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COMMENTARY

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Key Points:

- Cui et al. (2023, https://doi.org/10.1029/2022EF002984) comprehensively assessed the benefits of the global promotion of rice-animal co-culture (RAC) systems by meta-analysis
- RAC systems directly help sustainable development goal 2 (SDG2) and are positive to many sustainable development goals (SDGs) by their environmental and economic benefits
- The role of RAC systems in meeting SDGs needs to be further explored and quantified by identifying the current crucial gaps

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The Present and Future Role of Rice-Animal Co-Culture Systems in Meeting Sustainable Development Goals

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Abstract Rice-animal co-culture (RAC) systems are an integrated farming approach to mitigate the diverse challenges facing the food system. Studies of the production potential and ecological mechanisms of RAC systems have demonstrated natural advantages over traditional production systems. The quantification of the advantages and the potential promotion of RAC systems at regional and global scales, however, remains unclear. Writing in Earth's Future, Cui et al. (2023, https://doi.org/10.1029/2022EF002984) comprehensively assessed an ecological RAC system and identified the potential benefits of global promotion using a meta-analysis. In this commentary, we contextualized Cui et al.'s (2023, https://doi.org/10.1029/2022EF002984) study and further theoretically clarified the connections of RAC systems to the various sustainable development goals (SDGs) and targets, with references to the officially released list of SDG indicators. Moreover, we discussed the limitation of the current studies and pointed out some potential directions for future research to understand the present and future roles of RAC systems in meeting the multiple SDGs.

Plain Language Summary Rice-animal co-culture (RAC) systems provide a potential way to mitigate the great challenge of sustainably feeding the growing world population. RAC systems would substantially improve the progress of sustainable development goal 2 (SDG2, Zero hunger) by producing more diverse food, enhancing agricultural sustainability, and increasing farmers' income and would also benefit many other sustainable development goals (SDGs), such as SDG1 (No poverty), SDG8 (Decent work and economic growth), SDG6 (Clean water and sanitation), SDG12 (Responsible consumption and production), and SDG13 (Climate action). Quantifying the contributions of RAC systems to SDGs at the goal, target, and indicator levels needs to be further explored in future studies.

How can the growing global population be sustainably fed with sufficient and nutritious food? The answer to this question is essential to achieve food security, which is not only a challenge for national stability and socio-oeconomic development, but is also an opportunity to improve scientific innovation, trade, health, and social wealth (Battersby & Watson, 2018). Ever since the adverse impact of climate change became a scientific concern, intensive food production, which leads to substantial emissions of greenhouse gases, environmental pollution, and the depletion of natural resources, has put more pressure on achieving environmental sustainability (Zuo et al., 2018). Rice-animal co-culture (RAC) systems, with high species diversity for food production and environmental protection, provide a potential way to address the challenge that the food system is facing by combining rice cultivation and animal production in paddy fields (Lao et al., 2022). In the recent paper on Earth's Future, Cui et al. (2023) quantified the advantages of RAC systems and identified the potential benefits of their global promotion. Their results will help us better understand how RAC systems could benefit multiple SDGs by 2030 and beyond.

RAC systems are constructed on the premise of ensuring rice production, and with animals such as fish, ducks, frogs, crabs, crayfish, prawns, and turtles introduced into the paddy fields. Previous research has mostly focused on the production potential and ecological mechanisms of RAC systems, and the advantages of these systems have been widely recognized (Bashir et al., 2020). Relevant research is usually carried out at the local scale by site observations from field experiments (Li et al., 2022). Comprehensively clarifying the advantages of RAC systems at regional and global scales is lacking and further discussing the influence of their global promotion in diverse aspects is urgently needed. Cui et al. (2023) has elegantly resolved these limitations by conducting a global meta-analysis with data extracted from 155 peer-reviewed publications containing 2,066 observations,

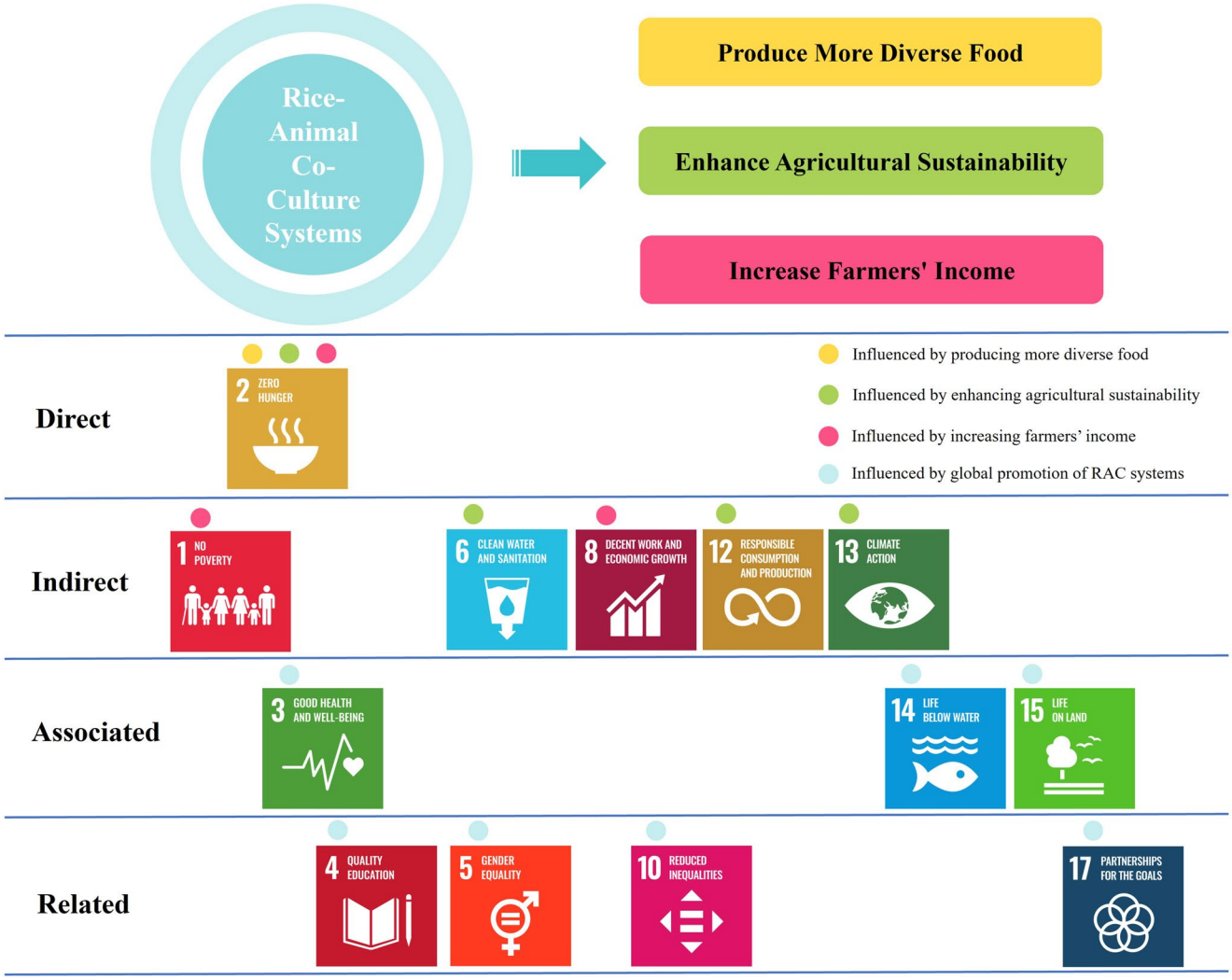

Figure 1. Simplified overview of the main contributions of rice-animal co-culture (RAC) systems to the sustainable development goals (SDGs). Top: the benefits of RAC systems extracted from Cui et al. (2023). The relationship between RAC systems and the SDGs was resolved by the authors, with references to the officially released list of SDG indicators. Direct: the SDG and its multiple targets and indicators were influenced by all dimensions of RAC systems promotion advantages. Indirect: the SDG and its multiple targets and indicators were influenced by one dimension of RAC systems promotion advantage. Associated: the SDG and its targets were influenced by RAC systems promotion. Related: the SDG was influenced by RAC systems promotion.

containing four categories of information, that is, publication information, basic soil characteristics, experimental details, and response variables. It has been widely known that meta-analysis has many advantages compared with individual studies, for example, meta-analysis combines the results of multiple studies and increases the sample size, and some relatively weak effects can be identified, which helps to improve the validity of the conclusions. In addition, the meta-analysis also deals with many similar studies, is not limited by the number of studies, and follows procedures to integrate and quantitatively analyze the literature, which increases the objectivity of the study results (Yu et al., 2023).

After data collection, the statistical analysis was conducted to quantify the magnitude of the effect of RAC introduction on the response variable, the scenario analysis was carried out to compare the effects of RAC promotion in different implementation plans, and the uncertainty analysis was used to quantify the uncertainty range of the RAC effect in scenario analysis. The results of Cui et al. (2023) stressed the advantages of RAC systems in three dimensions and then identified the potential benefits of the global promotion of RAC systems (Figure 1). The results indicated the direct influence of RAC systems on improving SDG2 (Zero hunger) and its multiple targets and indicators through producing more diverse food, enhancing agricultural sustainability, and increasing farmers' income. The SDGs of the United Nations are a collection of 17 global goals and 169 targets designed to be

a blueprint to achieve a better and more sustainable future for all developed and developing countries in a global partnership and were adopted by all member states (United Nations, 2015). We resolved the relationship between RAC systems and SDGs, with references to the officially released list of SDG indicators that contains the definition of each goal and target (https://unstats.un.org/sdgs/indicators/indicators-list/). SDG2 is to end hunger, achieve food security, improve nutrition, and promote sustainable agriculture. RAC systems benefit four of the eight targets of SDG2 (Table 1). Specifically, Cui et al. (2023) found that RAC systems significantly increased rice yield (e.g., the highest increase in rice yield of 11%) and animal cultivation (e.g., aquatic animals by 16% relative to animal monoculture). The increase in rice and animal production will help end hunger and ensure a sufficient food supply to all people (Indicators 2.1.1, 2.1.2), end all forms of malnutrition because animal-based foods are important sources of protein (Indicators 2.2.1, 2.2.2), and increase the volume of production per labor unit (Indicators 2.3.1). Moreover, with the obvious increase in rice and animal products, Cui et al. (2023) found that farmers' income almost doubled (with income change varied from +53% to +393%) after rice monoculture systems were converted to RAC systems, which is consistent with Indicator 2.3.2. Besides, the RAC systems also increased resource-use efficiency, for example, the nitrogen use efficiency was enhanced by 6%, the nitrogen losses were substantially reduced by lowering ammonia emissions to the atmosphere (−9%), runoff to surface water bodies (−16%), and leaching to groundwater (−13%), nitrogen, phosphorus, and potassium fertilizer uses are reduced by 30%, 22%, and 19%, respectively, to achieve high-level nutrient recycling within agroecosystems, which is helpful to ensure sustainable food production and to maintain ecosystems (Indicator 2.4.1).

In addition to the direct influence on SDG2, RAC systems also have some indirect influences derived from one dimension of promotion advantage to several SDGs and their targets and indicators (Figure 1, Table 1). For example, the increased farmers' income is also useful for promoting SDG1 (No poverty) and SDG8 (Decent work and economic growth). Specifically, Cui et al. (2023) indicated that most RAC systems were in developing countries such as India, Bangladesh, Vietnam, Indonesia, and Nigeria. The RAC systems increased the profits of farmers by using natural fertilizers to reduce the cost of inputs and simultaneously increased farmers' income, which has a huge potential to eradicate extreme poverty and reduce the proportion of people living in poverty, especially in the vast rural areas of Asia and Africa (Indicators 1.1.1, 1.2.1, 1.2.2). The implementation of RAC systems also helps the farmers to improve their ownership and control over land and other forms of property (Indicator 1.4.2). Based on the significant increase in rice yield and animal cultivation, the economic benefits from RAC systems converted to a large scale are also obvious, which would contribute to regional per capita economic growth in the areas promoted RAC systems (Indicator 8.1.1). While increasing farmers' income, the RAC systems also enhance resource use efficiency and reduce methane emissions, which helps endeavor to decouple economic growth from environmental degradation to support sustainable development (Indicator 8.4.1). Moreover, with the economic benefits, sustainable tourism could be devised and implemented in regions that promoted RAC systems, which would contribute to promoting the influences of local culture and products (Indicator 8.9.1).

RAC systems enhance agricultural sustainability and generate indirect positive impacts on other SDGs such as SDG6 (Clean water and sanitation), SDG12 (Responsible consumption and production), and SDG13 (Climate action) (Figure 1). More specifically, Cui et al. (2023) pointed out that RAC systems produced higher yields per unit area and saved water resources with a maximum potential of over 6,000 billion m^3, which is beneficial to address water scarcity (Indicator 6.4.2) (Table 1). RAC systems can also increase the efficiency of the use of resources of nitrogen, phosphorus, and potassium, and reduce the need for pesticide and herbicide application, which substantially improve water quality by reducing pollution and dumping (Indicator 6.3.2). The lower amounts of water and land used in RAC systems are positive for achieving sustainable management and efficient use of natural resources (Indicator 12.2.1). Rice and animals grow better in RAC systems, with the excreta of the aquatic animals providing nutrients for the rice and the rice providing shade and shelter to decrease the water temperature and intensity of sunlight in the field for the animals, which helps to reduce food losses along production and supply chains (Indicator 12.3.1). RAC systems could also reduce the emission of methane from paddy fields by over 10%. The development of climate-smart agricultural production with the widespread use of RAC systems would thus be useful to improve resilience and adaptive capacity and to mitigate the adverse impact of climate change (Indicators 13.1.1, 13.2.2).

Some SDGs are associated with and related to RAC systems and their global promotion (Figure 1). For example, RAC systems reduce the emission of pollutants to the air, water, and land, which could help to reduce the number of deaths and illnesses from pollution (Target 3.9), reduce marine pollution from land-based activities (Target 14.1), and promote the sustainable use of land and terrestrial ecosystems (Target 15.1) (Table 1). Furthermore,

Table 1
Overview of the Influenced Sustainable Development Goals and Targets by Rice-Animal Co-Culture Systems

	Influenced SDGs	Influenced SDG targets	Influence SDG indicators
Rice-Animal Co-Culture systems	1. End poverty in all its forms everywhere	1.1 By 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day	1.1.1 Proportion of the population living below the international poverty line by sex, age, employment status, and geographic location (urban/rural)
		1.2 By 2030, reduce at least by half the proportion of men, women, and children of all ages living in poverty in all its dimensions according to national definitions	1.2.1 Proportion of population living below the national poverty line, by sex and age
			1.2.2 Proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions
		1.4 By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance	1.4.2 Proportion of total adult population with secure tenure rights to land (a) with legally recognized documentation and (b) who perceive their rights to land as secure, by sex and type of tenure
	2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture	2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round	2.1.1 Prevalence of undernourishment
			2.1.2 Prevalence of moderate or severe food insecurity in the population, based on the Food Insecurity Experience Scale (FIES)
		2.2 By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant, and lactating women and older persons	2.2.1 Prevalence of stunting (height for age <−2 standard deviation from the median of the World Health Organization (WHO) Child Growth Standards) among children under 5 years of age
			2.2.2 Prevalence of malnutrition (weight for height >+2 or <−2 standard deviation from the median of the WHO Child Growth Standards) among children under 5 years of age, by type (wasting and overweight)
		2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists, and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment	2.3.1 Volume of production per labor unit by classes of farming/pastoral/forestry enterprise size
			2.3.2 Average income of small-scale food producers, by sex and indigenous status

Table 1
Continued

	Influenced SDGs	Influenced SDG targets	Influence SDG indicators
		2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters and that progressively improve land and soil quality	2.4.1 Proportion of agricultural area under productive and sustainable agriculture
	3. Ensure healthy lives and promote well-being for all at all ages	3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination	
	4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all		
	5. Achieve gender equality and empower all women and girls		
	6. Ensure availability and sustainable management of water and sanitation for all	6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	6.3.2 Proportion of bodies of water with good ambient water quality
		6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources
	8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	8.1 Sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7% gross domestic product growth per annum in the least developed countries	8.1.1 Annual growth rate of real GDP per capita
		8.4 Improve progressively, through 2030, global resource efficiency in consumption and production and endeavor to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programs on Sustainable Consumption and Production, with developed countries taking the lead	8.4.1 Material footprint, material footprint per capita, and material footprint per GDP
		8.9 By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products	8.9.1 Tourism direct GDP as a proportion of total GDP and in growth rate

Table 1
Continued

Influenced SDGs	Influenced SDG targets	Influence SDG indicators
10. Reduce inequality within and among countries		
12. Ensure sustainable consumption and production patterns	12.2 By 2030, achieve the sustainable management and efficient use of natural resources	12.2.1 Material footprint, material footprint per capita, and material footprint per GDP
	12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses	12.3.1 (a) Food loss index and (b) food waste index
13. Take urgent action to combat climate change and its impacts	13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries	13.1.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population
	13.2 Integrate climate change measures into national policies, strategies, and planning	13.2.2 Total greenhouse gas emissions per year
14. Conserve and sustainably use the oceans, seas, and marine resources for sustainable development	14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution	
15. Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements	
17. Strengthen the means of implementation and revitalize the global partnership for sustainable development		

Note. The definition of each SDG, goal, and indicator are referred from the official list of SDG Indicators by the United Nations (https://unstats.un.org/sdgs/indicators/indicators-list/).

the benefit on land and terrestrial ecosystems may possibly help to improve Indicator 15.1.2, especially in providing wetland habitat. The efficiency of RAC systems in maintaining food security and improving economic development would consequently help to obtain access to quality education (SDG4), improve the situation of women to achieve gender equality (SDG5), and reduce inequality within and among countries (SDG10), which is especially urgently needed in less-developed countries. The multiple aspects of the contributions of RAC systems to SDGs in different countries around the world would be helpful to develop a global partnership for sustainable development (SDG17).

Cui et al. (2023) stated the limitations of their study, mainly involving methodological barriers, technological adaptability, and societal acceptance. They suggested the expansion of the research areas involved in the global meta-analysis and the application of sophisticated economic analyses in future research, which would indeed be an important direction of development. We believe that much effort would be required to further understand the present and future roles of RAC systems in meeting the SDGs by theoretically summarizing the contributions of RAC systems to the SDGs and targets. First, the quantification of the contributions of RAC systems to the SDGs is currently limited. The advantages of RAC systems are gradually being recognized, and obtaining quantitative information for the design and implementation of evidence-based strategies globally is essential. Future research

is warranted to determine the degree to which the promotion of RAC systems would benefit SDGs and to clarify the differences among the SDGs and the spatial variation among regions. Based on our summary of the goal and target levels, the quantification could be further extended to the influence on the scores of the SDG indicators. Second, the interactions among the SDGs could be explored when quantifying the impact of RAC systems on SDGs. Cui et al. (2023) demonstrated the direct influence of RAC systems on SDG2, and our analysis further summarized their contributions to other SDGs. Previous studies have identified obvious synergies and trade-offs among various SDGs (Pham-Truffert et al., 2020; Pradhan et al., 2017). Taking these interactions into account would help to identify the complex mechanisms and consequences of RAC systems on meeting the SDGs. Third, the negative impacts of RAC systems should not be ignored. RAC systems usually have multifaceted positive effects on the achievement of the SDGs, but with some exceptions. For example, Cui et al. (2023) mentioned that rice yield was reduced in rice-crayfish and rice-prawn systems and that rice-fish co-culture systems would likely increase methane emissions by nearly 30%. Systematically assessing the adverse impacts of RAC systems and combining the assessments with the progress on the advantages to comprehensively understand the role of RAC systems in achieving SDGs are thus necessary.

In summary, Cui et al. (2023) comprehensively reported the specific advantages of RAC systems compared to conventional, separate agricultural, and aquacultural monocultures. We further theoretically clarified the connections of RAC systems to the various SDGs and targets. The role of RAC systems in meeting SDGs needs to be further explored and quantified by identifying the current crucial gaps.

Data Availability Statement

Data were not used, nor created for this research.

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