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Rice-Animal Co-Culture Systems Benefit Global Sustainable Intensification

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Key Points:

- Rice-animal co-culture systems could produce more diverse food with higher rice yield and extra animal protein
- Global promotion of rice-animal co-culture will reduce nitrogen loss and methane emissions from rice paddies
- Global promotion of rice-animal co-culture will increase income of producers by 152–171 billion US dollars annually

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Producing more food with less pollution and greenhouse gas emissions is a grand challenge for the 21st century. Strategies to successfully promote win-win outcomes for both food security and environmental health are not easy to identify. Here we comprehensively assess an ecological rice-animal co-culture system (RAC) (e.g., rice-fish, rice-duck, and rice-crayfish) through a global meta-analysis and identify the potential benefits of global promotion. Compared to traditional monoculture of rice or animal production, the RAC can not only reduce the demand for agricultural land areas, but also increase rice yields (+4%) as well as nitrogen use efficiency of rice (+6%). At the same time, RAC reduces nitrogen losses (−16% runoff and −13% leaching) and methane emissions (−11%), except for rice-fish coculture systems, which are likely to increase methane emissions (+29%). Furthermore, RAC increases the net income of farmers through reducing cost of fertilizer and pesticide input and achieving higher outputs with more marketable products. According to the development stage of different countries, promotion of RAC will thus realize multiple benefits and aid sustainable intensification.

Plain Language Summary

How to feed the growing world population with less pollution is a grand challenge for the 21st century. Rice-animal co-culture systems present an ecological integrated farming approach to tackle the challenge. Through a global consensus by synthesizing evidence from existing literature, we found that rice-animal co-culture systems could produce more diverse food types and nutrient sources, enhance resource use efficiency and reduce methane emissions, while increasing farmers' income. Global promotion of rice-animal coculture system has the potential to benefit sustainable development goals.

1. Introduction

Global population is projected to reach 8.5–10.0 billion by 2050 (Riahi et al., 2017), and feeding such large numbers of people in a sustainable manner presents a grand challenge, especially in fast growing developing economies. Rice as an important staple food sustains about half of the global population, who primarily live in developing economies where food insecurity and poverty issues are still prevalent (Woolston, 2014). With economic growth, human dietary structure tends to move toward healthier intakes of high-quality protein and calories, leading to a significant increase of global fish consumption (Costello et al., 2020). Given the stagnating production and unsustainable nature of capture fisheries, aquaculture is expected to fill in the forecast gap in demand and be a promising pathway to meet the nutritional demands of growing populations globally (FAO, 2020). Inland aquaculture currently provides 52% of global fish and 17% of animal-derived protein for human consumption, and has been seen to a rapidly increase in global food trade (FAO, 2020). However, intensive food production has resulted in substantial environmental pollution, natural resource depletion, and climate change associated with greenhouse emissions (Prosekov & Ivanova, 2018; Roe et al., 2019). Without technological innovation and mitigation measures, food production would have 50%–90% higher adverse environmental impacts by 2050, further pushing the food system beyond the environmental limits (Springmann et al., 2018). Therefore, how to produce food (especially high-quality protein) with less pollution and greenhouse gas emissions presents a grand challenge.

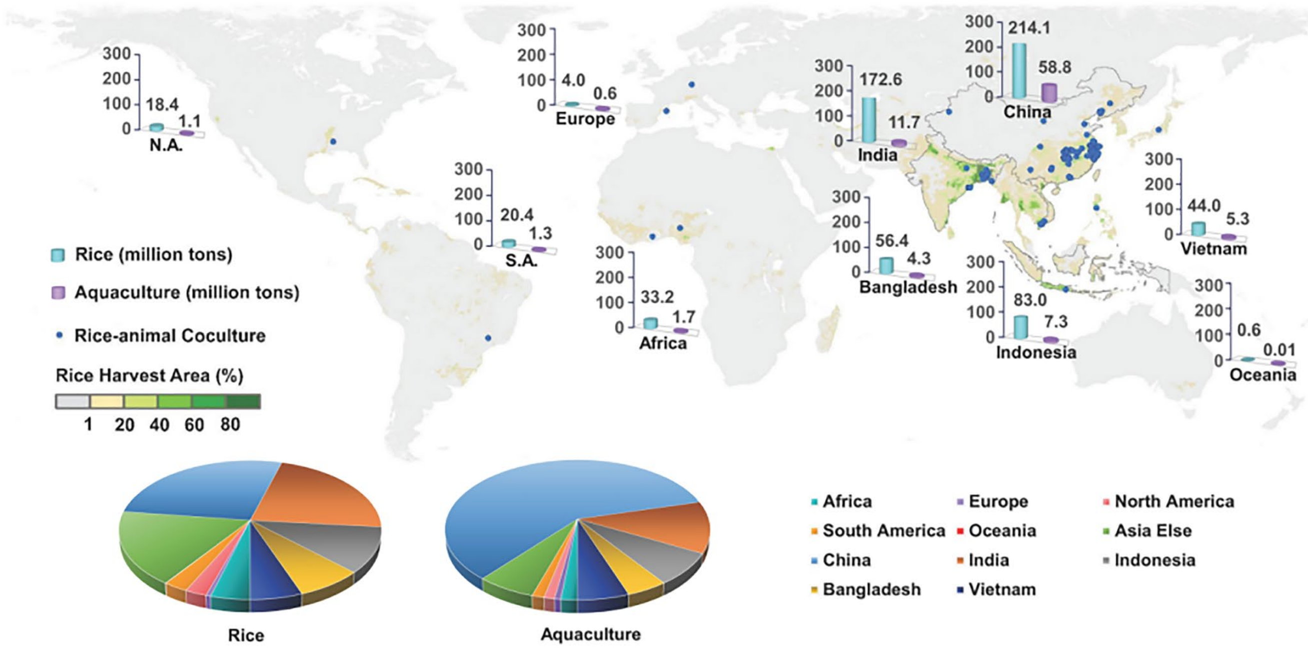

Figure 1. The global distribution of rice-animal coculture sites and production of rice and aquaculture. Vertical axes of bar charts show the rice and aquaculture production for the continents and top five rice-producing countries. "N.A." refers to North America and "S.A." refers to South America. The pie charts display the ratios of production quantities for the continents and countries. The rice harvest area fractions are from EARTHSTAT (Monfreda et al., 2008). Base map is applied without endorsement from GADM data (https://gadm.org/).

Rice-animal co-culture systems (RAC) combine rice planting and animal raising in paddy fields, building an integrated agroecosystem with high species diversity for food production and environmental protection (Kaleem & Bio Singou Sabi, 2021). Rice is the fundamental core of co-culture systems and animal raising should base on the premises of ensuring rice production. Besides fish, other animal species have been introduced into the paddy fields in recent decades, including ducks, frogs, crabs, crayfish, prawns, and turtles (Mirhaj et al., 2013; Sha et al., 2017; Souty-Grosset et al., 2016; Suh, 2014; Yan et al., 2014; Zhang et al., 2016). Various co-cultured animals constitute different RAC systems and a "composed system" is defined as comprising more than one animal species in paddy fields. Detailed information about the key RAC systems is provided in Table S1 of Supporting Information S1. Coculture refers to a setup of growing rice and animals simultaneously in the same field, while the concept can extend to including rice-animal rotation in the same field or rice-animal cultivation in compartments at the same time. RAC farming has been practiced worldwide, mainly in Asia, which accounts for more than 90% of both rice and aquaculture production (Figure 1). China, India, Indonesia, Bangladesh, and Vietnam are the top five rice producers in the world and all have implemented RAC systems to a varying degree. Some cases are also found in other continents, for instance, Ghana and Nigeria in Africa (Nnaji et al., 2013; Ofori et al., 2005), United States in North America (Halwart & Gupta, 2004), Brazil in South America (Boock et al., 2016), Spain and Germany in Europe (Clavero et al., 2015; Frei & Becker, 2005a).

The key innovative aspect of this agricultural method, building on heritage experiences, presents an integrated farming approach to tackle the multiple challenges that future food systems are facing (Guo et al., 2020; Ren et al., 2018). Previous research concentrates on the production potential and underlying ecological mechanisms of RAC system. The RAC systems were reported to promote rice yields and economic profit (Frei & Becker, 2005b; Hu et al., 2013). Meanwhile, RAC systems have natural advantages in pest control and weed control as well as biodiversity conservation (Lu & Li, 2006; Ren et al., 2018; Xie et al., 2011). The advantages of the RAC have attracted much attention, and extensive experiments have been carried out to evaluate the performance of various RAC systems at the local field sites. However, a comprehensive consensus to quantify the advantages of RAC systems is lacking at the regional and global scale, and the promotion potential of RAC systems globally remains unclear. Meta-analysis provide a well-established method for a comprehensive synthesis to quantify the effects of RAC systems on the ecosystem at the global scale, based on the site observations from field experiments.

Here we present a global meta-analysis on the performance of RAC systems from the perspectives of (a) food security, (b) resource use efficiency and agricultural sustainability, and (c) economic return. By using scenario analysis integrated with meta-analysis, we further identify the expected environmental and economic benefits of the promotion of RAC globally.

2. Material and Methods

2.1. Database

The data used in the meta-analysis was extracted from 155 peer-reviewed publications contained 2,066 observations through a literature search utilizing Web of Science, Scopus, and Google Scholar. The term "observation" here denotes paired data of a response variable under specific manipulation conditions versus the control condition in field study. For instance, the measurements of rice yield under rice-fish coculture versus rice monoculture at one study site are recorded as an observation for the response variable of rice yield in a comparative analysis of two specific systems. The majority of publications stem from Asia (China, India, Bangladesh, Vietnam, Indonesia), with some publications from Africa (Ghana, Nigeria), Latin America (Brazil), and Europe (Germany). Three papers were published before 2000, 69 papers in the period between 2000 and 2010, and 83 papers since 2010. The following search terms were used with an asterisk replacing any ending of the respective term: "rice-fish," "rice-animal," "rice* coculture" (asterisk indicates any number of arbitrary characters). The database was completed with relevant citations sourced from retrieved publications.

The database compiled in this study contains four categories of information extracted from publications: (a) publication information (i.e., publication year, country, longitude, latitude, altitude), (b) basic soil characteristics (i.e., soil type, soil texture, soil bulk density, pH, available nitrogen), (c) experimental details (i.e., co-cultured animal, co-cultured animal class, aquatic animal variety, co-culture duration, number of animals), and (d) response variables (i.e., control mean, treatment mean, number of replications). The data related to response variables, including yield attributes, nutritional attributes of rice, nutrient use efficiency, parameters of surface water, parameters of soil samples, runoff, leaching, gas emissions, use of agrochemicals, economic parameters, pests, and weeds, were extracted from the text and tables directly or from figures using WebPlotDigitizer (https://apps.automeris.io/wpd/). The response variables were standardized using the same units. The meta data set is available in Supporting Information (Data Set S1).

Nitrogen use efficiency (NUE) was either extracted from the publications determined by ^{15}N tracer approach or N difference approach (Quan et al., 2021), or calculated with the meta data as NUE = $N_{harvest}/N_{fertilizer}$, where $N_{harvest}$ is the harvest nitrogen estimated by multiplying rice yield and grain nitrogen content, and $N_{fertilizer}$ is the fertilizer nitrogen input.

The economic parameters for economic analysis were all extracted from publications of field studies. Total investment cost covers rice seeds, young animals, feed, fertilizer, pesticides, labor, machinery, electric, irrigation, etc. Both upfront investments for setting up the RAC system and for production and management are included in the total investment. Total income derives from rice and animal products. Net income equals total income minus total investment.

2.2. Statistical Analysis

The effect size indicates the magnitude of the effect of RAC introduction on the response variable. The effect size was calculated for each observation as the natural log-transformed response ratio (*lnR*) in the meta-analysis using the following equation (Gurevitch et al., 2018):

$$lnR = \ln\left[\frac{\overline{X_{\mathrm{RAC}}}}{\overline{X_C}}\right] \quad (1)$$

where $\overline{X_{\mathrm{RAC}}}$ and $\overline{X_C}$ are the means of response variables in RAC and rice monoculture (control, *C*), respectively. The mean effect sizes were considered significant ($P < 0.05$) if the 95% confidence interval (CI) did not overlap with zero.

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The weight of individual observations was calculated based on the experimental replications as follows (Pittelkow et al., 2015):

$$\text{Weight} = \frac{N_{\text{RAC}} \times N_C}{N_{\text{RAC}} + N_C} \tag{2}$$

where N_{RAC} and N_C are numbers of the replications in RAC and control, respectively.

The effect size was finally unlogged to percentage change of response variables ($R\%$) for convenient demonstration as:

$$R\% = (\exp\,(lnR) - 1) \times 100\% \tag{3}$$

Meta-regression was conducted to test whether the climate factors (i.e., mean annual temperature MAT, mean annual precipitation MAP) would moderate the effect sizes of response variables. All statistical analyses were conducted using "*metafor*" package in R (version 3.4.2., R Development Core Team, Vienna, Austria).

2.3. Scenario Analysis

In scenario A, multiple RAC systems were applied to all countries in the calculation based on the total mean effect sizes of the meta-analysis. In scenario B, in consideration of the following factors, we selected a rice-fish system for most developing countries and a rice-crayfish system for developed countries; multiple systems for countries with a good foundation of RAC, including China and Bangladesh. The rice-fish system produces the second-highest increase in rice yield, safeguarding food security which is the first priority in developing countries. Meanwhile, fish is a popular aquatic food source worldwide and various species can adapt to a wide range of environments under local conditions. Thus, we selected the rice-fish system for developing countries. The rice-crayfish system is the second-most profitable system in all RAC systems. The estimated price of crayfish is more than eight times higher than the main fish species in RAC system (e.g., carp and tilapia; 21,841 vs. 2,522 US dollars per ton) in high-income countries according to the global aquaculture production database from FAO fishery statistics (https://www.fao.org/fishery/statistics-query/en/aquaculture). Crayfish is marketed a luxury freshwater food in western markets. Farmers in developed countries would have a higher motivation to produce crayfish from a purely economic perspective. Although the paddy fields occupy a considerable number of available wetlands, the area of rice paddies is relatively small and rice is not the main cereal crop in developed countries of Europe, North America, and Oceania (Figure 1). The economic incentive for farmers to take up RAC systems may outweigh food security considerations. Crayfish is also very adaptive and a popular aquatic food in the regions. For example, crayfish has been successfully cocultured with rice in the United States (Halwart & Gupta, 2004). Besides, China and Bangladesh have good foundations for implementing multiple RAC systems, thereby multiple systems are selected for the two countries.

The productivity, environmental impact, and profitability of RAC systems were evaluated under a global promotion scenario. The selected parameters include rice production, nitrogen uptake, nitrogen loss to water, methane emissions, and net income. The rice productivity of RAC systems was evaluated in relation to rice production, which is defined as the total quantity of rice produced in a country or a continent. Nitrogen uptake, nitrogen loss, and methane emissions were used to evaluate the environmental impact of RAC systems. The nitrogen uptake is defined as the nitrogen content in rice shoot and grains. The nitrogen loss to water is defined as the sum of total nitrogen in runoff and leaching to water bodies. Methane emissions are defined as the quantity of methane emitted to the atmosphere from the agro-ecosystems. Net income was utilized to assess the profitability of RAC systems, calculated as total income minus investment.

The estimated change in the parameters (ΔP) for global promotion were calculated as:

$$\Delta P = \sum\nolimits_1^i \left(A_{\text{promotion},i} \times P_i \times R\% \right) \tag{4}$$

where the $A_{\text{promotion},i}$ refers to the land area suitable for promotion in country or area i, which is calculated as the gap between rice harvested area and the current RAC area (constrained by the suitable local climate, MAT 5–28°C and MAP 561–3,342 mm, as the ranges of the documented RAC systems in the meta database); P_i is the mean value of the parameter in rice monoculture system for country or area i; $R\%$ is the percentage change of parameters for RAC promotion.

The global rice harvest area map at 0.5 by 0.5° resolution is generated based on the rice harvest area from EARTHSTAT (Monfreda et al., 2008) and the statistical data of rice area at the country-level from FAOSTAT (https://www.fao.org/faostat/en/#data) in 2018. Data of current RAC area is basically attained from FAO country reports in Fisheries and Aquaculture Department (https://www.fao.org/fishery/en/home). The climate data were attained from the WorldClim (https://worldclim.org/data/index.html). The current RAC area is around 2 million hectares out of the global rice area of 167 million hectares in 2018. A total of 143 million hectares of rice paddies are assessed to be suitable for the future promotion of RAC systems, accounting for 87% of the rest rice area without cocultured animal (165 million hectares).

Statistical data about rice and aquaculture production (i.e., yield and production quantity) are also attained from FAOSTAT and the Fisheries and Aquaculture Division of FAO. The mean value of rice production is calculated by multiplying rice yield with the rice harvest area for each country or area. The mean value of other parameters including nitrogen loss, methane emission, and net income, derived from the overall control mean in the meta database; the percentage changes of rice production, nitrogen loss, methane emission derived from the effect sizes of parameters to rice-animal coculture in the meta-analysis. The positive value of estimated change indicates increase in the parameter, whereas the negative value indicates decrease in the parameter. Significant regression analysis results were found between methane emissions and climate factors and integrated into the scenario analysis (Figure S3 in Supporting Information S1), moderating the effect sizes of methane emissions based on the local climate within the confidential intervals. The country data set is available in Supporting Information (Data Set S2).

2.4. Uncertainty Analysis

Uncertainty analysis was carried out to quantify the uncertainty range of the effects of RAC in scenario analyses via Monte Carlo simulations over 1,000 iterations. Monte Carlo simulation is a method of simulation based on repeated random sampling and statistical analysis to compute the results (Fishman, 1995). The data sources and data distribution of the main input data sets are shown in Table S3 of Supporting Information S1.

3. Results and Discussion

3.1. Produces More Diverse Food

Overall, RAC significantly increases rice yield by 4% relative to rice monoculture despite animal refuges requiring some field space (Figures 2 and 3). The composed system has the highest increase in rice yield of 11%, followed by rice-duck at 7% and rice-fish at 5%. Although the rice-turtle system has 6% higher yield, the effects are not statistically significant due to the small sample size for the newly developed systems (Figure 2a). Excreta of aquatic animals and unconsumed feed are important organic fertilizers and provide nutrients for rice (Suh, 2014; Xie et al., 2011), increasing nutrient levels (+13% of total nitrogen, +42% of total phosphorus) in surface water and nitrogen uptake by rice (+12%) (Figure 2). Rice yield significantly increased with an addition of supplementary feed for animals in the RAC systems, while it was insignificant without feed supply (Figure S4d in Supporting Information S1). The predation and movement of animals largely eliminates weeds, pests, and pathogens in the paddy fields, as well as enhancing the aeration and nutrient exchanges at the water-soil-atmosphere interface which in turn strengthens rice roots and closely associated mycorrhiza, thus promoting rice growth (Xie et al., 2011). Plant hoppers and weeds are suppressed by 46% and 80%, respectively, when applying the same or a reduced amount of pesticides in RAC systems relative to rice monocultures (Figure S4c in Supporting Information S1). Bulk density of sediment decreases in the RAC (−7% for total mean, −5%, −11%, −12% for duck, crayfish and composed system, respectively) (Figure 2). In contrast, rice yield is reduced in rice-cray (−10%) and rice-prawn systems (−10%) (Figure 2). This is in line with some cases that refuges take up too much paddy field area due to overemphasizing the high-valued aquatic animal relative to the value of rice produced (Hu et al., 2016). If the refuge area is too large (>10% as a threshold reported in a survey of various RAC systems (Hu et al., 2016)), the rice yield declines. Rice production is important for national and regional food security in many developing countries where rice is a main staple, which could be threatened by a decline in rice yield. Therefore, it is essential to maintain a balance between animal and rice production to ensure RAC systems remain efficient overall. Government policy and guidelines may need to be established to safeguard stability of rice production.

Animal cultivation also benefits from rice planting, which can be attributed to the environmental amelioration associated with rice planting. Rice plants can optimize the microclimate and alleviate thermal oscillation by

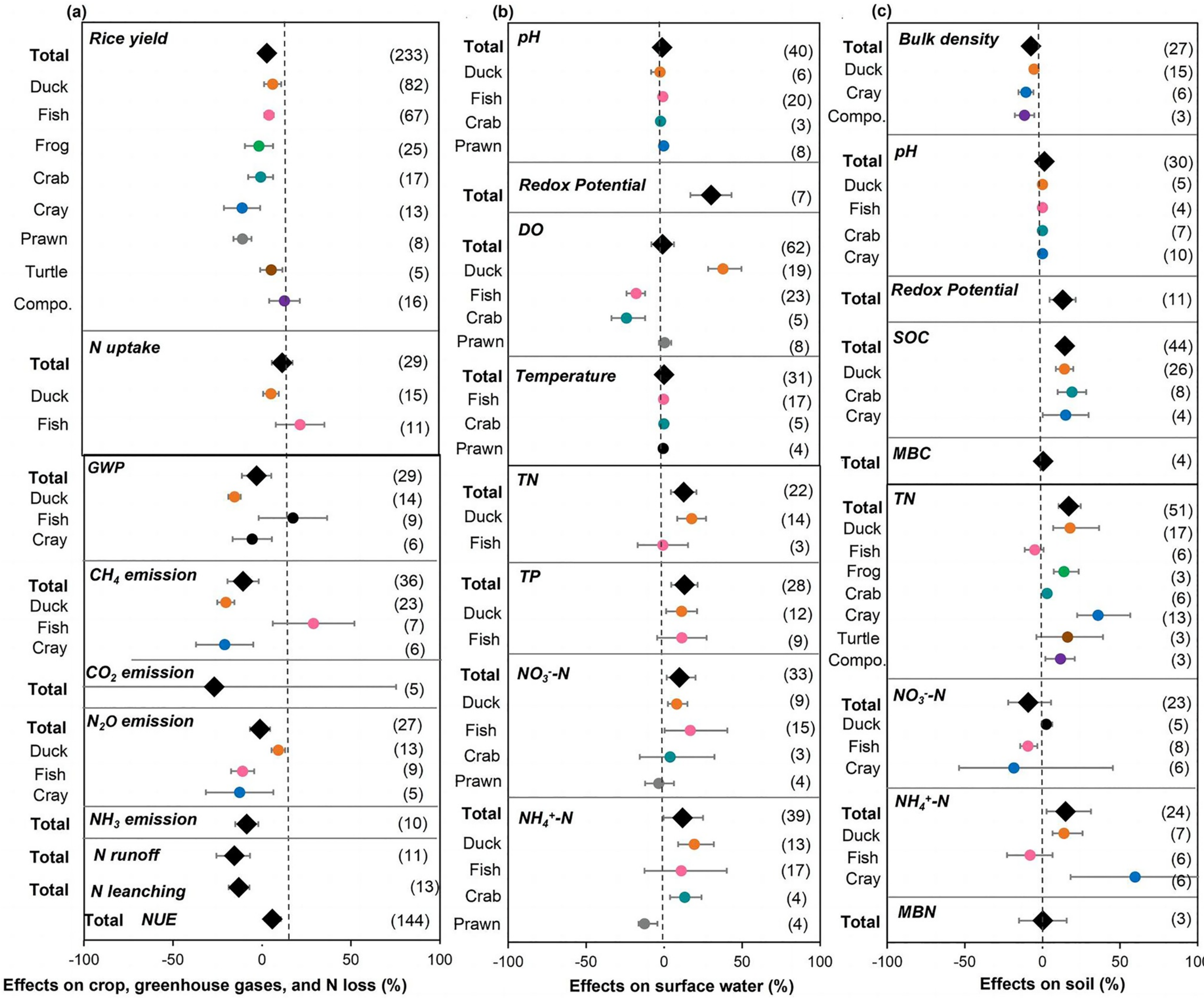

Figure 2. Effects of rice-animal coculture relative to rice monoculture on agriculture ecosystem (a) crop, greenhouse gases, and nitrogen loss (b) surface water, (c) soil. Values are mean effect sizes for the total mean and each category. Error bars indicate 95% CIs. Effect is significant if the 95% CI does not overlap zero. The numbers of observations are shown in parentheses. Composed (Compo.) is a system that comprises more than one animal species in paddy fields. (GWP, global warming potential; N runoff, total nitrogen in runoff; N leaching, total nitrogen in leaching; NUE, nitrogen use efficiency; DO, dissolved oxygen; TN, total nitrogen; TP, total phosphorus; SOC, soil organic carbon; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen).

providing shading and shelter thus lowering water temperature and sunlight intensity in the field (Xie et al., 2011). Fish tend to be more active with higher motion frequency and an expanded range of activity when cocultured with rice relative to fish monoculture (Zhang et al., 2017). RAC can promote the yield of aquatic animals by 16% relative to animal monoculture (Figure S4a in Supporting Information S1). Other factors influencing animal production include refuge design, stocking density, and polyculture. Although refuge areas providing shelter space for animals require some space otherwise available for rice cultivation, the positive "edge effect" can increase fish activity along the trenches and pits (Wu et al., 2010). Similarly, the stocking density of animals should be designed within an appropriate scope in terms of the environmental carrying capacity and feed application (Boock et al., 2016). The polyculture system of various species with distinct habits, that is, composed system, is likely to stimulate animal yield through utilizing different trophic niches (A. Dey et al., 2018; Guo et al., 2020). Therefore, RAC has the potential to enhance animal yield with adequate management strategies.

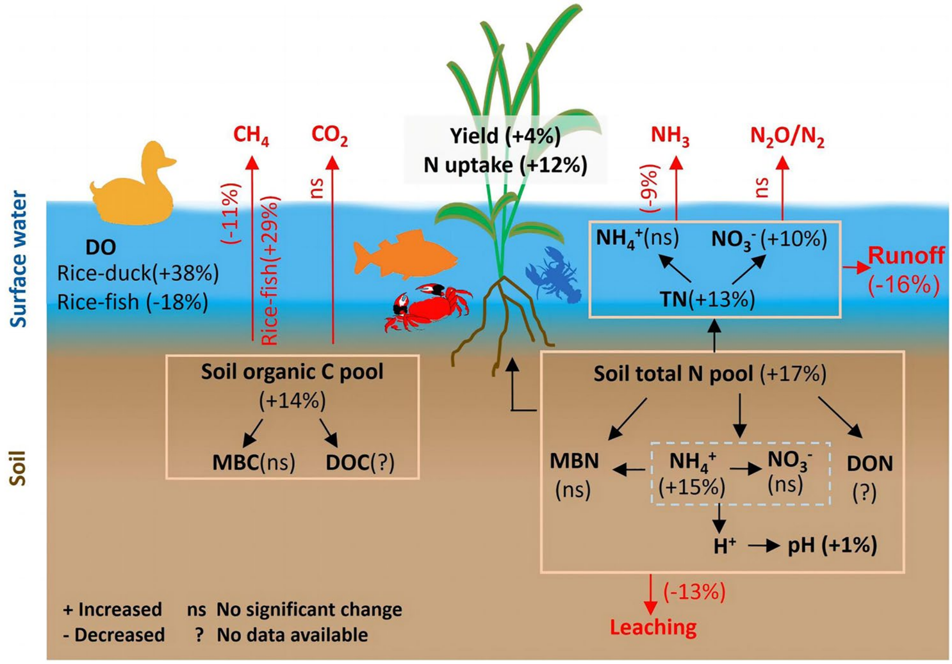

Figure 3. Schematic representation of ecosystem responses to rice-animal coculture farming. All data was derived from the results of this meta-analysis. The "+" and "−" in the parentheses denote increased and decreased percentage changes respectively, while "ns" denotes no significant change and "?" denotes no data available. (DO, dissolved oxygen; TN, total nitrogen; MBC, microbial biomass carbon; DOC, dissolved organic carbon; MBN, microbial biomass nitrogen; DON, dissolved organic nitrogen).

3.2. Enhances Agricultural Sustainability

RAC can increase resource use efficiency via utilizing complimentary ecological niches of rice and animals to achieve high-level nutrient recycling within the agroecosystem (Oehme et al., 2007). Nitrogen use efficiency (NUE) was enhanced by 6% in the conversion to the RAC systems. Nitrogen losses were substantially reduced for example, by lowering ammonia (NH_3) emissions to the atmosphere (−9%), runoff to surface water bodies (−16%) and leaching to groundwater (−13%), while more nitrogen is retained in rice (+12%), surface water (total nitrogen +13%, ammonium +10%) and soil (total nitrogen +17%, ammonium +15%) (Figure 3). Co-cultured animals help to transform organic nitrogen to ammonium that is easily absorbed by rice and the changes of soil texture also facilitate nitrogen uptake by rice plants (Li et al., 2019). As a consequence, less nitrogen fertilizer would need to be applied to RAC systems and the nitrogen loss to the environment is largely reduced. Compared to rice monoculture, nitrogen fertilizer use is reduced by 30% in RAC systems, and phosphorus and potassium fertilizer uses are reduced by 22% and 19%, respectively (Figure S4b in Supporting Information S1). Meanwhile, more organic fertilizers are used in RAC practice owing to its advantages in improving soil fertility and crop production (Geisseler et al., 2017). Furthermore, RAC reduces or even eliminates the need for pesticide and herbicide application through controls of weeding and pests by co-cultured animals. Pesticides are not applied to a majority of RAC systems, while they are widely applied in control studies for regular rice monoculture ($n = 87$). The average pesticide use in RAC systems decreased by 67% ($n = 9$) (Figure S4b in Supporting Information S1). As a consequence of the reduction in pesticides application, a restoration of agrochemical-polluted environments can be anticipated, with an associated increase in biodiversity and an increase in the abundance of natural enemies of pests, such as spiders and frogs, which have shown to be an effective means of biologic pest control (Lu & Li, 2006).

RAC could produce additional animal products on the same area of paddy fields, saving land and water resources. Global rice production increased steadily from 1.1 to 3.9 billion tons during the period 1961–2018 (Figure S1 in Supporting Information S1). The total aquaculture production including freshwater and marine aquaculture also increased from 2.0 million tons in 1961 to 16.0 million tons in 1990, and rapidly expanded to 105.9 million tons by 2018 at a growth rate of ~3 million tons per annum (Figure S1 in Supporting Information S1). The global land area suitable for RAC is estimated to be at around 143 million hectares with a potential to produce 143 million tons of aquatic products annually (assuming aquaculture yield at approximately 1 ton ha^{-1} yr^{-1}, and excluding rice-duck systems) (Verdegem et al., 2006). If this potential could be fully realized, the additional production of aquatic animal food would not only meet global demand, but also save 143 million ha of land and 6,435 billion m^3 of water resources (under the assumption that total water use is approximately 45,000 m^3 ton^{-1} in extensive ponds) (Verdegem et al., 2006).

RAC systems reduce overall methane (CH_4) emissions from paddy fields by 11% (Figure 3). The decreased methane emissions could be mainly attributed to overall higher dissolved oxygen levels (+6%) that facilitate methane oxidation in the RAC system (Yuan et al., 2019). Animal activity could also enhance releasing of methane entrapped in the soil via ebullition (Frei & Becker, 2005c). It is noteworthy that the responses of methane emissions vary between systems, for example, they decrease in rice-duck (−20%) and rice-crayfish (−21%) systems, while increasing (+29%) in the rice-fish system (Figure 2). This is attributable to the negative correlation between the effect sizes of methane emissions and dissolved oxygen concentrations in our meta-regression (Figure S2f in Supporting Information S1). In the rice-duck system, dissolved oxygen in surface water increases by 38% due to the activities and perturbations by ducks, resulting in the decrease of methane emissions (−20%). In contrast, a 18% decrease of dissolved oxygen in the rice-fish system results in an increase of methane emissions (+29%), which is likely due to deeper water and the substantial consumption of oxygen by fish this particular system. Moreover, the effect sizes of methane emissions are correlated to MAT and MAP (Figure S3 in Supporting Information S1). This suggests that climate factors could also moderate the magnitudes of effect of methane emissions. As rice paddies have been contributing substantially to rising atmospheric methane over the last decade (Nisbet et al., 2016), a widespread use of RAC systems could present a climate-smart agricultural production method which would support methane emission reductions and thus contribute to mitigating climate change, if appropriate RAC systems are employed. Besides, effective management methods are required for advanced mitigation approaches, for example, aeration can reduce methane emissions in the rice-fish system (Yuan et al., 2019).

3.3. Increases Farmers' Income

The average net income of farmers almost doubled from 1,019 US dollars ha^{-1} annually in rice monoculture systems to 2,212 US dollars ha^{-1} in RAC systems (Figure 4). The income change varied from +53% to +393% in different systems compared with the conventional rice monoculture. The composed system is the most profitable system (+393%), followed by the rice-crayfish (+197%) and rice-fish system (+98%). While it yielded the lowest increase percentage, the rice-crab system still demonstrated 53% higher income than the rice monoculture system. Meanwhile, increases of net income vary between countries, ranging from 41 US dollars ha^{-1} in Nigeria to 1,451 US dollars ha^{-1} in China, with baseline levels of farmers' income potentially being very different in different countries as well.

Although the total investment costs for RAC systems were higher by 142% (1,602 US dollars ha^{-1} for RAC relative to 662 US dollars ha^{-1} for rice monoculture), the total income from rice and animal products combined increased by 127% (3,815 US dollars ha^{-1} in RAC relative to 1,681 US dollars ha^{-1} in rice monoculture) (Figure 4). The lowest farm investment required is 843 ± 159 US dollars ha^{-1} for the rice-fish system, in contrast to the highest investment costs of 3,885 ± 611 US dollars ha^{-1} for the rice-crayfish system. Additional expenditure is needed for RAC to construct the facilities, purchase young animals, and increased requirements for farm labor compared to rice monoculture. At the same time, the cost of mineral fertilizer and pesticides can be reduced by 29% from 262 US dollars ha^{-1} in conventional rice monoculture to 187 US dollars ha^{-1} in RAC systems. The total income increase derived from enhanced quality rice products and additional animal products. The income of rice increased by 12% from 1,610 US dollars ha^{-1} to 1,801 US dollars ha^{-1}, which can be attributed to the enhanced rice production with higher yield and better quality as it can be labeled as organic rice. RAC systems enhanced rice tillering in growth course and protein content in plants (Zhang et al., 2017). Another key economic benefit of RAC systems lies in higher economic returns to farmers due to the value of additional products. The additional mean income from co-cultured animal products is 2,141 ± 463 US dollars ha^{-1}. The rice-crayfish system can generate the highest income of 6,150 US dollars ha^{-1} for animal products, followed by the composed system (4,971 US dollars ha^{-1}) and rice-crab system (1,552 US dollars ha^{-1}).

More importantly, products originating from RAC systems can apply for organic food certificates due to avoiding the use of mineral fertilizers and pesticides. Organic food, including organic rice as well as animal products, sell

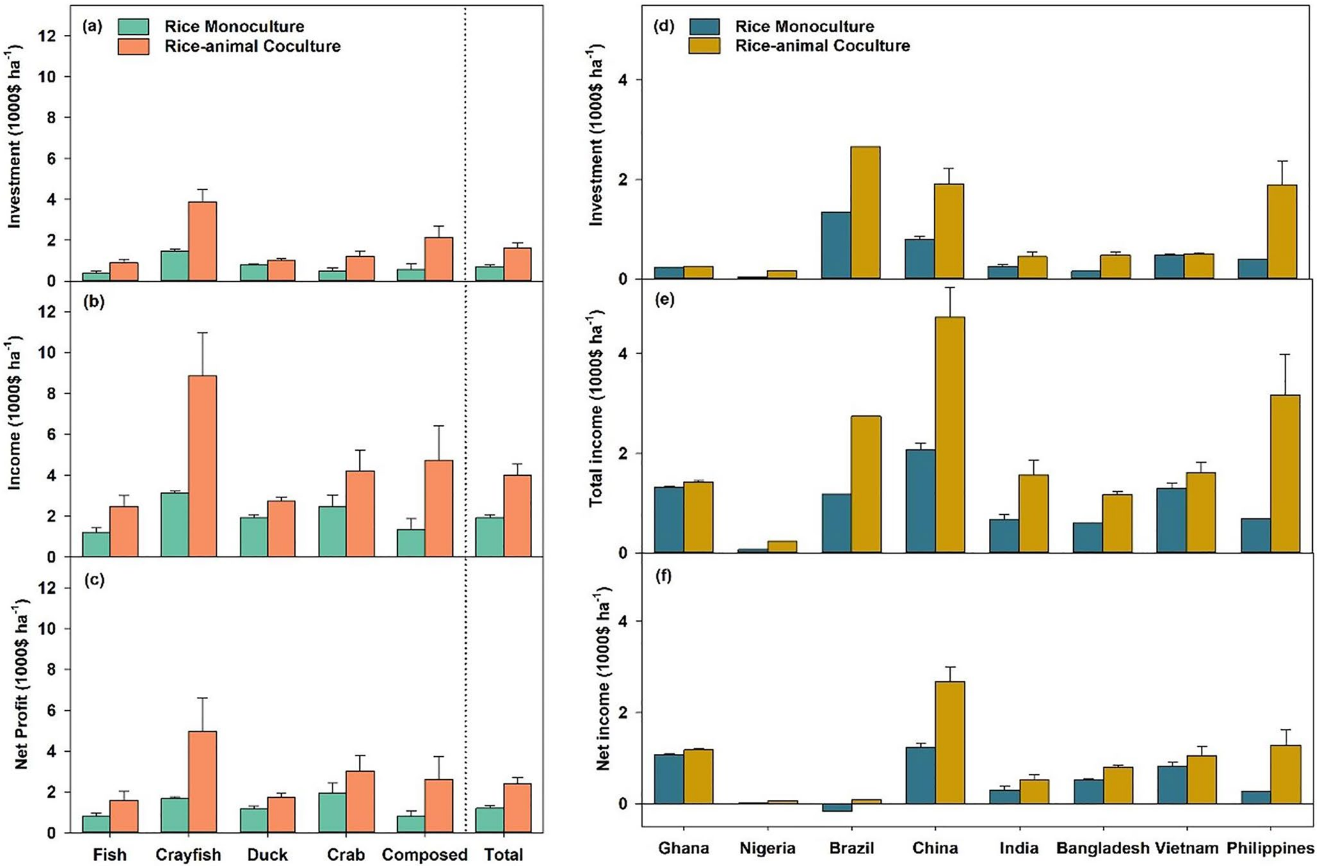

Figure 4. Economic analysis in rice-animal coculture systems relative to rice monoculture. By different RAC systems: (a) Investment of rice seeds, young animals, feed, fertilizer, pesticides, labor, machinery, electric, irrigation, etc.; (b) total income from rice and animal products; (c) net income equals total income minus investment. Error bars denote standard errors. Composed refers to a system that more than one animal species in paddy fields. By different countries: (d) Investment; (e) total income; (f) net income.

for much higher market prices. The value of the global organic food market has grown over the past 30 years from nearly zero to 64 billion US dollars in 2012 and is anticipated to grow steadily in the future (Willer et al., 2014). Oceania and Europe currently hold 62% of global agricultural land used for organic production methods and about 80% of European consumers have expressed a preference to purchase organic food (Willer et al., 2014). More affluent people have an emerging tendency to pay the price premium for better quality of food and lower risk of chemical contamination (Prein et al., 2013). Therefore, RAC systems have an enormous potential to alleviate hunger and poverty in developing economies, particularly in the vast rural areas of Asia and Africa, while providing high-quality organic food supply in high-income regions. Organic products were successfully marketed in developing economies including India and China (A. Dey et al., 2018; Nair et al., 2014; Sha et al., 2017; Teng et al., 2016).

3.4. Global Promotion of RAC

To estimate the potential benefits of RAC at a global scale, we conducted scenario analysis of the impact of global promotion in scenario A and B (Figure 5). Multiple RAC systems were applied globally in scenario A as a general situation. We selected a rice-crayfish system for developed countries due to profitability and a rice-fish system for most developing countries taking into account food security and feasibility (except for China and Bangladesh, a variety of systems were included due to existing good foundations of RAC practices) in scenario B. In the multiple systems of scenario A, annual global rice production is estimated to increase by 24 ± 1 million tons (close to the combined rice production of South America, Europe, and Oceania) and net income is increased by 171 ± 12 billion US dollars, while annual nitrogen losses and methane emissions are reduced by 0.3 ± 0.1 and 1.9 ± 0.1 million tons, respectively (Figure 5). The expected changes under scenario B lead to an increase in rice

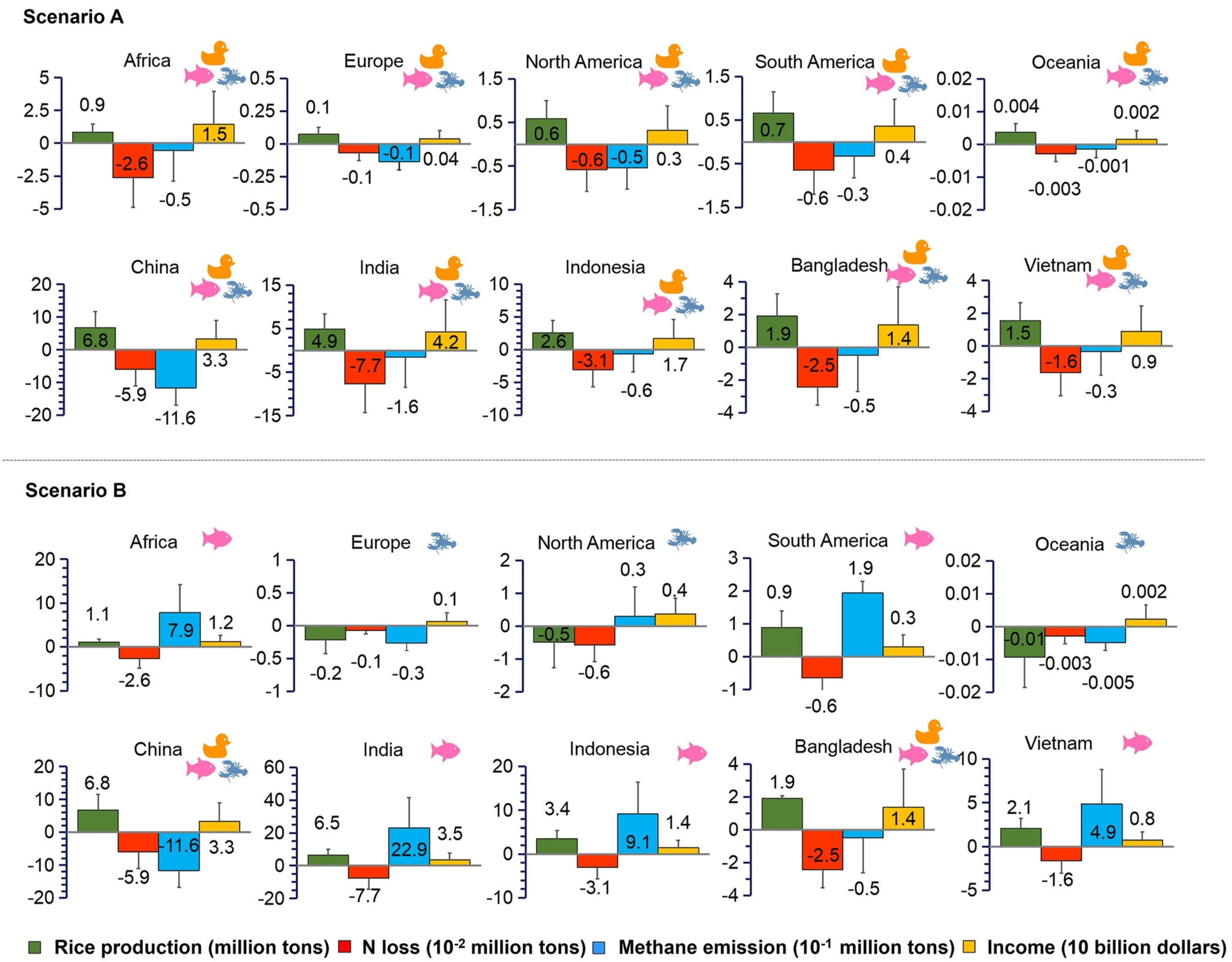

Figure 5. Estimated changes of rice production, nitrogen loss, methane emission, and net income in global promotion of rice-animal coculture (RAC) with scenario A and B in five continents and five top rice producers. In scenario A, multiple systems were applied to the calculation based on the total mean effect sizes of meta-analysis. In scenario B, we selected a rice-fish system for the developing countries and a rice-crayfish system for the developed countries; the multiple systems for China and Bangladesh. The icons of different animals indicate co-cultured animals in the respective systems. The error bars represent standard deviations.

production by 27 ± 2 million tons (a similar amount to the total rice production in Africa), an income increase by 152 ± 10 billion US dollars, but an increase in methane emissions by 5.3 ± 0.5 million tons (Figure 5).

Overall, it is feasible and promising to promote RAC systems at a global scale as a means for the sustainable intensification of agriculture. Global promotion of RAC systems with multiple benefits for food security, poverty alleviation, and environmental sustainability, would contribute substantially to achieving progress toward the Global Sustainable Development Goals (SDGs). Although the estimated increase in rice production only accounted for 3.0% and 3.5% of global rice production in scenarios A and B, respectively, it is of significance for safeguarding food security and promoting SDG 2 (zero hunger) in some developing economies as it would further stabilize rice production and generate additional animal protein. Compared with the multiple systems in scenario A, the rice-fish system used in scenario B resulted in an increase in rice production by about a third in Africa and Asia (India, Indonesia, and Vietnam). This would make a difference in these regions, which are traditionally prone to extreme famine and poverty issues. Meanwhile, the income increase expected to be in the range of 152~171 billion US dollars, approaches the value of global aquaculture production of 250 billion US dollars in 2018 (FAO, 2020), contributing to SDG 1 (no poverty) globally. Increased net income of farmers could particularly alleviate poverty in developing economies which are relying on agriculture as the primary industry. The rice-crayfish system applied in scenario B resulted in almost tripling income in developed countries including

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Australia, the United States, and most European countries, compared to the current situation of predominant rice monoculture systems. What is more, the reduction potential of nitrogen loss and methane emissions in global promotion of RAC systems would benefit SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), and SDG 12 (responsible consumption and production). A decrease in nitrogen losses estimated at about 0.3 million tons could benefit human and ecosystem health, given their adverse effects on environment inducing soil acidification, water eutrophication, and air pollution (Van Grinsven et al., 2013). As global rice cultivation contributed approximately 31.7 million tons of methane emissions to the atmosphere (Montzka et al., 2011), the two scenarios investigated demonstrate opposite effects on methane emissions with a 7% reduction in scenario A (−2.2 million tons), but a 21% increase in scenario B (+6.5 million tons). This increase in methane emissions in scenario B can be mainly originated from the rice-fish system, which has 29% higher emissions relative to rice monoculture systems. Thus, in cases where a promotion of the rice-fish system was intended, more sophisticated management methods for example, aeration should be considered to control the release of methane emissions (Yuan et al., 2019).

3.5. Policy Implications

Promotion of RAC systems is leading to their implementation in several countries, mainly in Asia such as China (1.3 million ha) (FAO, 2014) and India (0.2 million ha) (A. Dey et al., 2018). However, so far, the adoption of RAC in other regions has been fairly limited, and is constrained by several factors including technology, resources, policies, and potential risks. First, RAC systems can involve complex interactions between co-cultured species, and require advanced knowledge and skills compared to operating rice monoculture. The selection of animals and rice species and the timing of introducing animals to the paddy fields matter for maintaining the complementary and beneficial interactions between rice and animals. A second key risk would be a failure of maintaining interspecies balance, which may result in yields becoming unreliable (A. Dey et al., 2018). Lack of knowledge and skills for operating RAC systems would lead to low motivation to take the risk of converting from conventional approaches. Second, farmers might have limited access to the scarce resources including capital, labor, infrastructure, and market networks. The investment in RAC (1,602 US dollars ha^{-1}) is more than twice that of rice monoculture (662 US dollars ha^{-1}), which could be an obstacle to initiate RAC projects in particular for poor and credit-constrained farmers. The preparation of paddy fields to accommodate RAC farming systems entails land consolidation for trenching and ridging, specialized machinery, and related capital investments. The total labor requirement for RAC systems ranges from 134 to 352 person-days per ha, and is substantially more labor-intensive than rice monocultures (M. M. Dey et al., 2013; Nabi, 2008). The shortage of labor supply can be a constraint as a result of aging populations in rural communities and an increasing number of younger laborers migrating to urban areas with urbanization (Lu & Li, 2006; Suh, 2014). Other concerns have been raised about the insufficient supply as young animals, transportation infrastructure, and market networks (Frei & Becker, 2005b; Nabi, 2008). Third, prevailing agricultural policy paradigms favoring intensive rice monocultures may present a barrier for the adoption of RAC in many countries (Frei & Becker, 2005b). Finally, potential risks include the introduction of invasive alien species and potential pollution. The introduction of red swamp crayfish originating from North America to Europe, for instance, is responsible for the substantial biodiversity loss through the extinction of native crayfish species and have caused detrimental impacts on local aquatic ecosystems (Souty-Grosset et al., 2016). Potential pollution risks exist during the transformation of the rice field to RAC systems, deriving from construction activities or an overuse of agrochemicals.

Thus, to promote uptake of RAC systems on the global scale, stakeholder-driven strategies are needed to reinforce collaboration between public and private sectors. It is necessary for government and public organizations to advocate the concept, improve public recognition of RAC as a viable farming system, and provide training programs and extension services to deliver innovation of farming techniques (Halwart & Gupta, 2004). Demonstration projects could be established to highlight the advantages and performance of RAC systems. Policymakers can reward uptake of RAC systems and corresponding organic products as positive behavior providing public ecological benefits via subsides and rebates (Ren et al., 2014), and simultaneously control the overuse of agrochemicals and conserve the natural environment. Successful development of sustainable aquaculture and agriculture in general also require improved infrastructure, the implementation of effective rules and regulations, and accessible market networks. Meanwhile, farmers could be encouraged to cooperate to share resources and exchange experience for example, through community-based cooperatives as demonstrated in examples of good practice in China and South Korea, as a means to form larger markets (Hu et al., 2016; Suh, 2014). Branding of local RAC farming production would add value to the products and promote market acceptance. Extension of the value chain and development of ecotourism would in addition provide multiple pathways to elevate economic development of rural areas and create employment opportunities. Furthermore, successful implementation of RAC systems at global levels requires further research to ensure the stability of the operation and output in the RAC systems for agricultural sustainability. Further targeted studies, surveys and pilot projects on RAC should be established outside of Asia, to generate reliable information and data and fill gaps in current geographical coverage. The selection of specific RAC system is critical. The adaptivity of animals to the local climate and soil conditions, market and sales potentials for specific products, and farming skills should be taken into account as selection criteria. In addition, the development of RAC systems depends on the development level of local agricultural systems more generally. A majority of the RAC systems are traditional cropping systems run by smallholder farmers, particularly in developing economies. There are some trials to apply RAC systems at industrial scale cropping systems, for example, the development of machine-transplanted rice in the Chinese rice-duck farming systems (Yu et al., 2009), which can be promoted in regions with a solid foundation of industrial agricultural practices.

3.6. Limitations

Our estimates of the global uptake potential are subject to several limitations and uncertainties, in relation to methodological barriers, technology adaptability and societal acceptance. We incorporated potential effects of RAC on ecosystems based on a meta-analysis to conduct future scenario analysis. Although the meta-analysis demonstrates that advantages of RAC systems can be substantial at global scale, the majority of publications stemming from Asia as the main rice producing area, and studies have been little documented for Africa, Latin America, and Europe. To date, there is a lack of studies in Oceania and North America. Some countries only list rice-animal coculture as a sub-set of current agricultural practice, but publications identified did not meet key robustness criteria set for the integration into the meta-analysis. This applied, for instance, to the United States (Halwart & Gupta, 2004) and Spain (Clavero et al., 2015). Meanwhile, variations in the natural condition and social economy across the globe would affect the technology adaptability and social acceptance in the promotion of the RAC systems, which also contributes to the uncertainties. Besides, the economic analysis has not considered the spatial-temporal heterogeneity of economic parameters, for example, the fertilizer price varies with time and among different countries and regions. Sophisticated economic analysis is needed to assess the feasibility of RAC system and design optimal strategy according to local circumstances.

4. Conclusions

This is the first comprehensive consensus reporting the specific advantages of rice-animal coculture compared to conventional, separate monoculture of agriculture and aquaculture. We found that rice-animal co-culture systems could produce more diverse food types and nutrient sources, especially animal-derived protein, enhance resource use efficiency and reduce methane emissions, while increasing farmers' income. The technological innovation of rice-animal co-culture systems has an enormous potential to be promoted globally from both economic and environmental perspectives. The global promotion of rice-animal co-culture is expected to increase income of producers by 175–197 billion US dollars, reduce the annual nitrogen loss by 0.3 million tons, and avoid ∼7% of methane emissions to the atmosphere from global rice paddies. Therefore, rice-animal co-culture should be advocated as one of the key practices in the rice-planting regions for sustainable intensification of agriculture and inland aquaculture. Future studies are anticipated to overcome barriers in promoting rice-animal co-culture on a broader geographical coverage. Future research could also be extended to the higher environmental sustainability of RAC systems as improving biodiversity (i.e., indigenous species conservation, avoiding species invasion) and resource management (i.e., life cycle assessment, nutrient footprint and carbon neutrality).

Data Availability Statement

Data sets used in the study are available in Supporting Information and archived at figshare (https://doi.org/10.6084/m9.figshare.21827484.v1).

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