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To cite this article: Cynthia Rosenzweig *et al* 2026 *Environ. Res.: Food Syst.* **3** 035012

ENVIRONMENTAL RESEARCH
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RECEIVED
20 January 2026

REVISED
12 June 2026

ACCEPTED FOR PUBLICATION
17 June 2026

PUBLISHED
9 July 2026

PAPER

Modeling mitigation and adaptation co-benefits in rice systems in Bangladesh

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Keywords: climate change, agriculture, modeling, mitigation, adaptation, rice, Bangladesh

Supplementary material for this article is available online

Abstract

Climate change threatens rice yields and global food security, while conventional flooded rice remains a major source of methane emissions. Management options that enhance both mitigation and adaptation are therefore essential. We evaluate water-saving and low-emission rice management practices, alternate wetting and drying (AWD) and system of rice intensification (SRI), compared with continuous flooding across three districts in Bangladesh using an integrated climate–crop–economic modeling framework. The analysis links climate, crop, methane, water-use, and farm economic outcomes and assesses impacts across district and farm-size strata to capture spatial and socioeconomic heterogeneity. Under warmer futures, with each management system evaluated relative to its own current-climate baseline, farm net returns vary across strata, with modest gains of up to 5% in some regions but declines of up to 10% in most areas, while methane emissions increase by 12%–55%. The modeled adoption of SRI-AWD, relative to continuous conventional flooding under both current and future climate conditions, reduces methane emissions by 35% on average while improving farm income and water-use efficiency, although outcomes vary across farm populations. These results show that SRI-AWD can reduce economic losses and emissions relative to conventional management under both current and future changing climate conditions, while highlighting that scaling potential depends on where and for whom benefits occur across heterogeneous rice-farming systems.

1. Introduction

Agricultural production is both a major source of greenhouse gas (GHG) emissions and highly vulnerable to climate change, including shifting conditions and extreme events (Tubiello *et al* 2021, Jägermeyr *et al* 2021). These challenges are particularly important in rice systems, which provide a staple food for over 3 billion people globally while accounting for 10% of agricultural GHG emissions. Thus, there is an urgent need to identify rice management interventions that deliver benefits to farmers, enhance resilience to climate change, and contribute to mitigation efforts. Assessing such interventions requires explicit *ex-ante* characterization of their biophysical and socioeconomic co-benefits and trade-offs (Verspecht *et al* 2012, Mbow *et al* 2019, Antle and Valdivia 2021a). Such assessments can generate the evidence-based information needed to support decision-making, guide investments towards promising options, and promote widespread adoption of practices that support sustainable and climate-resilient rice systems.

This study aims to assess the biophysical and socioeconomic adaptation and mitigation co-benefits and trade-offs of the system of rice intensification (SRI) in rice cropping systems on both small and large farms across three representative districts in the North, East, and Southwest of Bangladesh during the Boro season (December–April). SRI is based on key agronomic management principles such as a focus on whole plant and root development and practices including alternate wetting and drying (AWD) water management, earlier seedling transplanting or direct seeding, and reduced plant density and/or wider spacing (Thakur *et al* 2010, 2016, LaHue *et al* 2016, Jat *et al* 2023). SRI has been reported to increase yields and reduce methane under certain local or regional growing conditions, and may also reduce sensitivity to altered hydro-climate conditions (Thakur *et al* 2016). Furthermore, complex interactions between these management principles may produce productivity gains over and above any singular principle (Gathorne-Hardy *et al* 2016, Thakur *et al* 2016, Uphoff 2023).

These possible benefits have led over ten countries to officially incorporate SRI (or some subset of SRI management principles and practices) into their national adaptation plans and nationally determined contributions (NDCs) for emissions reductions under the Paris Climate Agreement. In addition, another 40 countries have drafted plans to include SRI in their updated post-2025 NDCs, suggesting a growing recognition of it as a sustainable strategy for climate adaptation and mitigation (Government of Bangladesh 2022, SRI-2030 2023, 2025).

One element of SRI is AWD, which has been actively promoted in Bangladesh as a water-saving irrigation practice with the government pledging to scale up its adoption to help meet national mitigation and adaptation targets included in their NDCs (Dittmer *et al* 2024, IRRI 2024). However, a recent meta-analysis indicates that while AWD improves water use efficiency, it is generally accompanied by a small yield penalty for most farmers (Zhang *et al* 2023). Beyond yield effects, implementing AWD may present other challenges, including access to and control of water resources as well as increased labor costs and higher vulnerabilities for laborers such as increased exposure to heat stress, seasonal wage uncertainty, and disproportionate impacts on gender roles in rice cultivation (Sabarmatee *et al* 2025).

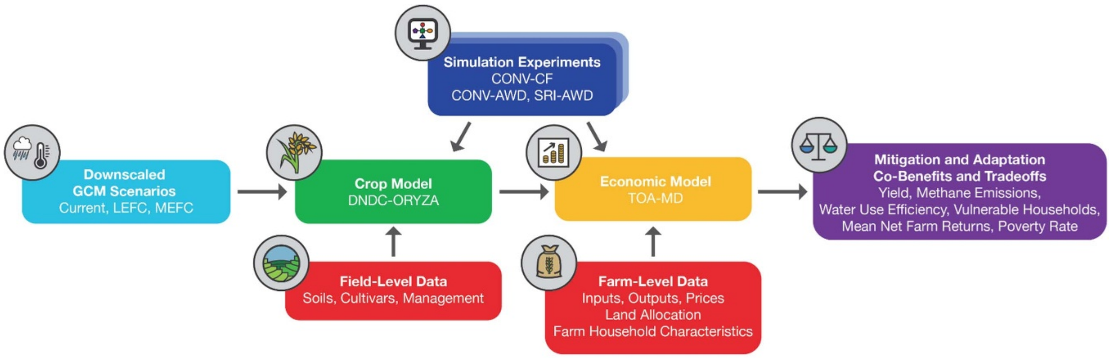
SRI, which includes AWD among other principles and practices, faces similar challenges (Gathorne-Hardy *et al* 2016). Nevertheless, previous studies have demonstrated that SRI can deliver higher yields and productivity benefits compared to AWD alone, while simultaneously reducing methane emissions (Thakur *et al* 2016, Barrett *et al* 2022, Uphoff 2023, Li *et al* 2024). Yield gains may provide an important incentive for farmers to adopt SRI, although realized adoption also depends on access to irrigation water supply, labor requirements, training, extension support, and other local constraints.

This study provides a forward-looking integrated assessment by linking climate, crop–soil–GHG, and economic modeling to evaluate how alternative rice management systems affect farm income, poverty, water-use efficiency (WUE), and methane emissions under current and future climate conditions. The objective is not to re-estimate historical adoption, but to assess how the distribution of economic and environmental co-benefits varies across districts, farm types, and climate futures. This mitigation-adaptation co-benefits (MAC-B) framework builds on the Agricultural Model Intercomparison and Improvement Project (AgMIP) regional integrated assessment (RIA) protocols (Rosenzweig *et al* 2013, Antle *et al* 2015). It extends their application to rice systems, complementing related applications in the Red River Delta, Vietnam (Li *et al* 2024), and crop-livestock systems in Zimbabwe (Homann-kee Tui *et al* 2021, 2023). The results can support national-scale planning, including NDCs and National Adaptation Plans (NAPs), as well as subnational decisions about where mitigation and adaptation strategies may generate combined benefits.

2. Methods

2.1. AgMIP MAC-B modeling approach

We applied an integrated assessment framework to evaluate MAC-B and tradeoffs in Bangladesh rice systems (figure 1). This framework links climate scenarios with DNDC-ORYZA, a process-based rice crop–soil model used to simulate yields, water use, soil carbon, and GHG emissions (Li *et al* 2017), and TOA-MD, a multi-dimensional impact assessment model used to assess net returns, poverty, vulnerability,



Climate Scenarios	
LEFC	Less Extreme Future Climate
MEFC	More Extreme Future Climate

Models	
DNDC-ORYZA	DeNitrification-DeComposition
TOA-MD	Tradeoff Analysis Model for Multi-Dimensional Impact Assessment

Management	
CONV	Conventional management
CF	Continuous flood
AWD	Alternate wetting and drying
SRI	System of Rice Intensification

Figure 1. Integrated assessment framework for mitigation–adaptation co-benefits and trade-offs in Bangladesh rice systems. The MAC-B framework links climate scenarios, DNDC-ORYZA crop–soil simulations, and TOA-MD impact assessment to evaluate rice yield, greenhouse gas emissions, water use, net returns, poverty, vulnerability, and adoption potential.

adoption potential, and environmental outcomes across heterogeneous farm populations (Antle and Valdivia 2021b).

2.2. Stakeholder engagement

Stakeholder input was used to ensure that the modeled practices reflected research and policy priorities in Bangladesh. Engagement included discussions with national research institutions, government agencies, NGOs, and CGIAR partners, including the Bangladesh Agricultural Research Institute, Bangladesh Rice Research Institute, BRAC Bangladesh, the Ministry of Public Administration, the Center for Environmental and Geographic Information Services, the International Rice Research Institute, and the International Maize and Wheat Improvement Center (CIMMYT). These discussions helped identify AWD and SRI as relevant management options for assessing MAC-B and trade-offs, and informed interpretation of results related to water management, farmer feasibility, and policy relevance.

2.3. Regional Integrated Assessments

The RIA approach uses a whole-farm characterization of agricultural households in a region. This requires information on household and farm-level production activities, including crop and non-crop enterprises, production costs, revenues, and non-farm income where available. Data description and sources are listed in table S1 in supplementary material. Plot-based crop simulations are linked to distributions of climate, soils, and crop management for a population of farms in a region (e.g., the Bangladesh districts shown in figure 2). The regions provide a representative sample of farms in North, East, and Southwest Bangladesh with complete agronomic and economic data for the three management systems. This enables the estimation of distributions of farm net returns and the parameters for the TOA-MD model. The utilized models and their outputs are shown in table S2 in the supplementary material, as are the analyses these outputs enable.

3. Climate data for soil–crop modeling

The crop–soil simulations required climate information at the daily timestep for 30 continuous years, including temperature (maximum and minimum), precipitation, solar radiation, along with relative humidity and wind speed. We leveraged daily station data for these quantities for 1980–2010 from the Bangladesh Meteorological Department using one station site for each of the eight focus districts. Missing data was gap-filled using AgMIP methodology (Ruane *et al* 2015). In brief, these district station data were used to further bias-correct the spatially-explicit 0.25° latitude × longitude AgMERRA climate dataset (Ruane *et al* 2015) to produce a complete daily, 30-year dataset.

This new data was then used to fill gaps in the district station data record, and the district-wise biases identified were further removed from other AgMERRA 1980–2010 timeseries corresponding to the surveyed farm sites, using the gridcell closest to the site location within the respective district. These

Figure 2. Study regions in the North, East, and Southwest of Bangladesh.

approaches have been widely applied to a range of climate-crop model applications. Future mean climate anomalies were evaluated by taking the difference (i.e., delta) between monthly averages for the model-simulated baseline (1980–2010) and future (2040–2070) shared socioeconomic pathway (SSP) 2-4.5 climate scenarios.

These month-wise anomalies were then applied to each day of the corresponding month in the above-described site-specific baseline climate data. These methods also account for changes in variability resulting from future climate changes by adjusting the baseline climate series by monthly changes in the standard deviation of maximum temperature, the standard deviation of minimum temperature, and the number of rainy days (precipitation >0.1 mm) (Ruane *et al* 2015).

Future climate scenarios were constructed using downscaled outputs from the Sixth Coupled Model Intercomparison Project (CMIP6) (Eyring *et al* 2016) applying the AgMIP methodology (Ruane and McDermid 2017, Ruane *et al* 2017). Specifically, monthly mean anomalies and changes to daily variation in the relevant climate variables from two global climate models (GCMs) were obtained from the NASA NEX GDDP bias-corrected downscaled climate model datasets (Thrasher *et al* 2022). GCMs designated a 'less extreme future climate' (LEFC; MIROC6 climate model (Tatebe *et al* 2019, Ando *et al* 2021)) and a 'more extreme future climate' (MEFC; KACE-1-0-G, NIMS-KMA climate model (Sung *et al* 2021)) were selected from a set of 24 GCMs.

The LEFC and MEFC scenarios were selected from 24 downscaled GCMs to represent lower- and higher-warming responses for the study region, as shown in figure 3. We focused on temperature responses as we expected these to have more demonstrable impacts than the variation in precipitation for irrigated rice systems. Nevertheless, we acknowledge that this approach does not characterize the full distribution of modeled climate change uncertainty as present in CMIP6.

Anomalies between the future climate projections for SSP2-4.5 (medium mitigation ambition climate scenario) for 30 years centered on 2050 and baseline simulated climate (1980–2010) were then applied to the baseline, bias-corrected AgMERRA datasets at each site. Atmospheric CO_2 concentrations (365.5ppm for baseline weather and 506.9 ppm for the 2050s) were utilized for the middle-year of the 30-year baseline and future climate simulations for the respective crop–soil model simulations.

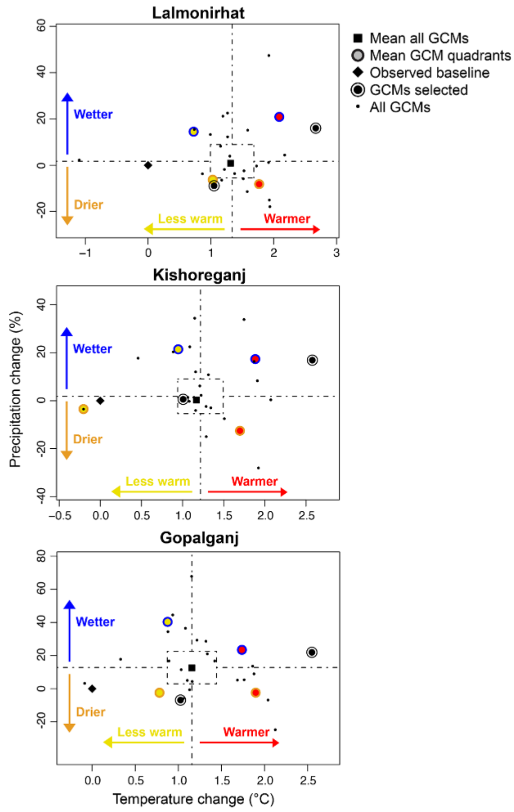


Figure 3. Distribution of mean Boro season temperature and precipitation anomalies for 24 downscaled global climate model (GCM) projections representing SSP2-4.5, centered on 2050. The median is identified by dashed lines, defined by ± one standard deviation of change on each axis. The black square represents the mean anomaly across all GCMs. The colored circles with contrasting borders represent the mean of each quadrant, which delineates warmer/less warm and drier/wetter anomalies, relative to the distribution of climate model anomalies. The black diamond represents baseline (baseline) climate conditions, situated at 0 temperature and precipitation change. The black circles with black borders represent the site-specific anomalies of the selected models, 'LEFC' (MIROC6) and 'MEFC' (KACE-1-0-G).

All conclusions are limited to the SSP2-4.5 scenario and cannot be extrapolated to other emission scenarios. A range of CMIP6 emissions scenarios exist (Riahi *et al* 2017) with associated levels of CO_2 that affect crop growth and water use. However, there is uncertainty in the magnitude of the CO_2 fertilization effects (Toreti *et al* 2020). Future work will utilize AgMIP methods, protocols, and modeling frameworks to conduct tests across the uncertainty space of climate scenarios and factors shaping rice productivity, including CO_2, temperature, water, and nutrient management (McDermid *et al* 2015).

4. Soil–crop modeling

The DNDC-ORYZA model was used to simulate rice growth, grain yield, soil carbon dynamics, and GHG emissions. The model couples DNDC soil biogeochemical processes with the ORYZA rice crop model, enabling rice crop development and soil processes to be represented jointly (Li *et al* 2017). By incorporating rice physiological responses, DNDC-ORYZA supports analysis of interactions among genotype, environment, and management (GxExM) in rice production systems.

Crop model simulations require daily weather data, soil characteristics, crop information, and land-management inputs. The core weather variables include precipitation, maximum and minimum temperature, and solar radiation, with relative humidity and wind speed included when available to improve model performance. Management inputs include planting and harvest dates, fertilizer application, irrigation management, and observed grain yield; the latter was used for crop model calibration and validation of simulated rice production.

Field-level soil properties were derived from SoilGrids 2.0 (Poggio *et al* 2021) using the geographic coordinates reported in the survey datasets. Extracted variables included soil texture, organic carbon, nitrogen, and pH. Soil organic carbon and nitrogen values were then adjusted using available soil-profile information. Rice management information was extracted from the survey, including the geo-coordinates and administrative location; rice cultivar; sowing, transplanting, and harvest dates; fertilizer type and amount; general water management description; and grain yield. The cost of cultivation data available in the dataset was used in the economic model.

GHG data from rice fields in Bangladesh were unavailable so GHG calibration was done using expert judgment based on similar MAC-B studies in Vietnam with DNDC-ORYZA. DNDC has been combined with the crop growth and physiological processes of ORYZA to create a DNDC-ORYZA version, where the soil biochemical processes are from the original DNDC whose capability of estimating GHG emissions in many environments has been proved in many studies (Yin *et al* 2020, Hwang *et al* 2021, Li *et al* 2024).

A data quality check was conducted to identify the subset of survey observations suitable for DNDC-ORYZA calibration and validation. The full dataset included survey data from 8,981 farmers' fields, but crop-model calibration required complete and internally consistent information on cultivar, planting and harvest dates, fertilizer management, water management, soil characteristics, location, and grain yield. Observations with incomplete crop-model inputs were excluded from the calibration dataset, leaving 4427 observations with sufficient information for crop modeling. A further consistency check was then applied to remove observations with implausible combinations of reported grain yield and fertilizer management.

The final calibration and validation dataset included 1458 plots for the two dominant cultivars, BRRI dhan28 and BRRI dhan29. This dataset was split into calibration and validation subsets, with approximately two-thirds of observations used for calibration and one-third for validation. The calibration subsets for BRRI dhan28 and BRRI dhan29 included 813 and 160 sites, respectively, while the validation subsets included 404 and 81 sites. The retained calibration and validation dataset covered the target regions and management systems, providing sufficient variation in soils, management, and yields to estimate cultivar-specific parameters. Model performance was then evaluated against independent validation observations using regression statistics and normalized RMSE, as reported in Fig. S1 and table S3.

Using this calibrated modeling framework, we tested three rice management systems under Baseline and future climates: conventional with continuous flooding (CONV-CF); Conventional with AWD (CONV-AWD); and SRI with AWD (SRI-AWD) (figure 4). CONV-CF maintains continuous flood from transplanting (or one week after direct-seeding) to one week before physical maturity, while AWD alone was implemented in cycles of five 'wetting days' and seven 'drying days' in the period from transplanting to one week before crop maturity. During wet periods, the total of irrigation plus rainfall was set to maintain at least 1 cm standing surface water. This represents SRI and AWD-based systems that not only can enhance yield potential but also reduce environmental impact with less variability (see table S4).

5. Socioeconomic modeling

The tradeoff analysis for multi-dimensional impact assessment model (TOA-MD) (Antle and Valdivia 2021b) was used to evaluate potential climate change impacts on socio-economic and environmental outcomes, as well as the benefits of adopting AWD technology and SRI management practices, following the methods described in the AgMIP RIA Handbook (Antle *et al* 2015, Rosenzweig *et al* 2016). These outcomes provide the basis for the climate change impact, vulnerability, and adaptation and mitigation analyses.

TOA-MD. TOA-MD is a parsimonious model for technology adoption, impact assessment, and ecosystem services analysis. It integrates outputs from climate, crop, livestock, and economic analyses to evaluate relationships among economic indicators, such as farm income and poverty rates, environmental indicators, such as GHG emissions, and social indicators, such as food security and gender. The fundamental parameters of the model are population statistics, including means, variances, and correlations of economic variables and associated outcome indicators. These parameters are estimated for current systems and then used to evaluate how alternative systems or climate conditions affect the distribution of outcomes across the farm population.

Data. Data to characterize whole-farm production activities were extracted from the BRAC/Monash household surveys conducted between 2014 and 2016 as part of a randomized SRI intervention study (Barrett *et al* 2022). Although the original survey covered a larger set of districts, this analysis used observations from the three districts selected for the MAC-B Bangladesh assessment: Lalmonirhat, Gopalganj, and Kishoreganj. After removing observations with incomplete or inconsistent information on production, costs, prices, outputs, and whole-farm activities, the economic dataset used in this analysis

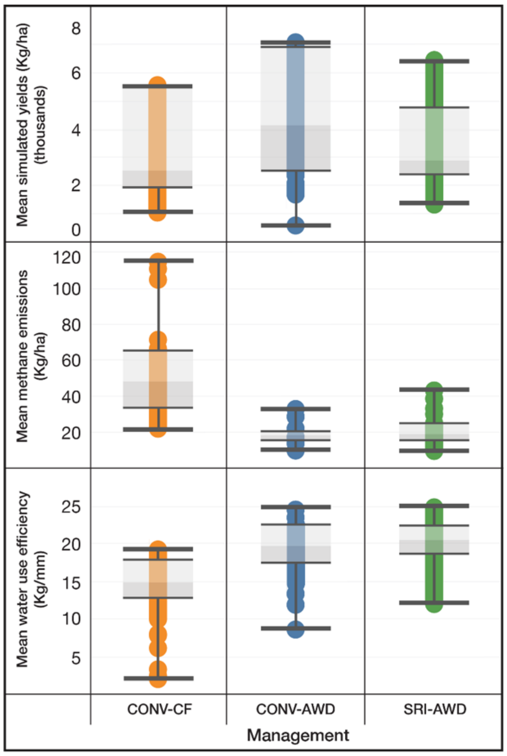


Figure 4. Baseline, historical climate distribution of simulated yields, CH4 emissions, and water use efficiency across sites and districts in the study regions for conventional (CONV) continuous flooding (CF), alternate wetting and drying (AWD), and Sustainable rice intensification (SRI).

included 601 farms under conventional flooding, 2,116 farms under AWD, and 472 farms under SRI-AWD.

Experimental design. The experimental design and repeated observations provided information on farms under conventional and alternative rice management practices, including farms transitioning from conventional practices to SRI-AWD. For TOA-MD, these data were organized into district-by-farm-size strata. Each stratum represents a population of heterogeneous farms, not a single representative farm. TOA-MD uses within-stratum distributions of net returns and related outcomes to estimate opportunity costs, adoption potential, vulnerability, and impacts.

Two reference comparisons were used in the socioeconomic modeling experiments. For the climate-impact analysis, each rice management system under future climate was compared with the same management system under baseline climate. For the adoption analysis, the AWD and SRI-AWD alternatives were compared with conventional CF under the same climate condition: baseline, LEFC, or MEFC. These comparisons are summarized in table S5.

Links to DNDC-ORYZA crop model and adoption analysis. Outputs from the DNDC-ORYZA crop simulations were used to estimate relative yield changes for the TOA-MD simulation experiments. Simulated GHG emissions, including CH_4, N_2O, and CO_2eq, were used to estimate how adoption of alternative rice management practices or climate change can generate MAC-B and trade-offs.

For the adoption analysis, TOA-MD follows a treatment-effects logic in which farms self-select between a base system, System 1, and an alternative system, System 2. Adoption is estimated by comparing the distribution of expected net returns under the two systems. These distributions are combined into an opportunity-cost distribution, also referred to as the marginal treatment effect. Farms for which the alternative system has higher expected net returns are treated as potential adopters, while farms for which the base system has higher expected net returns remain in the current system (Antle 2011). Thus, a higher average net return for SRI-AWD or CONV-AWD does not imply universal adoption, because some farms may still face lower expected returns under the alternative system due to heterogeneity in soils, climate exposure, management practices, costs, yields, and household characteristics.

The adoption estimates should therefore be interpreted as economically feasible adoption potential under the modeled conditions, not as a complete long-term behavioral prediction of realized adoption.

Social norms, risk preferences, credit constraints, land tenure, labor availability, collective water management, information access, and extension support can also affect whether households adopt and fully implement AWD or SRI-AWD. These factors are not represented as separate model inputs in this analysis. Rather, TOA-MD estimates the economic component of adoption and its associated socioeconomic and environmental impacts for a heterogeneous farm population.

The model then estimates differences in outcomes associated with adoption, including changes in farm net returns, poverty rates, and environmental outcomes. Changes in aggregate methane emissions depend on the proportion of farms that adopt the alternative management practice, such as SRI-AWD, and the proportion that remain under the base system, such as conventional CF.

Impacts of climate change. TOA-MD uses a similar distributional logic to simulate the impacts of climate change. In this case, vulnerability is defined as the percentage of households projected to lose income under a future climate relative to baseline climate conditions. The model also estimates the associated gains and losses for households that benefit from climate change and those that lose, enabling climate impacts to be characterized across the farm population rather than only through changes in average outcomes (Antle and Valdivia 2021b).

Economic and environmental indicators. In this study, economic and environmental indicators, including average farm net returns, poverty rates, vulnerability, adoption rates, and average GHG emissions, were calculated across relevant sub-populations: gainers and losers in the climate-impact analysis, and adopters and non-adopters in the adoption analysis. Poverty rates were estimated using the Foster–Greer–Thorbecke poverty measure with $\alpha = 0$, which corresponds to the headcount ratio, or the share of households with per-capita income below the poverty line (Foster *et al* 1984). We used the international extreme poverty line of US\$2.15 per person per day in 2017 purchasing power parity, equivalent to approximately BDT 165.55 per person per day in the study data.

The same poverty line was applied across baseline and future climate scenarios so that poverty changes reflect modeled changes in farm net returns and income under each climate-management scenario. These estimates should therefore be interpreted as relative changes in poverty associated with climate and management effects, not as forecasts of absolute poverty levels in 2050.

Caveats. This study focused on co-benefits and tradeoffs under current socioeconomic conditions, baseline climate, and selected future climate scenarios. Future socioeconomic conditions, including changes in prices, production costs, policies, and broader agricultural development pathways, were not included as separate scenarios, but could be incorporated in future analyses through AgMIP representative agricultural pathways (Valdivia *et al* 2021).

6. Results

6.1. Baseline distributions of cropping system variables

Baseline distributions of key cropping system variables in the three study regions of Bangladesh are shown in figure 4. The distributions of simulated yields show that both CONV-AWD and SRI-AWD management systems tend to produce higher average yields than CONV-CF across most regions and farm types. The results also show different degrees of variability across management systems. While CONV-AWD shows the highest mean yield, it also tends to have greater variability. SRI-AWD, on the other hand, shows lower mean yields compared to CONV-AWD with relatively lower variance, suggesting more consistent performance across sites.

In terms of methane emissions, both CONV-AWD and SRI-AWD consistently result in lower mean CH_4 emissions compared to CONV-CF. The distributions of emissions under these systems also exhibit tighter spreads and lower standard deviations, indicating more stable and predictable reductions in GHG emissions. These results suggest that SRI and AWD-based systems enhance yield potential and reduce environmental impact with less variability. Both CONV-AWD and SRI-AWD had higher mean water use efficiency than CONV-CF.

6.2. Future climate scenarios

The distributions of temperature and precipitation anomalies do not widely differ between districts and sites, in that most GCMs produce similar anomalies across the sites (figure 3). Precipitation changes

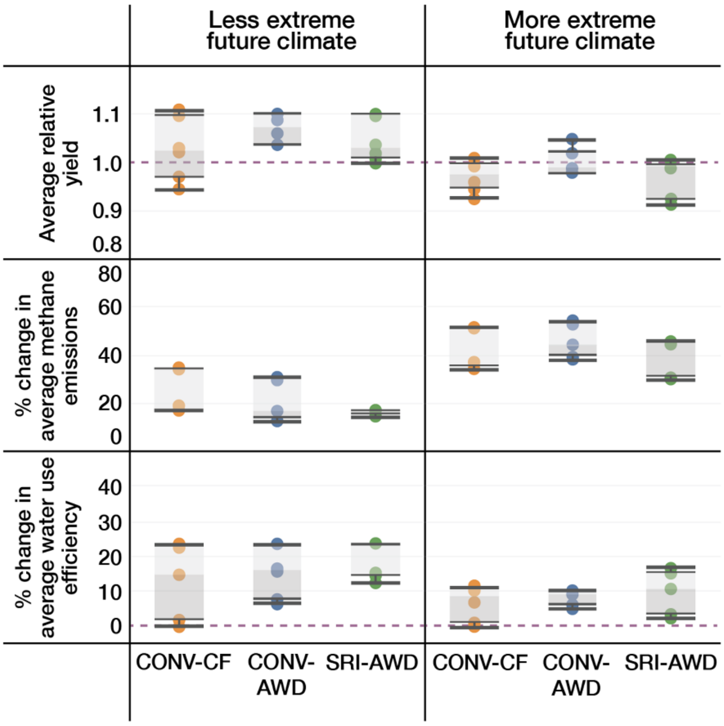


Figure 5. Climate impacts on biophysical outcomes under LEFC and MEFC across six strata: small and large farms in Lalmonirhat, Kishoreganj, and Gopalganj districts. Values show changes under each future climate relative to the same management system under baseline climate: CONV-CF future versus CONV-CF baseline, CONV-AWD future versus CONV-AWD baseline, and SRI-AWD future versus SRI-AWD baseline. Outcomes shown are relative yield, percentage change in methane emissions, and percentage change in water-use efficiency.

ranged mostly from −20% to +20% of the baseline, while temperature changes ranged as low as −1 °C from Baseline to 3 °C. We note that even under AWD conditions, rice production across these districts in Bangladesh is irrigated and yield sensitivity to precipitation is expected to be lower than its sensitivity to temperature. However, this reduced sensitivity to rainfall may not always be the case for methane emissions.

As temperature is the key climate variable to which rice systems respond, both for productivity and methane emissions, we select GCMs that represent the mean and maximum of the model distribution. This results in a LEFC to MEFC range from ∼1 °C to ∼3 °C, depending on the district. These two scenarios are used to examine sensitivity to contrasting climate realizations within SSP2-4.5 and are not intended to represent the full distribution of CMIP6 climate uncertainty.

6.3. Impact of climate change on conventional and SRI management systems

In this section, climate impacts are reported relative to the same management system under baseline climate. Therefore, future outcomes for CONV-CF, CONV-AWD, and SRI-AWD are each compared with their respective baseline-climate counterparts. These results show the effect of climate change within each management system, rather than the effect of switching management systems.

6.3.1. Biophysical

The LEFC and MEFC show different responses across some key biophysical outcomes relevant to mitigation and adaptation (figure 5).

Yield. Under the LEFC scenario, rice yields increase for all strata under CONV-AWD management systems, and for most strata under SRI (figure 5, top row). For CONV-CF, impacts vary across strata, with yield changes from −5% to +10%. Positive responses (i.e., yield increases) in most strata, including under CONV-CF management, likely reflect benefits from differing soil type or crop variety responses. Under MEFC, rice yields decrease across most strata and management systems, with higher temperatures likely driving these reductions compared to the less extreme LEFC scenario. In some strata with CONV -AWD, however, yield gains persist, possibly due to combination of the varieties, management and other favorable biophysical conditions that enhance resilience under more extreme climates. This

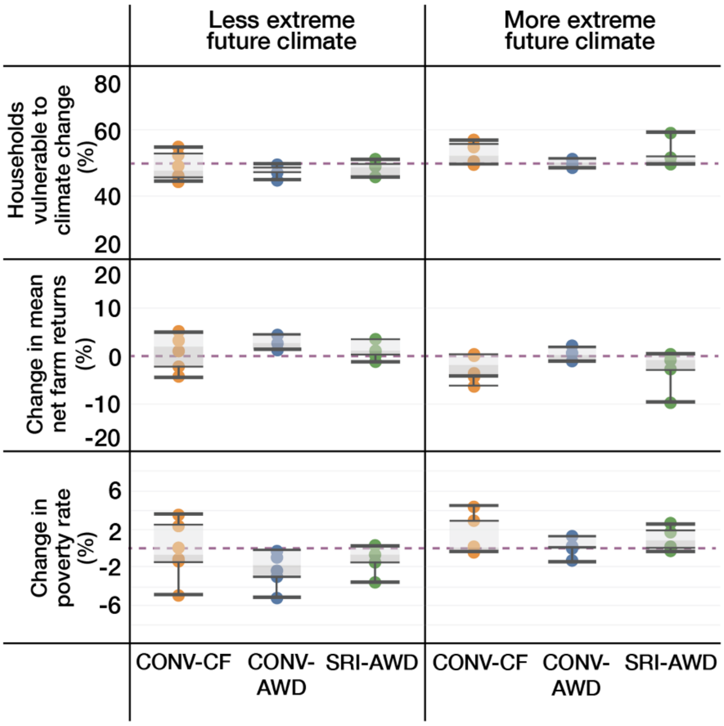


Figure 6. Climate impacts on socioeconomic outcomes under LEFC and MEFC across six strata: small and large farms in Lalmonirhat, Kishoreganj, and Gopalganj districts. Values are calculated by comparing each management system under future climate with the same management system under baseline climate. Outcomes shown are the proportion of households vulnerable to climate change, defined as the percentage of households projected to lose income under future climate relative to baseline climate; percentage change in mean farm net returns; and percentage change in poverty rate.

variability across strata in response to climate change, specifically to temperature changes, is consistent with previous studies (Hossain *et al* 2021).

Methane emissions. Climate change, under both LEFC and MEFC, is projected to increase methane emissions across all management systems. In the LEFC scenario, the range of percentage changes is similar for CONV-CF and CONV-AWD, while under MEFC, the magnitude of percentage changes is comparable across all three management systems (figure 5, middle row). However, because these results are expressed as relative (%) changes, they must be interpreted in the context of baseline emissions, which are substantially higher for CONV-CF than for AWD or SRI-AWD.

Consequently, even when relative increases appear similar, absolute CH_4 emissions can rise much more under CONV-CF. Variation in methane changes across strata is greater in CONV-CF and CONV-AWD than in SRI-AWD, likely reflecting the more consistent application of prescribed SRI management principles compared to the greater heterogeneity in conventional and AWD practices. MEFC methane emissions increase relative to LEFC indicating that higher temperatures strongly amplify methanogenesis across management systems. SRI-AWD continues to produce lower methane emissions across most strata under MEFC, although its distribution widens compared to LEFC.

Water use efficiency. Climate change increases WUE across all management systems under both LEFC and MEFC. In the LEFC scenario, median gains across strata are greater for AWD and SRI-AWD than for CONV-CF; however, variability across strata overlaps among the three management systems (figure 5, bottom row). Under MEFC, the changes in WUE are smaller for all managements compared to LEFC, but AWD and especially SRI-AWD maintain higher medians than CONV-CF. While percentage increases are similar across management systems within each climate scenario, higher baseline WUE in AWD-based systems means that absolute efficiency advantages increase under more extreme climatic conditions.

6.3.2. Socioeconomic

The LEFC and MEFC also show different responses across key socioeconomic outcomes (figure 6)

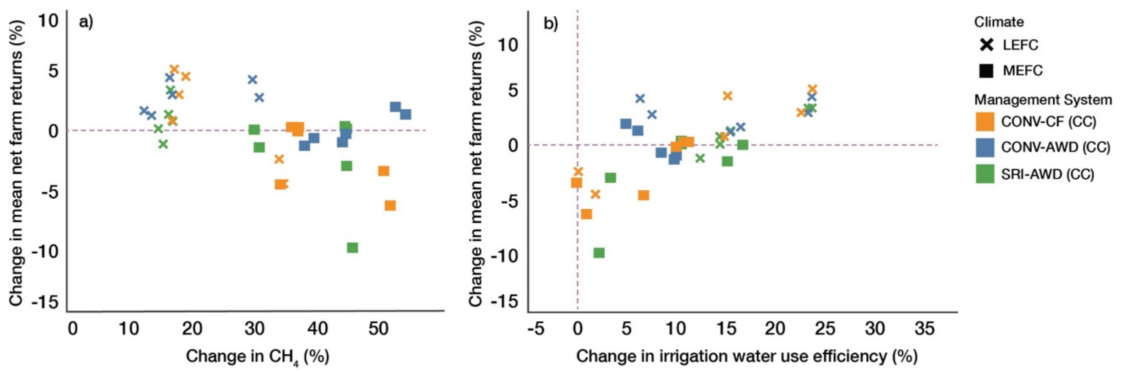


Figure 7. Trade-off and co-benefit analysis for climate impacts and adoption. Panels (a) and (b) show climate-impact results, where each future climate outcome is compared with the same management system under baseline climate. Panel (a) shows percentage change in mean farm net returns versus percentage change in methane emissions, and panel (b) shows percentage change in mean farm net returns versus percentage change in water-use efficiency. Points represent district-by-farm-size strata.

Vulnerable households. Vulnerability is reported as the proportion of households with lower simulated income under future climate relative to the same management system under baseline climate. Consistent with yield responses, vulnerability varies across climate scenarios and management systems. Under LEFC, the proportion of households vulnerable to climate change remains below 50% for most strata, particularly under CONV-AWD and SRI-AWD systems, whereas CONV-CF shows a wider distribution (44%–55%). Under MEFC, vulnerability increases in all cases, with most strata across all managements clustering at or above 50%. The range of vulnerability under CONV-CF and SRI-AWD is larger compared to CONV-AWD due to higher vulnerability values projected in selected strata under SRI-AWD (e.g., large farms in Kishoreganj, 59%), comparable to large conventional farms in Gopalganj (57%).

Mean farm net returns. The vulnerability results are also reflected by the proportional changes in mean farm net returns. Under LEFC, most strata across the three management systems show small increases in mean farm net returns, with some declines in specific cases (e.g., CONV-CF farms in Gopalganj and SRI-AWD farms in Kishoreganj). In contrast, the mean farm net returns under the MEFC decline across strata, with the largest losses occurring under CONV-CF and SRI-AWD, particularly for large farms in Kishoreganj.

Poverty rate. Changes in poverty outcomes depend on the effects of climate change on mean farm net returns and the associated changes in per-capita income. Under LEFC, poverty rates decrease slightly in most strata under CONV-AWD and SRI-AWD, while outcomes under CONV-CF are more variable, with some strata projecting increases. Under MEFC, poverty rates increase across most strata as a consequence of yield declines and associated income losses as shown above, with the largest increases occurring under CONV-CF. Some strata under CONV-AWD still show a small decline to no change in poverty rates, while SRI-AWD exhibits relatively larger poverty increases.

6.4. Co-benefits and trade-offs under future climate change

While figures 5 and 6 show univariate results across key outcomes, we seek to explicitly consider the trade-offs (or co-benefits) between key biophysical and socioeconomic dimensions of the rice management systems across strata and districts. Climate change drives methane emissions increases, between 30% and 50%+, across all rice systems (figure 7(a)): CONV with CF); SRI with AWD, and also CONV with AWD. For the MEFC, climate change reduces mean farm net returns more substantially, although in some strata mean farm net returns change slightly (i.e., the mean change for the strata lies close to the zero-change line). The LEFC appears to confer slight benefits to some districts and strata: net farm returns increase and methane increases as well; the methane increases are smaller (between 10% and 20% lower) than that of the MEFC case. Because methane emissions increase in all cases, there are only win-lose situations (gains in farm net returns and losses in methane emissions.

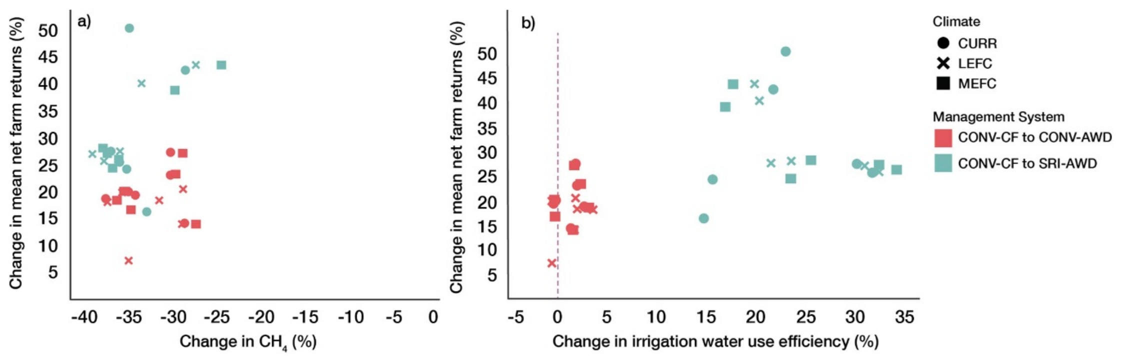


Figure 8. Trade-off and co-benefit analysis for climate impacts and adoption. Panels (a) and (b) show adoption results, where CONV-AWD and SRI-AWD are compared with CONV-CF under the same climate condition: baseline, LEFC, or MEFC. Panel (a) shows percentage change in mean farm net returns versus percentage change in methane emissions, and panel (b) shows percentage change in mean farm net returns versus percentage change in water-use efficiency. Points represent district-by-farm-size strata.

With respect to WUE, the trade-offs results are more mixed across future climate conditions. Nearly all strata and districts show WUE gains, although the magnitude of these gains varies significantly and these are higher under LEFC, per the results in figure 7(b) above. Contrary to the methane versus farm net returns case (figure 7(a)), the impact of climate change on WUE and farm net returns result in some win–win outcomes where both net returns and WUE increase (strata above the horizontal zero line). However, there are still some farmers that are likely to see their farm net returns decline which turns into a lose-win situation (strata under the horizontal zero line).

These results show the tradeoffs between mean farm net returns, methane emissions, and WUE and indicate that the differing levels of climate change generate both 'gainers' and 'losers' across the focus districts of this study.

6.5. Adoption of AWD and SRI under baseline and future climate change

In the adoption analysis, CONV-AWD and SRI-AWD are compared with CONV-CF under the same climate condition. Thus, baseline, LEFC, and MEFC adoption results each use a climate-specific CONV-CF reference system. The results indicate that shifting from CONV-CF to either CONV-AWD or SRI-AWD can generate win–win outcomes by delivering both MAC-B.

Across districts and strata, adoption of AWD-based systems increases mean farm net returns while simultaneously reducing methane emissions (figure 8(a)). Switching to SRI-AWD provides greater co-benefits than CONV-AWD, with farm net returns increasing by approximately 15%–50% and methane emissions declining by 25%–40%. By comparison, adoption of CONV-AWD achieves methane reductions of a similar magnitude but smaller improvements in farm net returns (5%–25%). Gains in WUE are also markedly greater under SRI-AWD, with increases well above 15% across districts and strata, compared to smaller (<5%) improvements under CONV-AWD (figure 8(b)).

Population mean outcomes include both adopters and non-adopters, and thus depend on projected adoption rates. For transitions from CONV-CF to SRI-AWD, adoption rates under current climate range between 49% and 66% across districts, approximately 49%–52% in Gopalganj, 55%–66% in Kishoreganj, and 59%–60% in Lalmonirhat. Under both LEFC and MEFC conditions, adoption rates range between 51% and 64%, with Lalmonirhat showing the highest potential adoption (61%–63%). In contrast, potential adoption rates of CONV-AWD range around 48%–51% across all districts, with little variation under future climate scenarios.

These adoption results should be interpreted within the simulation experimental design used in this study. For practical and policy purposes, the key comparisons evaluate the effect of switching management under the same climate condition; a separate comparison of future SRI-AWD against current-climate CONV-CF could provide additional insight into whether SRI-AWD fully offsets climate-related losses in absolute terms, but was outside the scope of the present analysis.

7. Mitigation and adaptation

Our analysis indicates that even under MEFC conditions, switching from CONV-CF to SRI-AWD provides substantial opportunities for joint mitigation and adaptation (figure 9). Average adoption rates for

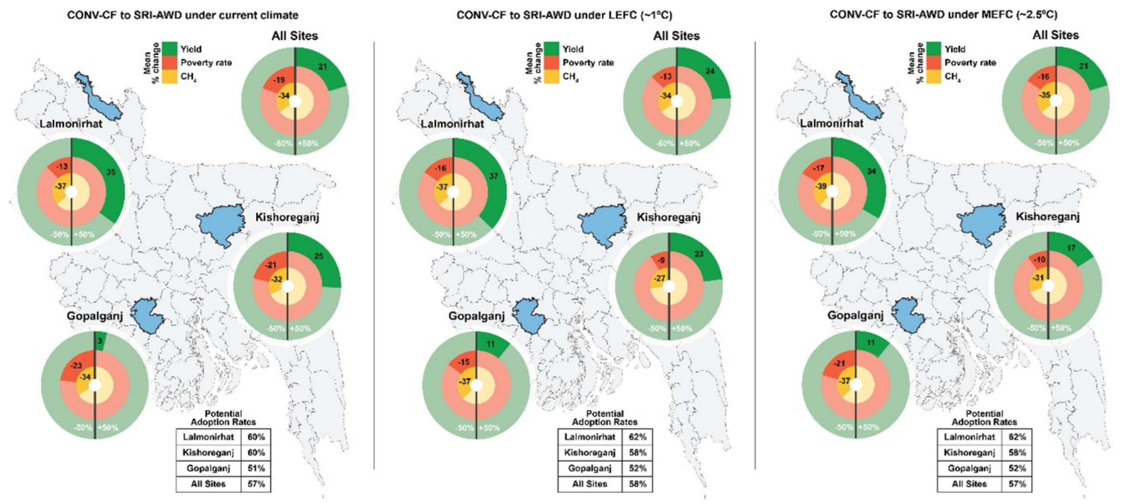


Figure 9. District-level adoption impacts from switching from conventional continuous flooding to SRI-AWD under baseline climate, LEFC, and MEFC. Within each climate condition, SRI-AWD is compared with CONV-CF under the same climate. Tables beneath the figures show projected district-wise adoption rates. District-level outcomes aggregate across small and large farm strata.

SRI-AWD are about 57% across sites, with the highest adoption in Lalmonirhat (62%), where yield gains are also largest. On average, SRI-AWD increases yield by 22% relative to conventional management with conventional flooding, reduces methane emissions by 34%, and lowers poverty by 15%.

Yield improvements vary, ranging from 34% in Lalmonirhat to 21%–25% in Kishoreganj and 3%–10% in Gopalganj. Despite relatively small yield gains, Gopalganj exhibits the largest poverty reduction (20%), reflecting the district's income distribution as per-capita income in this district is close to the poverty line. As a result, even small improvements in farm net returns are sufficient to lift a greater proportion of households out of poverty. Methane reductions are similar across sites, between 30% and 40%.

8. Conclusion

Within the SSP2-4.5 scenarios evaluated here, the warmer climate realization produced larger yield losses, lower farm income, higher poverty rates, and greater methane emissions than the less extreme climate realization. Warmer conditions lower yields and increase methane-to-yield ratios through soil–plant–microbial interactions that enhance carbon decomposition and root exudation, processes that occur even under AWD 'wetting' phases or SRI nutrient management (Li *et al* 2024). Elevated CO_2 also improves WUE across all systems, with AWD and SRI providing additional conservation benefits under both moderate and severe warming. These findings highlight the importance of management strategies that integrate mitigation and adaptation, as even improved practices will face increasing pressure under continued warming.

While our results indicate substantial co-benefits from SRI adoption compared with conventional rice management, several further sources of uncertainty should be considered. First, the future climate scenarios used herein, generated with delta downscaling methods, capture changes in mean climate conditions and some daily variability, but not changes in the frequency, duration, or severity of extreme events such as droughts, floods, cyclones, or compound shocks. As such, these methods preclude analyses of the impacts of extreme events, and how these are changing with time, on our rice simulations. Such shocks could reduce yields and farm income, push households near the poverty line into poverty, deepen poverty among already-poor households, and affect potential adoption of new management practices. These effects may also differ across households depending on household size, income sources, assets, labor availability, and recovery capacity. Future work should employ downscaling methods that explicitly resolve changing characteristics of extreme events and link them to longer-term poverty and adoption dynamics.

Second, farmer decisions to adopt new practices are based on expected outcomes, including expected production, output value, production costs, and risks. In this analysis, adoption potential is assessed by considering production outcomes jointly with prices and costs through their combined effects on expected net returns. Other incentives and expectations, such as carbon payments, subsidies, risk perceptions, expectations of poor rainfall or extreme weather, and uncertainty about future prices, may also influence adoption but were not explicitly represented in this analysis. Future adoption studies could build on this framework by incorporating these behavioral, policy, and risk-related factors more directly.

Third, our coupled rice-soil model was calibrated primarily for yields and methane, and analyses focused on relative changes to mitigate biases in absolute values. Other important outcomes, including nutrient use efficiency, nitrous oxide, and soil carbon dynamics, may vary more and introduce additional uncertainty in assessing mitigation potential (Kritee *et al* 2018, Cheng *et al* 2022). Our approach assessed SRI as a system, demonstrating that practicing multiple principles generates greater co-benefits (Uphoff 2023, Li *et al* 2024), but future studies should decompose the effects of individual practices and their interactions (Li *et al* 2024).

The development of the AgMIP Bangladesh MAC-B framework provides a novel approach to evaluating mitigation and adaptation in rice systems, which are critical for global food security and major contributors to GHG emissions. Its relevance was reinforced through stakeholder engagement, which highlighted the need for integrated assessments that can guide field experimentation, improved multi-model simulations, effective management practices, and enabling policies in Bangladesh. By systematically screening multiple interventions and their interactions across sites, this modeling approach captures implications for agricultural, socioeconomic and environmental outcomes. Empirical research can then validate promising options and strengthen the social and institutional mechanisms needed for wider adoption.

The SRI is now present in over 60 countries. Initiatives such as ClimateRice and SRI-2030 2023 aim to scale SRI globally by targeting 50–55 million hectares by 2030-2033, embedding it into national policies, and using its potential to lower GHG emissions while improving farmers livelihoods (SRI-2030 2023, 2025; ClimateRice 2025). Evidence from assessments such as this one is critical for informing urgent policy actions and investment strategies to accelerate climate-resilient, low-emission rice systems and to advance NDCs and NAPs under the UNFCCC Paris Agreement.

Acknowledgment

The authors acknowledge funding support from the Australian Centre for International Agricultural Research (ACIAR) via Grant CLIM/2021/109 to Columbia University and the Agricultural Model Intercomparison and Improvement Project (AgMIP). Timothy Krupnik and Tek Sapkota acknowledge the CGIAR initiatives: Climate Action Science Program supported through CGIAR Fund Donors and Transforming Agrifood Systems in South Asia (TAFSSA) and Research for Low Emissions Food Systems (MITIGATE+) through the funding contribution of CGIAR donors to the CGIAR Trust Fund. Sonali McDermid acknowledges support from the Carnegie Corporation (Grant #G-F-21-58368). Cynthia Rosenzweig acknowledges support from NASA (WBS 281945.02.80.01.13). The authors thank the Bangladesh Agricultural Research Institute (BARI), the Bangladesh Rice Research Institute (BRRI), the Bangladesh Meteorological Department (BMD), and the Bangladesh Ministry of Public Administration for their contributions to the research study. BMD is a government organization under the administrative control of the Ministry of Defense, Government of the People's Republic of Bangladesh. The authors thank Dr Christopher Barrett (Cornell University) and Dr Mohammad A. Malek (University of Tsukuba) for sharing the survey data collected by BRAC Bangladesh and Monash University. This study is part of the Mitigation and Adaptation Co-Benefits Flagship Project of the Global Research Alliance on Agricultural Greenhouse Gases (GRA). The authors also acknowledge contributions from Hom Gartaula and Jonas Jägermeyr.

Data availability statement

Restrictions apply. Data cannot be shared publicly via a URL/DOI.

The data that support the findings of this study are available from Barrett *et al* (2022) and from CIMMYT-Bangladesh (www.cimmyt.org/location/asia/bangladesh/) but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Barrett *et al* and CIMMYT.

SM1 Explanatory Notes: Methods available at https://doi.org/10.1088/2976-601X/ae7e8e/data1.

Conflict of interest

Several participating researchers and institutions involved in the study team and stakeholder engagement process have experience in the development, evaluation, or promotion of AWD and SRI. The authors acknowledge this potential source of bias. However, stakeholder engagement included a range of perspectives, with views both supportive and critical of these practices. Stakeholder input was used to identify policy-relevant management options and implementation considerations as part of the study. The authors declare no other competing interests.

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References

Ando T, Higuchi T, Hotta H and Iwakiri T 2021 Description of MIROC6 AGCM

Antle J M 2011 Parsimonious multi-dimensional impact assessment *Am. J. Agric. Econ.* **93** 1292–311

Antle J M *et al* 2015 *AgMIP's Transdisciplinary Agricultural Systems Approach to Regional Integrated Assessment of Climate Impacts, Vulnerability, and Adaptation* (Handbook of climate change and agroecosystems) pp 27–44

Antle J M and Valdivia R O 2021a Trade-off analysis of agri-food systems for sustainable research and development *Q Open* **1** qoaa005

Antle J M and Valdivia R O 2021b TOA-MD Trade-off analysis model for multi-dimensional impact assessment of agricultural systems. version 7 (available at: https://agsci.oregonstate.edu/tradeoff-analysis-project/)

Barrett C B, Islam A, Mohammad Malek A, Pakrashi D and Ruthbah U 2022 Experimental evidence on adoption and impact of the system of rice intensification *Am. J. Agric. Econ.* **104** 4–32

Bwire D, Saito H, Sidle R C and Nishiwaki J 2024 Water management and hydrological characteristics of paddy-rice fields under alternate wetting and drying irrigation practice as climate smart practice: a review *Agronomy* **14** 1421

Cheng Y, Elrys A S, Wang J, Xu C, Ni K, Zhang J, Wang S, Cai Z and Pacholski A 2022 Application of enhanced-efficiency nitrogen fertilizers reduces mineral nitrogen usage and emissions of both N2O and NH3 while sustaining yields in a wheat-rice rotation system *Agric. Ecosyst. Environ.* **324** 107720

Chidthaisong A, Cha-un N, Rossopa B, Buddaboon C, Kunuthai C, Sriphirom P, Towprayoon S, Tokida T, Padre A T and Minamikawa K 2018 Evaluating the effects of alternate wetting and drying (AWD) on methane and nitrous oxide emissions from a paddy field in Thailand *J. Soil Sci. Plant Nutr.* **64** 31–38

ClimateRice 2025 Climate Resilient Farming Systems Program Cornell University & CarbonFarm Technology (available at: www.climaterice.org/)

Dahlgreen J and Parr A 2024 Exploring the impact of alternate wetting and drying and the system of rice intensification on greenhouse gas emissions: a review of rice cultivation practices *Agronomy* **14** 378

Dittmer K M *et al* 2024 Agricultural sub-sectors in new and updated NDCs: 2020–2024

Enriquez Y, Yadav S, Evangelista G K, Villanueva D, Burac M A and Pede V 2021 Disentangling challenges to scaling alternate wetting and drying technology for rice cultivation: distilling lessons from 20 years of experience in the Philippines *Front. Sustain. Food Syst.* **5**

Eyring V, Bony S, Meehl G A, Senior C A, Stevens B, Stouffer R J and Taylor K E 2016 Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization *Geosci. Model Dev.* **9** 1937–58

Foster J, Greer J and Thorbecke E 1984 A class of decomposable poverty measures *Econometrica* **52** 761–6

Gathorne-Hardy A, Reddy D N, Venkatanarayana M and Harriss-white B 2016 System of rice intensification provides environmental and economic gains but at the expense of social sustainability—A multidisciplinary analysis in India *Agric. Syst.* **143** 159–68

Government of Bangladesh 2022 National adaptation plan of Bangladesh (available at: https://moef.portal.gov.bd/sites/default/files/files/moef.portal.gov.bd/npfblock/903c6d55_3fa3_4d24_a4e1_0611eaa3cb69/National%20Adaptation%20Plan%20of%20Bangladesh%20%282023-2050%29%20%281%29.pdf)

Graf S L and Oya C 2021 Is the system of rice intensification (SRI) pro poor? Labour, class and technological change in West Africa *Agric. Syst.* **193** 103229

Homann-kee Tui S, Descheemaeker K, Valdivia R O, Masikati P, Sisito G, Moyo E N, Crespo O, Ruane A C and Rosenzweig C 2021 Climate change impacts and adaptation for dryland farming systems in Zimbabwe: a stakeholder-driven integrated multi-model assessment *Clim. Change* **168** 10

Homann-kee Tui S, Valdivia R O, Descheemaeker K, Sisito G, Moyo E N and Mapanda F 2023 Balancing co-benefits and trade-offs between climate change mitigation and adaptation innovations under mixed crop-livestock systems in semi-arid Zimbabwe *CABI Agricul. Biosci.* **4** 24

Hossain M B, Roy D, Maniruzzaman M, Biswas J C, Naher U A, Haque M M and Kalra N 2021 response of crop water requirement and yield of irrigated rice to elevated temperature in Bangladesh *Int. J. Agron.* **2021** 1–11

Hwang W, Kim C, Cho K and Hyun S 2021 Characteristics of greenhouse gas emissions from rice paddy fields in South Korea under climate change scenario RCP-8.5 using the DNDC model *Pedosphere* **31** 332–41

IRRI 2024 GHG mitigation in rice: Bangladesh (South Asia) (available at: https://ghgmitigation.irri.org/focus-countries/bangladesh)

Jägermeyr J *et al* 2021 Climate impacts on global agriculture emerge earlier in new generation of climate and crop models *Nat. Food* **2** 873–85

Jat R A *et al* 2023 System-based integrated nutrient management improves productivity, profitability, energy use efficiency and soil quality in peanut-wheat cropping sequence in light black soils *Sustainability* **15** 1361

Kritee K *et al 2018* High nitrous oxide fluxes from rice indicate the need to manage water for both long- and short-term climate impacts *Proc. Natl Acad. Sci.* **115** 9720–5

Kumar N *et al* 2022 *et al* Challenges and opportunities in productivity and sustainability of rice cultivation system: a critical review in Indian perspective *Cereal Res. Commun.* **50** 573–601

LaHue G T, Chaney R L, Adviento-borbe M A and Linquist B A 2016 Alternate wetting and drying in high yielding direct-seeded rice systems accomplishes multiple environmental and agronomic objectives *Agric. Ecosyst. Environ.* **229** 30–39

Li T, Angeles O, Marcaida M, Manalo E, Manalili M P, Radanielson A and Mohanty S 2017 *et al* From ORYZA2000 to ORYZA (v3): an improved simulation model for rice in drought and nitrogen-deficient environments *Agric. For. Meteorol.* **237–238** 246–56

Li T, McDermid S S, Valdivia R O and Sundaram P 2024 Climate change mitigation and adaptation for rice-based farming systems in the Red River Delta, Vietnam *CABI Agricul. Biosci.* **5** 109

Mbow C *et al* 2019 Food Security *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* ed P R Shukla *et al*

McDermid S P, Ruane A C, Rosenzweig C, Hudson N I, Morales M D, Agalawatte P and Zubair L 2015 The AgMIP coordinated climate-crop modeling project (C3MP): methods and protocols *HANDBOOK OF CLIMATE CHANGE AND AGROECOSYSTEMS: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 1* pp 191–220

Poggio L, De Sousa L M, Batjes N H, Heuvelink G, Kempen B, Ribeiro E and Rossiter D 2021 SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty *Soil* **7** 217–40

Riahi K *et al* 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68

Rosenzweig C *et al* 2013 The agricultural model intercomparison and improvement project (AgMIP): protocols and pilot studies *Agric. For. Meteorol.* **170** 166–82

Rosenzweig C, Antle J M, Ruane A C, Jones J W and Hatfield J 2016 Protocols for AgMIP regional integrated assessments, version 7.0 (available at: https://agmip.org/wp-content/uploads/2018/08/AgMIP-Protocols-for-Regional-Integrated-Assessment-v7-0-20180218-1-ilovepdf-compressed.pdf)

Ruane A C, Goldberg R and Chryssanthacopoulos J 2015 Climate forcing datasets for agricultural modeling: merged products for gap-filling and historical climate series estimation *Agric. For. Meteorol.* **200** 233–48

Ruane A *et al* 2017 An AgMIP framework for improved agricultural representation in integrated assessment models *Environ. Res. Lett.* **12** 125003

Ruane A and McDermid S P 2017 Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment *Earth Perspect.* **4** 1

Sabarmatee P *et al* 2025 Masculine tools and feminine tasks: the dynamic interplay of gender and technology through system of rice intensification *Int. J. Rural Manag.*

SRI-2030 2023 Policy Action for SRI (available at: www.sri-2030.org/policy-action-for-sri#item-1) (Accessed 15 01 2026)

SRI-2030 2025 Scaling SRI for climate, food, and farmer prosperity SRI 2030 initiative (available at: www.sri-2030.org/) (Accessed 15 01 2026)

Sung H M *et al* 2021 Climate change projection in the twenty-first century simulated by NIMS-KMA CMIP6 model based on new GHGs concentration pathways *Asia Pac. J. Atmos. Sci.* **57** 851–62

Tatebe H *et al* 2019 Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity in MIROC6 *Geosci. Model Dev.* **12** 2727–65

Thakur A K, Rath S, Roychowdhury S and Uphoff N 2010 comparative performance of rice with system of rice intensification (SRI) and conventional management using different plant spacings *J. Agron. Crop Sci.* **196** 146–59

Thakur A K, Uphoff N T and Stoop W A 2016 Do system of rice intensification practices produce rice plants phenotypically and physiologically superior to conventional practice? *Agronomy* **13** 147–79

Thrasher B, Wang W, Michaelis A, Melton F, Lee T and Nemani R 2022 NASA global daily downscaled projections, CMIP6 *Sci. Data* **9** 262

Toreti A *et al* 2020 Narrowing uncertainties in the effects of elevated CO_2 on crops *Nat. Food* **1** 775–82

Tubiello F N *et al* 2021 Greenhouse gas emissions from food systems: building the evidence base *Environ. Res. Lett.* **16** 065007

Uphoff N 2023 SRI 2.0 and beyond: sequencing the protean evolution of the system of rice intensification *Agronomy* **13** 1253

Valdivia R O *et al* Representative agricultural pathways: a multi-scale foresight process to support transformation and resilience of farming systems 47–102

Verspecht A, Vandermeulen V, Ter Avest E and Van Huylenbroeck G 2012 Review of trade-offs and co-benefits from greenhouse gas mitigation measures in agricultural production *J. Integr. Environ. Sci.* **9** 147–57

Yin S, Zhang X, Lyu J, Zhi Y, Chen F, Wang L, Liu C and Zhou S 2020 Carbon sequestration and emissions mitigation in paddy fields based on the DNDC model: a review *Artif. Intell. Agric.* **4** 140–9

Zhang Y, Wang W, Li S, Zhu K, Hua X, Harrison M T, Liu K, Yang J, Liu L and Chen Y 2023 Integrated management approaches enabling sustainable rice production under alternate wetting and drying irrigation *Agric. Water Manag.* **281** 108265