Global Sustainability

cambridge.org/sus

Intelligence Briefing

Cite this article: Edwards GI, Nelson KM, Le Clec'h S, Luu T, Coast O, Futakuchi K, Kok K (2024). Twenty-five rice research priorities for sustainable rice systems by 2050. *Global Sustainability* **7**, e23, 1–10. https://doi.org/10.1017/sus.2024.17

Received: 27 February 2023
Revised: 8 December 2023
Accepted: 14 March 2024

Keywords:
adaptation and mitigation; agriculture; ecology and biodiversity; food security

Corresponding author:
Glory I. Edwards; Email: glory.edwards@wur.nl

Twenty-five rice research priorities for sustainable rice systems by 2050

Glory I. Edwards[1], Katherine M. Nelson[2], Solen Le Clec'h[1], Tang Luu[3], Onoriode Coast[4], Koichi Futakuchi[5] and Kasper Kok[1]

[1]Wageningen University & Research, Earth Systems and Global Change Group, Wageningen, the Netherlands; [2]International Rice Research Institute, Climate Change Department, Hanoi, Vietnam; [3]University of Potsdam, Institute of Environmental Sciences and Geography, Potsdam, Germany; [4]University of New England, School of Environmental and Rural Science, Armidale, NSW, Australia and [5]Africa Rice Center (AfricaRice), Sustainable Productivity Enhancement Programme, Bouaké, Cote d'Ivoire

Abstract

Non-technical Summary. Agricultural research is vital for sustainable food production, amid changing challenges. To address these challenges effectively and achieve sustainable food systems, researchers and funding bodies have to prioritize research efforts. We conducted horizon scanning to determine how rice systems might change by 2050 and to identify key research gaps. The study involved 101 rice experts from 31 countries who rated the research gaps based on novelty and relevance. The top 25 research gaps encompass sustainability, agricultural development, rice crop science (including genetics, breeding, and physiology), and policies. Addressing these research gaps will contribute toward the sustainability of rice systems.

Technical Summary. Agricultural research and development (AgR&D) is crucial for increasing productivity while preserving natural capital and ensuring sustainable food security. Traditional AgR&D approaches along monodisciplinary lines often have unintended consequences and trade-offs, which can be avoided through integrated and interdisciplinary approaches. One such approach is horizon scanning. We conducted a horizon-scanning activity to identify research gaps to be prioritized for sustainable rice systems by 2050. The horizon scan involved a global and diverse panel of rice experts (101 from 31 countries). The panel responded to questionnaires on the drivers, projections, and research needs for rice AgR&D. Afterward, research gaps were rated on their relevance and novelty to sustainable rice systems. We identified the top 25 research gaps under four themes: sustainability interactions, agricultural development, genetics, breeding and crop physiology, and governance and policies. These gaps highlight research that needs to be prioritized to achieve sustainable rice systems that enhance resilience, conserve biodiversity, and promote socio-economic well-being.

Social media summary. Rice experts select top rice research gaps for achieving sustainable rice systems by 2050.

1. Introduction

Crop-production systems must increase productivity while preserving natural capital to ensure sustainable global food security (Foley et al., 2011). Agricultural research and development (AgR&D) offer opportunities to achieve this challenging objective (Kristkova et al., 2017). Moreover, AgR&D drives long-term agricultural productivity and innovation with high returns on investments (Alston, 2010; Alston et al., 2000; Heisey & Fuglie, 2007; Hurley et al., 2014).

Traditionally, AgR&D has addressed most issues along single disciplines, which has led to unintended consequences and trade-offs. For example, the Green Revolution of the late 1960s led to significant crop yield and food-production increases but also had several negative social, economic, and ecological outcomes (Borlaug, 2007; Renkow & Byerlee, 2010; Stevenson et al., 2013). The Green Revolution primarily benefited large-scale commercial farmers and unintentionally neglected small-scale farmers and rural communities (Davis et al., 2022; Gollin et al., 2021; Pingali, 2012). In addition, the Green Revolution relied heavily on synthetic fertilizers and pesticides and focused on a few high-yielding varieties and crops, resulting in decreased crop diversity, increased vulnerability to pests and diseases, and environmental degradation. Hence, while the Green Revolution was instrumental in averting hunger and generating wealth for many countries, it resulted in fragile agricultural systems (Bhatt et al., 2021; Brainerd & Menon, 2014; Chand & Haque, 1998; Chauhan et al., 2012; Gupta et al., 2015).

A more integrated and interdisciplinary approach to AgR&D will reduce unintended consequences and trade-offs. Such an approach considers the complex interactions among agriculture, the environment, and farming communities. This results in sustainable agricultural systems that are resilient to climate change and promote food security, biodiversity, and social, cultural, and economic well-being (Pingali et al., 2019; Sachs et al., 2010).

Research gaps must be identified and prioritized by considering research topics, locations, and methods (MacMillan & Benton, 2014; Pardey et al., 2016). This research-priority setting requires foresight to identify future trends, challenges, and opportunities (van Rij, 2010). One such foresight activity is horizon scanning, which can anticipate and plan for change (Cuhls, 2020). Horizon scanning identifies novel ideas at the margins of current knowledge (Sutherland et al., 2019). It also captures signals of emerging trends with potential future impacts that involve threats and opportunities (Esmail et al., 2020). Horizon scanning in AgR&D can help funding agencies and policymakers identify important research gaps and enable them to allocate resources effectively and efficiently (National Academies of Sciences, 2020).

Given the importance of AgR&D and the usefulness of horizon scanning in AgR&D to sustainable agricultural systems, we conducted a horizon-scanning activity with a global and diverse panel of rice-related research experts to identify gaps that should be prioritized to achieve sustainable rice systems by 2050.

2. Rice agriculture and research

Rice cultivation and research have a long history, which dates to ancient civilizations (Fuller, 2011; Sweeney & McCouch, 2007). For example, early records in China describe seed selection and irrigation to improve rice yields (Anderson, 1988). In the 19th and early 20th centuries, scientists began studying rice and improved its productivity through breeding. Later, politics, ecology, and genetic research heralded the Green Revolution (Baranski, 2022; Perkins, 1997). Increased productivity was the leading research innovation that drove rice production growth, especially in Asia.

Researchers are nowadays concerned that increases in global (Yuan et al., 2021) and regional rice yields (van Oort et al., 2015) have stabilized and that investment in rice research has stagnated (Mohanty et al., 2010; Zeigler & Barclay, 2008). For these reasons, we argue that rice research gaps must be identified and prioritized to increase production, productivity, and sustainability in rice systems by 2050. In addition, we highlight some of the importance of rice below.

First, rice plays an important role in global food security. Rice is a staple food for over half of the world's population. It is grown in more than 150 countries (Brooks & Place, 2019; Seck et al., 2012), in areas that extend from latitude 39 °S to 50 °N, and in environments encompassing temperate to sub-humid and humid climatic conditions. Rice production needs to increase to meet increasing global demands (Samal et al., 2022; Timmer et al., 2010). However, rice production systems face many challenges in achieving sustainable growth related to environmental factors (soil quality and water and nutrient availability), national and international policy initiatives, labor scarcity and increased competition for arable land.

Second, climate change exacerbates challenges in rice production systems. Increasing intensity and frequency of extreme climatic events such as droughts and floods will reduce rice yield (Hatfield et al., 2011; Singh et al., 2017; Wassmann et al., 2009). More so, rice is mainly produced by small-holder farmers with limited ability to adapt to climate change (Ho et al., 2022; Misra, 2017; Nyadzi et al., 2019; Ojo & Baiyegunhi, 2020; Redfern et al., 2012). Climate change also inhibits sustainable management practices. For example, practicing alternate wetting and drying, which reduces water use and methane emissions, is determined by climatic conditions (Nelson et al., 2015; Sander et al., 2017).

Third, rice production is affected by climate change, but it also contributes to climate change through greenhouse gas emissions. Rice contributes more to agricultural greenhouse gas emissions than other major cereals (Linquist et al., 2012; Tubiello et al., 2013). In addition, rice production is often associated with groundwater depletion, soil degradation, and widespread biodiversity decline (Bhatt et al., 2021; Brainerd & Menon, 2014; Gupta et al., 2015).

3. Methods

Our study follows a Delphi technique with two rounds (Mukherjee et al., 2015; Rowe & Wright, 1999), involving a global and diverse set of rice experts. (In Supplementary material A we introduce the horizon scanning method and give more details of how we carried out our horizon scan. We also provide information on the demographics of participants including their geographical location, research domain, and years of research experience.). In Round 1, experts answered open-ended questions on the macro-drivers that enable or constrain sustainable rice systems and the research needs. The responses were analyzed and classified into seven issues and 54 research gaps that formed the basis of Round 2.

In Round 2, a subset of the experts rated the research gaps on relevance and novelty. Relevance ratings for sustainable rice systems had four levels: 'high relevance', 'moderate relevance', 'little relevance', and 'no idea'. High, moderate, and low relevance reflect the importance of the research gap in achieving sustainable rice systems, whereas 'no idea' indicated that the issue fell outside the expert's knowledge. Novelty ratings had three levels: 'novel' (available knowledge is limited), 'not novel' (sufficient knowledge exists), and 'new to me' (unfamiliar subject) (The questionnaires of Rounds 1 and 2 are provided in Supplementary material B).

To analyze the results from Round 2, we assessed the level of agreement among participants. A consensus was reached when at least 50% of the participants gave the same rating. If there was no consensus on any rating, we selected the most frequently given rating (even if it was less than 50%). To prioritize the research gaps, we assigned scores based on the rating and the level of consensus, with higher scores given to research gaps with consensus. The top 25 research gaps were then selected in order of their rank.

4. Results

4.1 Drivers

The drivers were listed under present and future times and categorized under social, technological, economic, environmental, and political. Environmental drivers were identified as the most important category for present and future rice systems, with political drivers as the lowest (Figure 1). Other driver categories such as economic, were considered more important now than in the future, whereas technological drivers more important in the future than now. Climate change and technology emerged as important drivers in present and future times (see Figures SC1 and SC2 in Supplementary material C).

4.2 Projections, opportunities, and challenges

The analysis of future projections, opportunities, and challenges resulted in the identification of seven key issues: climate change,

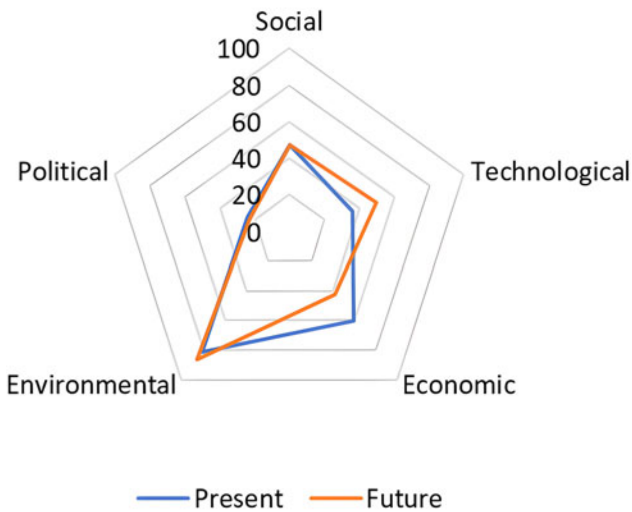

Figure 1. Relative importance of driver categories in the present and future times.

changes in consumer profiles, urbanization, market and policy shifts, changes in labor demographics, constraints on natural resources, and technological advancements (All projections mentioned by participants are provided in Supplementary material C). These issues are interconnected; for example, urbanization is linked to both changes in labor demographics and consumer preferences.

4.3 Research techniques

Proposed research techniques to meet research needs included rice-vegetable systems modeling, digitalization of value chains, spatial data analytics, stakeholder engagement, lowland development, inter- and transdisciplinary research, remote sensing, water accounting, climate finance, and low-emission business models (All research techniques mentioned are provided in Supplementary material E).

Experts also proposed that more research techniques should be applied to achieve sustainable rice systems. These include digital agriculture, multi-stakeholder engagement, social impact research, satellite imagery, crop insurance, space applications, machine learning, automated crop monitoring, nature-based solutions, and systems thinking. In addition, they advocated for shifts in research focus, for example, from crop genetics and plot-level research to farming systems research.

Experts called for 'out-of-the-box' thinking and proposed more inter- and trans-disciplinary research. However, some experts wanted basic research that applies critical core expertise. A few other experts called for a long-term vision and funding, while others advocated for rapid technology development and quick R&D cycles.

5. The top 25 rice research gaps

Fifty-four research gaps from Round 1 were rated by experts and ranked in order of their relevance, novelty, and consensus among experts (Table 1). The agreement between experts on the ratings of each research gap is shown in Figure 2, with a higher consensus for relevance ratings (70%, $n = 54$) compared to novelty ratings (37%, $n = 54$). All relevance ratings with consensus were for 'highly relevant' whereas all but one novelty ratings with consensus were for 'not novel' ratings. The exception is the research gap rank 1 (see Table 1) related to the trade-offs between mitigating rice greenhouse gas emissions and local food security, rated 'highly relevant' and 'novel' with consensus (see Figure 2). The top 25 rice research gaps are discussed below under four themes.

5.1 Theme 1: sustainability interactions

In achieving sustainable rice systems, differences in views often arise between objectives such as food security and environmental protection (Klapwijk et al., 2014). Balancing these competing objectives and finding trade-offs requires research that considers the interdependencies between different components of rice production systems and involves stakeholders in the decision-making process.

Climate-change impacts generally lead to a decline in rice production (Hatfield et al., 2011; Singh et al., 2017; Wassmann et al., 2009). However, some studies indeed show that climate change could benefit rice production through increased temperatures (Waha et al., 2020; Yang et al., 2015). Therefore, a comprehensive analysis of climate-change impacts is important for innovation in rice production systems.

Research on sustainability interactions includes:

(1) Understanding the potential trade-offs between mitigating rice greenhouse gas emissions and local food security;
(2) Maximizing higher CO_2 levels to improve rice-crop ecology and productivity;
(3) Integration of regenerative and agro-ecosystem approaches in rice systems to optimize productivity and resource-use efficiency;
(4) Quantifying the local effects on and responses of rice cultivation to abiotic stresses;
(5) Developing innovative agro-ecological fertilizers to improve soil fertility; and
(6) Utilizing by-products from rice production for other purposes (e.g. rice straw for biofuels and fertilizers).

5.2 Theme 2: agricultural development

Agricultural developments and their impacts on social, economic, and ecological factors must be thoroughly analyzed as they can have far-reaching implications. For example, small-holder farmers grow most of the rice produced and play a substantial role in rice-food security (Pandey et al., 2010) but often receive little monetary benefits from rice production despite rice system expansion. Small-holder farmers receive as little as 4% of the consumer price (Alliot & Fechner, 2018). This trend counteracts the vision of equitable and sustainable agriculture. Relevant research on agricultural development includes:

(7) The replacement of manual, in-person monitoring, reporting, and verification with remote sensing and satellite technologies;
(8) Monitoring and assessing environmental impacts of new rice technology;
(9) Impacts of increasing rice production on Africa's food-crop production and diversity;
(10) Expanding dryland and upland rice production;
(11) Socio-economic drivers of rice-yield gaps across the world;
(12) Understanding farmers' actual conditions to bridge the profit-loss margin;
(13) Understanding the process of farmers' transformation to sustainable management practices;

https://doi.org/10.1017/sus.2024.17 Published online by Cambridge University Press

Table 1. Research gaps ordered by rank

Rank	Rank score	Research gap
1	60	Understanding the potential trade-offs between mitigating rice greenhouse-gas emissions and local food security;
2	45	The replacement of manual, in-person monitoring, reporting, and verification (MRV) with remote sensing/satellite technology
3	45	Monitoring and assessing the environmental impacts of new rice technology
4	45	Impacts of increasing rice production on Africa's food-crop production and diversity
5	45	Rice varieties that are more efficient in capturing and using environmental resources such as solar energy and aerobic rice that use less water
6	45	Development of perennial rice varieties; that is, can be harvested season in and season out.
7	45	Maximizing increasing CO_2 levels to improve rice-crop ecology and productivity;
8	45	Integration of regenerative and agro-ecosystem approaches in rice systems to optimize productivity and resource-use efficiency
9	45	Expanding dryland and upland rice production
10	45	The governance of surface water use as a collective regional resource and for a balanced supply of rice in a region
11	45	Policy options to mitigate the envisaged rice production loss in some parts of the world, such as Asia
12	40	Socio-economic drivers of rice yield gaps across the world
13	40	Understanding farmers' actual conditions to bridge the profit-loss margin
14	40	Understanding the process of farmers' transformation to sustainable management practices
15	40	Quantifying the local effects on and responses of rice cultivation to abiotic stresses, including climate change
16	40	The effect of increased food insecurity and food prices on farmers' practices of sustainable methods
17	40	The potential socio-economic impact of technological change to small-scale farmers
18	40	Developing accurate climate and water information at local scales
19	40	Developing climate-resilient varieties that can thrive under harsh conditions, for example, varieties with better stress avoidance traits, highly developed root systems, and the ability to grow in saline conditions
20	40	Developing rice varieties with improved grain qualities (such as high milling recovery, head rice, and length to width ratio)
21	40	Developing methanogenic inhibitors to reduce methane emissions from rice production systems
22	40	Developing innovative agro-ecological fertilizers to improve soil fertility
23	40	Utilizing by-products from rice production for other purposes (e.g. rice straw for biofuels, fertilizers, etc.)
24	40	Translating science to practice, (e.g. the application of genetic advancements)
25	40	The policy options needed to boost rice productivity, sustainability and inclusive transformation in lagging regions
26	35	Developing indicators to assess the actual drivers of change in different rice systems, for example, whether due to climate change and/or human population changes.
27	35	Understanding the emerging land grabs and large scale land acquisitions by wealthy farmers/investors due to rising profitability in rice production
28	35	Geospatial analyses of cropland expansion and development of crop-type maps
29	35	Understanding the shifting dynamics of rice consumption due to increasing incomes and urbanization in different parts of the world
30	35	Developing rice varieties richer in nutritional qualities such as Omega rice, vitamin E rice, high Fe, Zn, and low glycemic content
31	35	Altering the photosynthesis of rice from C3 to C4 pathway
32	35	Developing sustainable local seed systems
33	35	Developing proactive measures to curtail emerging diseases and pests brought by climate change
34	35	Fair sustainable business models and supply chains that results in economic benefits to producers and environmental sustainability
35	35	Planetary health diets: healthy diets with minimal environmental footprint
36	35	Upscaling findings from farm-level (micro-level) to regional/global scale (macro-level)
37	35	Improving the agricultural literacy of rice producers
38	35	Developing indigenous technology to support the rice value chain
39	30	Shared information systems between key players in the rice value chain for increased transparency in MRV

(*Continued*)

https://doi.org/10.1017/sus.2024.17 Published online by Cambridge University Press

Table 1. (*Continued*).

Rank	Rank score	Research gap
40	30	Converting unproductive areas to rice croplands due to the rising scarcity of arable land
41	25	Developing and utilizing genetically modified rice (GMO) and understanding its consequences.
42	25	Impact of urbanization and industrialization on the availability of arable land for rice production
43	25	Developing floating rice varieties
44	25	New technology development and adaptation of old technology to be suitable and affordable for small-holder farmers
45	20	Understanding the selection and conservation of traditional varieties by farmers.
46	20	The sectoral migration away from farming by youths and existing farmers
47	20	The impact of changing dynamics in global rice markets, such as the attainment of self-sufficiency by current rice importers
48	20	Understanding the interplay and price dynamics between different staple crops (e.g. wheat/rice prices) at the global scale
49	20	Growing rice on soil-less media
50	20	Carbon farming solutions towards sustainable systems
51	20	The integration of rice systems with tourism
52	15	Understanding different rice market segments to target rice products to specific markets
53	15	Redirecting rice production from export-oriented production to production for local consumption
54	15	Developing diverse food products from rice grains

(14) The effect of increased food insecurity and food prices on farmers' practices of sustainable methods;
(15) The potential socio-economic impact of technological change on small-scale farmers; and
(16) Developing accurate climate and water information at local scales.

5.3 Theme 3: genetics, breeding and physiology

Rice is one of the first crops to have had its complete genome sequenced (Jackson, 2016; Sasaki et al., 2002). This advancement marked a milestone in rice research and opened new opportunities for genetic research for rice and other crops (Izawa & Shimamoto, 1996; Rezvi et al., 2022). Despite the tremendous success recorded in rice-genetics research (Bajaj & Mohanty, 2005; Hossain et al., 2000), much rice genetic and breeding research is still in a developmental stage (Mohd Hanafiah et al., 2020). Bottlenecks in high-throughput phenotyping of physiological traits have also limited the extent to which advances in genomics can be exploited in breeding (Rebetzke et al., 2019; Song et al., 2021; Yang et al., 2020). With the increasing impact of stressors, genetic and physiological research needs to be accelerated (Gregorio et al., 2002; Hasanuzzaman et al., 2018; Jagadish et al., 2012; Lesk et al., 2022). The research gaps list the directions for rice genetic research on developing:

(17) Rice varieties that are more efficient in capturing and using environmental resources such as solar energy and aerobic rice that use less water;
(18) Perennial (i.e. can be harvested season in and season out) rice varieties;
(19) Climate-resilient varieties that can thrive under harsh conditions (e.g. varieties with better stress avoidance traits, highly developed root systems, and the ability to grow in saline conditions);
(20) Varieties with improved grain qualities (such as high milling recovery, head rice, and length-to-width ration); and
(21) Methanogenic inhibitors to reduce methane emissions from rice production systems.

5.4 Theme 4: governance and policies

Policies and equitable governance support agriculture in achieving diverse objectives, offering the opportunity to minimize losses and maximize synergies across scales. For example, persistent transboundary policy-practice mismatches in the international Mekong Delta's management have led to lower agricultural production and poor water management (Sithirith, 2021; Thu & Wehn, 2016; Tran & Tortajada, 2022). Effective policies must integrate knowledge from multiple fields and scales (Sterner et al., 2019). The research gaps under this theme relate to the science-policy-practice gap and the implementation of effective policies to resolve sustainability issues. Research on governance and policies include:

(22) The governance of surface water use as a collective regional resource and for a balanced supply of rice in a region;
(23) The policy options to mitigate the envisaged rice production loss in some parts of the world, such as Asia;
(24) Translating science to practice (e.g. the application and adoption of genetic advancements); and
(25) The policy options needed to boost rice productivity, sustainability and inclusive transformation in lagging regions.

6. Synthesis

We conducted a horizon scanning activity to identify research gaps that must be prioritized for sustainable rice systems by 2050. The horizon scanning involved a global panel of rice experts in a two-round Delphi-technique. The activity resulted in the

https://doi.org/10.1017/sus.2024.17 Published online by Cambridge University Press

Rank order	Ratings of relevance: LR	MR	HR	Ratings of novelty: NOV	NTM	NTNOV
1	7	28	65	51	13	36
2	14	34	52	43	23	34
3	2	26	72	49	6	45
4	5	38	56	40	30	30
5	0	29	71	37	30	33
6	10	35	55	37	35	28
7	12	32	56	37	33	30
8	5	23	72	48	9	43
9	15	31	54	39	24	37
10	7	36	57	38	29	33
11	5	20	75	47	22	31
12	7	20	74	26	11	63
13	0	36	64	32	9	60
14	0	33	67	41	9	50
15	4	22	73	32	9	60
16	11	32	57	36	13	51
17	2	41	57	32	17	51
18	4	31	64	40	9	51
19	0	19	81	35	11	54
20	2	39	59	22	24	54
21	11	32	58	35	39	26
22	10	19	71	35	15	50
23	10	19	71	37	9	54
24	9	40	51	31	16	53
25	2	26	72	36	11	53
26	7	22	71	43	13	43
27	13	38	50	33	33	35
28	9	41	50	30	28	41
29	5	41	55	32	23	45
30	12	21	67	30	22	48
31	11	26	63	22	33	46
32	5	33	63	37	15	48
33	2	29	69	37	17	46
34	5	35	60	35	17	48
35	19	26	55	28	30	41
36	5	44	51	38	16	47
37	14	31	55	27	27	47
38	29	21	50	31	22	47
39	7	44	49	38	36	26
40	20	34	46	40	31	29
41	26	26	49	26	23	51
42	13	42	44	28	17	55
43	33	33	35	20	30	50
44	16	35	49	29	20	51
45	16	43	41	17	9	74
46	14	37	49	28	23	49
47	15	43	43	30	28	43
48	20	35	45	26	34	40
49	41	24	35	41	39	20
50	5	46	49	37	26	37
51	46	26	28	38	31	31
52	7	47	47	33	18	49
53	31	38	31	20	31	49
54	35	33	33	20	24	56

Figure 2. Heat map visualizing the percentage of experts who chose a rating. A green-yellow-red gradient is used, indicating increasing agreement on the rating. The red circle icons represent ratings with majority agreement (⩾50%). LR stands for low relevance, MR for moderate relevance, HR for high relevance, NOV for novel, NTM for new to me, and NTNOV for not novel.

identification of drivers, projections, opportunities, challenges, research gaps, and techniques.

Most research gaps were considered 'highly relevant' and 'not novel', revealing that research is needed to tackle persistent issues. Further research should build upon existing findings and help end-users utilize research results. Our study aligns with Dalton's notion of horizon scanning (Dalton, 2002), which identifies both novel and persistent research gaps. A sustainability transition is described as a shift toward a sustainable state in response to the persistent issues facing modern societies (Grin et al., 2010). Hence, it is important to address the persistent issues identified in our study to achieve sustainable rice systems.

https://doi.org/10.1017/sus.2024.17 Published online by Cambridge University Press

The top 25 rice-research gaps have different degrees of agreement among the global panel of experts and this shows a diverging consensus on several issues. Research gaps that are future-oriented and at the margins of our current thinking are rarely a product of consensus (Kramer et al., 2017). Also, little conformity in knowledge is expected when experts come from diverse research and cultural backgrounds. However, consensus serves as evidence to support the ranking of the horizon-scan output (Hines et al., 2019).

Horizon scanning is a crucial first step in the foresight process, as it identifies emerging trends and potential challenges (Cuhls, 2020; National Academies of Sciences, 2020) and thus should be conducted regularly to keep track of changes over time (van Rij, 2010). The success of horizon scanning can be seen in examples such as the yearly scans on global conservation issues (Sutherland et al., 2019). In this context, our study could be considered the first phase in a long-term foresight process, which can help track the progress of rice research over time. We are cautious that only 101 experts from 31 countries contributed to this horizon scan and as such, the research gaps identified are limited. However, some other horizon scans of global significance with smaller number of contributors, for example, Sutherland et al. (2019; global scan on conservation, with $n = 28$), Kennicutt et al. (2014; Antarctic Science Horizon scan, $n = 75$), have had meaningful impacts on scientific research (Esmail et al., 2020).

Our study involved experts from the broad domain of rice research, but further research can take the same approach to different groups of experts or stakeholders. The research gaps could be further categorized based on location to allow for more locally relevant research gaps to be highlighted. Results could be compared to see where results align or differ between stakeholder groups, increasing the results' applicability to policy and practice. Further research could, for example, engage farmers who apply research results (MacMillan & Benton, 2014); government funding agencies who are the key investors in AgR&D (Alston et al., 2012); and businesses in the agriculture or private sector that increasingly invest in research (Pardey et al., 2016).

Our study also contributes to the research priority setting by being conducted worldwide. Research priority setting for rice is often regional or national (e.g. Barker & Herdt, 2019; Evenson et al., 1996) or focused on sub-domains of rice research (Hossain et al., 2000; Willocquet et al., 2004). Furthermore, a few worldwide studies have been conducted, but these relied on bibliometric analysis to prioritize research (Bin Rahman & Zhang, 2022; Pandey et al., 2010). In contrast to the bibliometric-based studies, our study capitalizes on knowledge from a global panel of rice experts. Hence, research gaps are relevant to global food security and sustainability. By presenting the top 25 rice research gaps, experts can focus on the areas of need and collaborate, leading to more effective and impactful research outcomes. In addition, our study acts as a bridge among researchers, funding agencies, policymakers, and end users by highlighting a set of research to be prioritized.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/sus.2024.17.

Acknowledgements. We appreciate the 101 experts who took the time to participate in the study. OC acknowledges and recognizes the Nganyaywana (Anaiwan) people as the traditional owners and custodians of the land on which he works and lives, and he pays respect to their Elders past and present. He also extends his respect to all Aboriginal and Torres Strait Islander peoples. Prof. Rik Leemans gave suggestions on earlier versions of the manuscript and these are highly appreciated. Thank you also to the anonymous reviewers who provided helpful comments to improve the manuscript during the peer-review process.

Author contributions. GIE conceived the idea. GIE, KN, SL, and KK jointly designed the study. All authors invited participants, pretested and improved the surveys. GIE wrote the first draft of the manuscript. GIE, KN, SL, OC, LT, KF, and KK discussed the results and edited the manuscript. All authors approved the final version of the manuscript.

Funding statement. This research was supported by Mitigate+: Research for Low Emissions Food Systems and the Global Research Alliance on Agricultural Greenhouse Gases (GRA) through their CLIFF-GRADS programme. Funding for Mitigate+comes from the CGIAR Trust Fund and the Government of New Zealand. In addition, we thank the International Rice Research Institute, Hanoi, Vietnam for hosting GIE.

Open access is provided by Wageningen University and Research, the Netherlands.

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The Social Sciences Ethics Committee of Wageningen University granted ethics approval for research involving human participants.

Research transparency and reproducibility. Additional data and information are available in the Supplementary material. Further requests for data and information should be directed to the corresponding author.

References

Alliot, C., & Fechner, T. (2018). Distribution of value in Asian rice value chains. *Oxfam Research Reports*.

Alston, J. M. (2010). The benefits from agricultural research and development, innovation, and productivity growth (OECD Food, Agriculture and Fisheries Papers). Organization for Economic Co-Operation and Development (OECD). https://doi.org/10.1787/5km91nfsnkwg-en

Alston, J. M., Andersen, M., James, J. S., & Pardey, P. G. (2012). *Persistence pays: U.S. Agricultural productivity growth and the benefits from public R&D spending* (2010th ed.). Springer New York.

Alston, J. M., Marra, M. C., Pardey, P. G., & Wyatt, T. J. (2000). Research returns redux: A meta-analysis of the returns to agricultural R&D. *The Australian Journal of Agricultural and Resource Economics*, *44*(2), 185–215.

Amanatidou, E., Butter, M., Carabias, V., Könnölä, T., Leis, M., Saritas, O., Schaper-Rinkel, P., & van Rij, V. (2012). On concepts and methods in horizon scanning: Lessons from initiating policy dialogues on emerging issues. *Science & Public Policy*, *39*(2), 208–221.

Anderson, E. N. (1988). *The food of China*. Yale University Press.

Bajaj, S., & Mohanty, A. (2005). Recent advances in rice biotechnology – Towards genetically superior transgenic rice. *Plant Biotechnology Journal*, *3*(3), 275–307.

Baranski, M. (2022). *The globalization of wheat: A critical history of the green revolution*. University of Pittsburgh Press.

Barker, R., & Herdt, R. W. (2019). Setting priorities for rice research in Asia. In R. S. Anderson, P. R. Brass, E. Levy, & B. Morrison (Eds.), *Science, politics, and the agricultural revolution in Asia* (pp. 427–461). Routledge.

Bhatt, R., Singh, P., Hossain, A., & Timsina, J. (2021). Rice–wheat system in the northwest Indo-Gangetic plains of South Asia: Issues and technological interventions for increasing productivity and sustainability. *Paddy and Water Environment*, *19*(3), 345–365.

Bin Rahman, A. N. M. R., & Zhang, J. (2022). Trends in rice research: 2030 and beyond. *Food Energy Security*, *12*(2), e390. https://doi.org/10.1002/fes3.390

Borlaug, N. (2007). Feeding a hungry world. *Science (New York, N.Y.)*, *318* (5849), 359.

Brainerd, E., & Menon, N. (2014). Seasonal effects of water quality: The hidden costs of the green revolution to infant and child health in India. *Journal of Development Economics*, *107*, 49–64.

Brooks, K., & Place, F. (2019). Global food systems: Can foresight learn from hindsight? *Global Food Security*, *20*, 66–71.

Brown, M. J. F., Dicks, L. V., Paxton, R. J., Baldock, K. C. R., Barron, A. B., Chauzat, M.-P., Freitas, B. M., Goulson, D., Jepsen, S., Kremen, C., Li, J., Neumann, P., Pattemore, D. E., Potts, S. G., Schweiger, O., Seymour, C. L., & Stout, J. C. (2016). A horizon scan of future threats and opportunities for pollinators and pollination. *PeerJ*, *4*, e2249.

Chand, R., & Haque, T. (1998). Rice-wheat crop system in Indo-Gangetic Region: Issues concerning sustainability. *Economic and Political Weekly*, *33*(26), A108–A112.

Chauhan, B. S., Mahajan, G., Sardana, V., Timsina, J., & Jat, M. L. (2012). Productivity and sustainability of the rice–wheat cropping system in the Indo-Gangetic plains of the Indian subcontinent: Problems, opportunities, and strategies. *Advances in agronomy*, *117*, 315–369.

Cuhls, K. (2020). Horizon scanning in foresight – why horizon scanning is only a part of the game. *Futures & Foresight Science*, *2*(1), e23. https://doi.org/10.1002/ffo2.23

Cuhls, K., Erdmann, L., Warnke, P., Toivanen, H., Toivanen, M., van der Giessen, A. M., & Seiffert, L. (2015). *Models of horizon scanning: How to integrate horizon scanning into European research and innovation policies.* European Commission.

Dalton, H. (2002). *Defra's horizon scanning strategy for science*. Department for Environment. Food and Rural Affairs (Defra).

Davis, K. F., Dalin, C., Kummu, M., Marston, L., Pingali, P., & Tuninetti, M. (2022). Beyond the green revolution: A roadmap for sustainable food systems research and action. *Environmental Research Letters*, *17*(10), 100401.

Duboff, R. S. (2007). *The wisdom of (expert) crowds*. Harvard Business Review.

Esmail, N., Wintle, B. C., t Sas-Rolfes, M., Athanas, A., Beale, C. M., Bending, Z., Dai, R., Fabinyi, M., Gluszek, S., Haenlein, C., Harrington, L. A., Hinsley, A., Kariuki, K., Lam, J., Markus, M., Paudel, K., Shukhova, S., Sutherland, W. J., Verissimo, D., … & Milner-Gulland, E. J. (2020). Emerging illegal wildlife trade issues: A global horizon scan. *Conservation Letters*, *13*(4), e12715. https://doi.org/10.1111/conl.12715

Evenson, R. E., Herdt, R. W., & Hossain, M. (Eds.). (1996). *Rice research in Asia*. CABI Publishing.

Fleming, A., Jakku, E., Fielke, S., Taylor, B. M., Lacey, J., Terhorst, A., & Stitzlein, C. (2021). Foresighting Australian digital agricultural futures: Applying responsible innovation thinking to anticipate research and development impact under different scenarios. *Agricultural Systems*, *190*, 103120.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, M. E., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., … Zaks, D. P. (2011). Solutions for a cultivated planet. *Nature*, *478*(7369), 337–342.

Fuller, D. Q. (2011). Pathways to Asian civilizations: Tracing the origins and spread of rice and rice cultures. *Rice*, *4*(3), 78–92.

Glaros, A., Marquis, S., Major, C., Quarshie, P., Ashton, L., Green, A. G., Kc, K. B., Newman, L., Newell, R., Yada, R. Y., & Fraser, E. D. G. (2022). Horizon scanning and review of the impact of five food and food production models for the global food system in 2050. *Trends in Food Science & Technology*, *119*, 550–564.

Gollin, D., Hansen, C. W., & Wingender, A. M. (2021). Two blades of grass: The impact of the green revolution. *The Journal of Political Economy*, *129* (8), 2344–2384.

Gregorio, G. B., Senadhira, D., Mendoza, R. D., Manigbas, N. L., Roxas, J. P., & Guerta, C. Q. (2002). Progress in breeding for salinity tolerance and associated abiotic stresses in rice. *Field Crops Research*, *76*(2), 91–101.

Grin, J., Rotmans, J., & Schot, J. (2010). *Transitions to sustainable development: New directions in the study of long term transformative change*. Routledge.

Gupta, R. K., Naresh, R. K., Hobbs, P. R., Jiaguo, Z., & Ladha, J. K. (2015). Sustainability of post-green revolution agriculture: The rice-wheat cropping systems of the indo-gangetic plains and China. *Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts*, *65*, 1–25.

Hasanuzzaman, M., Fujita, M., Nahar, K., & Biswas, J. K. (2018). *Advances in rice research for abiotic stress tolerance*. Woodhead Publishing.

Hatfield, J. L., Boote, K. J., Kimball, B. A., Ziska, L. H., Izaurralde, R. C., Ort, D., Thomson, A. M., & Wolfe, D. (2011). Climate impacts on agriculture: Implications for crop production. *Agronomy Journal*, *103*(2), 351–370.

Heisey, P., & Fuglie, K. (2007). Economic returns to public agricultural research. *USDA-ERS Economic Brief*, *10*, 1–9. https://doi.org/10.2139/ssrn.1084926

Hines, P., Hiu Yu, L., Guy, R. H., Brand, A., & Papaluca-Amati, M. (2019). Scanning the horizon: A systematic literature review of methodologies. *BMJ Open*, *9*(5), e026764.

Ho, T. D. N., Kuwornu, J. K. M., & Tsusaka, T. W. (2022). Factors influencing small-holder rice farmers' vulnerability to climate change and variability in the Mekong delta region of Vietnam. *European Journal of Development Research*, *34*(1), 272–302.

Hossain, M., Bennett, J., Datta, S., Leung, H., & Khush, G. (2000). Biotechnology research in rice for Asia: Priorities, focus and directions. In M. Qaim, A. F. Krattiger, & J. von Braun (Eds.), *Agricultural biotechnology in developing countries: Towards optimizing the benefits for the poor* (pp. 99–120). Springer US.

Hurley, T. M., Rao, X., & Pardey, P. G. (2014). Re-examining the reported rates of return to food and agricultural research and development. *American Journal of Agricultural Economics*, *96*(5), 1492–1504.

Ingram, J., Maye, D., Bailye, C., Barnes, A., Bear, C., Bell, M., Cutress, D., Davies, L., de Boon, A., Dinnie, L., Gairdner, J., Hafferty, C., Holloway, L., Kindred, D., Kirby, D., Leake, B., Manning, L., Marchant, B., Morse, A., … & Wilson, L. (2022). What are the priority research questions for digital agriculture? *Land Use Policy*, *114*, 105962.

Izawa, T., & Shimamoto, K. (1996). Becoming a model plant: The importance of rice to plant science. *Trends in Plant Science*, *1*(3), 95–99.

Jackson, S. A. (2016). Rice: The first crop genome. *Rice*, *9*(1), 14.

Jagadish, S. V. K., Septiningsih, E. M., Kohli, A., Thomson, M. J., Ye, C., Redona, E., Kumar, A., Gregorio, G. B., Wassmann, R., Ismail, A. M., & Singh, R. K. (2012). Genetic advances in adapting rice to a rapidly changing climate. *Journal of Agronomy and Crop Science*, *198*(5), 360–373.

Kennicutt, M. C., Chown, S. L., Cassano, J. J., Liggett, D., Massom, R., Peck, L. S., Rintoul, S. R., Storey, J. W., Vaughan, D. G., Wilson, T. J., & Sutherland, W. J. (2014). Polar research: Six priorities for Antarctic science. *Nature*, *512* (7512), 23–25.

Klapwijk, C. J., van Wijk, M. T., Rosenstock, T. S., van Asten, P. J. A., Thornton, P. K., & Giller, K. E. (2014). Analysis of trade-offs in agricultural systems: Current status and way forward. *Current Opinion in Environmental Sustainability*, *6*, 110–115.

Könnölä, T., Salo, A., Cagnin, C., Carabias, V., & Vilkkumaa, E. (2012). Facing the future: Scanning, synthesizing and sense-making in horizon scanning. *Science & Public Policy*, *39*(2), 222–231.

Kramer, D. B., Hartter, J., Boag, A. E., Jain, M., Stevens, K., Nicholas, K. A., McConnell, W. J., & Liu, A. J. (2017). Top 40 questions in coupled human and natural systems (CHANS) research. *Ecology and Society*, *22*(2), 44.

Kristkova, Z. S., Van Dijk, M., & Van Meijl, H. (2017). Assessing the impact of agricultural R&D investments on long-term projections of food security. In A. Schmitz, P. L. Kennedy, & T. G. Schmitz (Eds.), *World agricultural resources and food security*, *17* (pp. 1–17). Emerald Publishing Limited.

Lesk, C., Anderson, W., Rigden, A., Coast, O., Jägermeyr, J., McDermid, S., Davis, K. F., & Konar, M. (2022). Compound heat and moisture extreme impacts on global crop yields under climate change. *Nature Reviews Earth & Environment*, *3*(12), 872–889.

Linquist, B., Groenigen, K. J., Adviento-Borbe, M. A., Pittelkow, C., & Kessel, C. (2012). An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*, *18*(1), 194–209.

MacMillan, T., & Benton, T. G. (2014). Agriculture: Engage farmers in research. *Nature*, *509*(7498), 25–27.

Misra, M. (2017). Small-holder agriculture and climate change adaptation in Bangladesh: Questioning the technological optimism. *Climate and Development*, *9*(4), 337–347.

Mohanty, S., Wailes, E., & Chavez, E. (2010). The global rice supply and demand outlook: the need for greater productivity growth to keep rice affordable. *Rice in the Global Economy: Strategic Research and Policy Issues for Food Security*. International Rice Research Institute, Los Baños, Philippines.

Mohd Hanafiah, N., Mispan, M. S., Lim, P. E., Baisakh, N., & Cheng, A. (2020). The 21st century agriculture: When rice research draws attention to climate variability and how weedy rice and underutilized grains come in handy. *Plants*, *9*(3), 365.

Mukherjee, N., Hugé, J., Sutherland, W. J., McNeill, J., Van Opstal, M., Dahdouh-Guebas, F., & Koedam, N. (2015). The Delphi technique in ecology and biological conservation: Applications and guidelines. *Methods in Ecology and Evolution*, *6*(9), 1097–1109.

National Academies of Sciences. (2020). *Horizon scanning and foresight methods*. National Academies Press.

Nelson, A., Wassmann, R., Sander, B. O., & Palao, L. K. (2015). Climate-determined suitability of the water saving technology “alternate wetting and drying” in rice systems: A scalable methodology demonstrated for a province in the Philippines. *PloS One*, *10*(12), e0145268.

Neve, P., Barney, J. N., Buckley, Y., Cousens, R. D., Graham, S., Jordan, N. R., Lawton-Rauh, A., Liebman, M., Mesgaran, M. B., Schut, M., Shaw, J., Storkey, J., Baraibar, B., Baucom, R. S., Chalak, M., Childs, D. Z., Christensen, S., Eizenberg, H., Fernández-Quintanilla, C., … & Williams, M. (2018). Reviewing research priorities in weed ecology, evolution and management: A horizon scan. *Weed Research*, *58*(4), 250–258.

Nyadzi, E., Saskia Werners, E., Biesbroek, R., Long, P. H., Franssen, W., & Ludwig, F. (2019). Verification of seasonal climate forecast toward hydroclimatic information needs of rice farmers in Northern Ghana. *Weather, Climate, and Society*, *11*(1), 127–142.

Ojo, T. O., & Baiyegunhi, L. J. S. (2020). Determinants of climate change adaptation strategies and its impact on the net farm income of rice farmers in south-west Nigeria. *Land Use Policy*, *95*, 103946.

Pandey, S., Byerlee, D., Dawe, D., Dobermann, A., Mohanty, S., Rozelle, S., & Hardy, B. (2010). *Rice in the global economy: Strategic research and policy issues for food security*. International Rice Research Institute.

Pardey, P. G., Chan-Kang, C., Dehmer, S. P., & Beddow, J. M. (2016). Agricultural R&D is on the move. *Nature*, *537*(7620), 301–303.

Perkins, J. H. (1997). *Geopolitics and the green revolution: Wheat, genes, and the cold war*. Oxford University Press.

Pingali, P. (2012). Green revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(31), 12302–12308.

Pingali, P., Aiyar, A., Abraham, M., & Rahman, A. (2019). The way forward: Food systems for enabling rural prosperity and nutrition security. In C. B. Barrett (Ed.), *Transforming food systems for a rising India* (pp. 277–311). Springer International Publishing.

Pretty, J., Sutherland, W. J., Ashby, J., Auburn, J., Baulcombe, D., Bell, M., Bentley, J., Bickersteth, S., Brown, K., Burke, J., Campbell, H., Chen, K., Crowley, E., Crute, I., Dobbelaere, D., Edwards-Jones, G., Funes-Monzote, F., Godfray, H. C. J., Griffon, M., … Pilgrim, S. (2010). The top 100 questions of importance to the future of global agriculture. *International Journal of Agricultural Sustainability*, *8*(4), 219–236.

Rebetzke, G. J., Jimenez-Berni, J., Fischer, R. A., Deery, D. M., & Smith, D. J. (2019). High-throughput phenotyping to enhance the use of crop genetic resources. *Plant Science*, *282*, 40–48.

Redfern, S. K., Azzu, N., & Binamira, J. S. (2012). Rice in Southeast Asia: Facing risks and vulnerabilities to respond to climate change. *Build Resilience Adapt Climate Change Agri Sector*, *23*(295), 1–14.

Renkow, M., & Byerlee, D. (2010). The impacts of CGIAR research: A review of recent evidence. *Food Policy*, *35*(5), 391–402.

Rezvi, H. U. A., Tahjib-Ul-Arif, M., Azim, M. A., Tumpa, T. A., Tipu, M. M. H., Najnine, F., Dawood, M. F. A., Skalicky, M., & Brestič, M. (2022). Rice and food security: Climate change implications and the future prospects for nutritional security. *Food and Energy Security*, *12*(1), e430.

Rowe, G., & Wright, G. (1999). The Delphi technique as a forecasting tool: Issues and analysis. *International Journal of Forecasting*, *15*(4), 353–375.

Rowe, G., & Wright, G. (2001). Expert opinions in forecasting: The role of the Delphi technique. In J. S. Armstrong (Ed.), *Principles of forecasting: A handbook for researchers and practitioners* (pp. 125–144). Springer.

Sachs, J., Remans, R., Smukler, S., Winowiecki, L., Andelman, S. J., Cassman, K. G., Castle, D., DeFries, R., Denning, G., Fanzo, J., Jackson, L. E., Leemans, R., Lehmann, J., Milder, J. C., Naeem, S., Nziguheba, G., Palm, C. A., Pingali, P. L., Reganold, J. P., … & Sanchez, P. A. (2010). Monitoring the world’s agriculture. *Nature*, *466*(7306), 558–560.

Samal, P., Babu, S. C., Mondal, B., & Mishra, S. N. (2022). The global rice agriculture towards 2050: An inter-continental perspective. *Outlook on Agriculture*, *51*(2), 164–172.

Sander, B. O., Wassmann, R., Palao, L. K., & Nelson, A. (2017). Climate-based suitability assessment for alternate wetting and drying water management in the Philippines: A novel approach for mapping methane mitigation potential in rice production. *Carbon Management*, *8*(4), 331–342.

Sasaki, T., Matsumoto, T., Yamamoto, K., Sakata, K., Baba, T., Katayose, Y., Wu, J., Niimura, Y., Cheng, Z., Nagamura, Y., Antonio, B. A., Kanamori, H., Hosokawa, S., Masukawa, M., Arikawa, K., Chiden, Y., Hayashi, M., Okamoto, M., Ando, T., … Gojobori, T. (2002). The genome sequence and structure of rice chromosome 1. *Nature*, *420*(6913), 312–316.

Seck, P. A., Diagne, A., Mohanty, S., & Wopereis, M. C. S. (2012). Crops that feed the world 7: Rice. *Food Security*, *4*(1), 7–24.

Singh, K., McClean, C. J., Büker, P., Hartley, S. E., & Hill, J. K. (2017). Mapping regional risks from climate change for rainfed rice cultivation in India. *Agricultural Systems*, *156*, 76–84.

Sithirith, M. (2021). Downstream state and water security in the Mekong region: A case of Cambodia between too much and too little water. *Water*, *13*(6), 802.

Song, P., Wang, J., Guo, X., Yang, W., & Zhao, C. (2021). High-throughput phenotyping: Breaking through the bottleneck in future crop breeding. *The Crop Journal*, *9*(3), 633–645.

Sterner, T., Barbier, E. B., Bateman, I., van den Bijgaart, I., Crépin, A.-S., Edenhofer, O., Fischer, C., Habla, W., Hassler, J., Johansson-Stenman, O., Lange, A., Polasky, S., Rockström, J., Smith, H. G., Steffen, W., Wagner, G., Wilen, J. E., Alpízar, F., Azar, C., … & Robinson, A. (2019). Policy design for the Anthropocene. *Nature Sustainability*, *2*(1), 14–21.

Stevenson, J. R., Villoria, N., Byerlee, D., Kelley, T., & Maredia, M. (2013). Green revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(21), 8363–8368.

Sutherland, W. J., Fleishman, E., Clout, M., Gibbons, D. W., Lickorish, F., Peck, L. S., Pretty, J., Spalding, M., & Ockendon, N. (2019). Ten years on: A review of the first global conservation horizon scan. *Trends in Ecology & Evolution*, *34*(2), 139–153.

Sweeney, M., & McCouch, S. (2007). The complex history of the domestication of rice. *Annals of Botany*, *100*(5), 951–957.

Thu, H. N., & Wehn, U. (2016). Data sharing in international transboundary contexts: The Vietnamese perspective on data sharing in the lower Mekong basin. *Journal of Hydrology*, *536*, 351–364.

Timmer, C. P., Block, S., & Dawe, D. (2010) Long-run dynamics of rice consumption, 1960–2050. In S. Pandey, D. Byerlee, D. Dawe, A. Dobermann, S. Mohanty, S. Rozelle, & B. Hardy (Eds.), *Rice in the global economy: Strategic research and policy issues for food security* (pp. 139–174). International Rice Research Institute.

Tran, T. A., & Tortajada, C. (2022). Responding to transboundary water challenges in the Vietnamese Mekong Delta: In search of institutional fit. *Environmental Policy and Governance*, *32*(4), 331–347.

Tubiello, F. N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., & Smith, P. (2013). The FAOSTAT database of greenhouse gas emissions from agriculture. *Environmental Research Letters*, *8*(1), 015009.

van Oort, P. A. J., Saito, K., Tanaka, A., Amovin-Assagba, E., Van Bussel, L. G. J., van Wart, J., de Groot, H., van Ittersum, M. K., Cassman, K. G., & Wopereis, M. C. S. (2015). Assessment of rice self-sufficiency in 2025 in eight African countries. *Global Food Security*, *5*, 39–49.

van Rij, V. (2010). Joint horizon scanning: Identifying common strategic choices and questions for knowledge. *Science & Public Policy*, *37*(1), 7–18.

Waha, K., Dietrich, J. P., Portmann, F. T., Siebert, S., Thornton, P. K., Bondeau, A., & Herrero, M. (2020). Multiple cropping systems of the world and the potential for increasing cropping intensity. *Global Environmental Change: Human and Policy Dimensions*, *64*, 102131.

Wassmann, R., Jagadish, S. V. K., Heuer, S., Ismail, A., Redona, E., Serraj, R., Singh, R. K., Howell, G., Pathak, H., & Sumfleth, K. (2009). Chapter 2 climate change affecting rice production: The physiological and agronomic basis for possible adaptation strategies. *Advances in Agronomy*, *101*, 59–122.

Willocquet, L., Elazegui, F. A., Castilla, N., Fernandez, L., Fischer, K. S., Peng, S., Teng, P. S., Srivastava, R. K., Singh, H. M., Zhu, D., & Savary, S. (2004).

Research priorities for rice pest management in tropical Asia: A simulation analysis of yield losses and management efficiencies. *Phytopathology*, *94*(7), 672–682.

Wintle, B. C., Kennicutt, M. C., II, & Sutherland, W. J. (2020). Scanning horizons in research, policy and practice. In W. J. Sutherland, P. N. M. Brotherton, Z. G. Davies, N. Ockendon, N. Pettorelli, & J. A. Vickery (Eds.), *Conservation research, policy and Practice* (pp. 29–47). Cambridge University Press.

Yang, W., Feng, H., Zhang, X., Zhang, J., Doonan, J. H., Batchelor, W. D., Xiong, L., & Yan, J. (2020). Crop phenomics and high-throughput phenotyping: Past decades, current challenges, and future perspectives. *Molecular Plant*, *13*, 187–214.

Yang, X., Chen, F., Lin, X., Liu, Z., Zhang, H., Zhao, J., Li, K., Ye, Q., Li, Y., Lv, S., Yang, P., Wu, W., Li, Z., Lal, R., & Tang, H. (2015). Potential benefits of climate change for crop productivity in China. *Agricultural and Forest Meteorology*, *208*, 76–84.

Yuan, S., Linquist, B. A., Wilson, L. T., Cassman, K. G., Stuart, A. M., Pede, V., Miro, B., Saito, K., Agustiani, N., Aristya, V. E., Krisnadi, L. Y., Zanon, A. J., Heinemann, A. B., Carracelas, G., Subash, N., Brahmanand, P. S., Li, T., Peng, S., & Grassini, P.… (2021). Sustainable intensification for a larger global rice bowl. *Nature Communications*, *12*(1), 7163.

Zeigler, R. S., & Barclay, A. (2008). The relevance of rice. *Rice*, *1*, 3–10. https://doi.org/10.1007/s12284-008-9001-z