Delhi, India	3.2–8.8	0.3–0.8
[1]	Hubei, China	8.6–11.2	–
[43]	Karnal, India	6.4–8.1	0.1–0.6
[37]	Jiangsu, China	9.3–45.1	1.4–2.4
[44]	New Delhi, India	8.9–10.7	0.1–0.3
This study	Jiangsu, China	7.5–19.5	0.8–1.4

NH_3 is one of the important reactive N pollutants [45] and is the main cause of land acidification. According to the LCA results (Figure 4), the TA of each treatment mainly occurred during the rice and wheat cultivation stages, accounting for 55.9% and 19.6%, respectively. Moreover, the NH_3 generated in rice–wheat rotation systems forms inorganic aerosols in the troposphere with acidic substances (such as sulfuric acid and nitric acid), mainly composed of ammonium sulfate and nitrate, which can cause haze [46]. In the future, the appropriate use of slow- and controlled-release N fertilizers may further alleviate the environmental burden of reactive N.

The indicator with the greatest impact on the weighting index was WD (30.8–58.5%), mainly due to the inclusion of agricultural irrigation water during the rice cultivation stage in the life cycle assessment modeling. In this study, the irrigation water for the rice–wheat rotation system mainly originated from the rice season, whereas the wheat season mainly relied on rainfall. Despite the numerous rivers and lakes in the Yangtze River Basin in China, water resources are relatively abundant. However, owing to the frequent occurrence of extreme climate events in recent years [47,48], there is often a lack of irrigation water during the rice-growing season, indicating that future rice–wheat rotation systems should adopt more water-saving irrigation measures during the rice season to reduce the comprehensive environmental impact index [16].

This study has several limitations. First, the optimal N application rate in this study was determined by considering only the timescale of the two years. However, N in soil is in a dynamic state of accumulation and loss, and long-term experiments are warranted to determine the optimal annual N application rate. Second, although the uncertainties in the GW, FPMF, and TA were relatively low, several toxic effects exhibited significant variability. In future experiments, in situ monitoring of heavy metals is required to increase the accuracy of the evaluation results. Finally, the changes in soil C were not significant in the short term because this study only conducted a 2-year field experiment; thus, the soil carbon sink was not considered in the evaluation of GW. In the future, as the experiment continues, the soil carbon sink should be included in the evaluation scope.

5. Conclusions

In this study, the environmental impact, human and ecological toxicity, and resource consumption of rice–wheat rotation with different N fertilizer applications were evaluated based on field experimental data combined with a life cycle assessment method. The area-based weighting index of the R300W240 treatment was 6.01, ranking 20th out of the 30 treatments. However, both the yield-based (0.34) and profit-based (0.23) weighting indices of the R300W240 treatment were the lowest, with average reductions of 14.9% and 28.7%, respectively, compared to the other treatments. Considering the yield, economic profit, and environmental impacts of the rice–wheat rotation system, R300W240 was the best annual N application strategy. Based on this study, future research should be conducted to optimize N fertilizer management (i.e., application period and high-efficiency N fertilizer type) to achieve a win–win relationship between increasing grain production and reducing the environmental burden.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy14010151/s1, Figure S1: Environmental impacts per CNY 10^3 economic profit of rice–wheat rotation system with different fertilization modes; Table S1: Life cycle inventory of rice–wheat rotation from 2020 to 2021; Table S2: Life cycle inventory of rice–wheat rotation from 2021 to 2022; Table S3: On-field environmental pollutants from rice cultivation (2021); Table S4: On-field environmental pollutants from wheat cultivation (2021–2022); Table S5: Emission factors of reactive N from N fertilization and P loss in the field; Table S6: Normalization reference value and weight coefficient of world per capita environmental impact for 2010; Table S7: Economic profit analysis of rice–wheat rotation with different N-fertilizer treatment (2021–2022); Table S8: Uncertainty analysis of environmental impacts for rice–wheat rotation (Treatment: R300W240). References [22–28,34] are cited in the supplementary materials.

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Abbreviations

GW: global warming; FPMF: fine particulate matter formation; TA: territorial discrimination; FE: freshwater eutrophication; TET: territorial ecotoxicity; FET: freshwater ecotoxicity; HTc: human carcinogenic toxicity; HTnc: human non-carcinogenic toxicity; FRS: fossil resource scale; WD: water demand.

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