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Climate adaptive rice planting strategies diverge across environmental gradients in the Indo-Gangetic Plains

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Abstract

The timing of rice planting has a profound influence on the productivity of the rice-wheat cropping pattern in the Indo-Gangetic Plains (IGP), a system that provides the foundation for food security in South Asia. Nevertheless, strategies for adaptive rice planting in a rapidly changing climate are not well established. In this *ex-ante* analysis, regional gridded crop model simulations are deployed to investigate the impact of different rice planting strategies on system level productivity, resilience, and environmental benefits. Our results suggest that synchronizing rice planting dates with the monsoon onset substantially outperforms farmer practice (+41%) and static state recommendations in the Eastern IGP. However, planting long-duration rice with the monsoon onset is ineffective in the Northwestern IGP since the later arrival of the monsoon increases the probability of cold damage to rice and terminal heat stress in wheat. Here, fixed planting dates (+12.5%) or planting medium duration varieties at monsoon onset (+18%) performed best. We conclude that resilient and productive rice planting strategies must account for interannual weather variability and divergent climate conditions across sub-regions in the IGP.

1. Introduction

Climate change, population growth, and persistent food insecurity require agricultural systems to become more productive and resilient (FAO, IFAD, UNICEF, WFP, & WHO 2020), especially in smallholder systems where limited adaptive capacity exacerbates vulnerability to shocks. In general, smallholder systems are projected to be disproportionately affected by climatic change, but also hold the highest potential for increasing crop yields with attendant implications for global food security (Rockström *et al* 2017). The rice-wheat cropping system of the Indo-Gangetic Plains (IGP) extends across Pakistan, India, Nepal, and Bangladesh, constituting the 'breadbasket' of South Asia, although ca. 129 million people living in the IGP remain undernourished (Erenstein *et al* 2010, Rawal *et al* 2019, Singh *et al* 2020). South Asia being a global hotspot for climate hazards further challenges efforts for boosting production and resilience of agricultural systems (IPCC 2022). Accordingly, early wheat establishment has emerged as a powerful climate adaptation strategy to stabilize and enhance yields in the region, but depends on timely rice planting to allow for timely clearing of the field (Newport *et al* 2020, Devkota *et al* 2021, Urfels *et al* 2021). Less certainty exists for rice planting strategies that (a) tend to respond to the monsoon onset as typical farmers' practices, (b) follow fixed calendar dates, or (c) or proactively align transplanting with the predicted monsoon onset. Besides, poor knowledge on optimal rice planting strategies limits the use of advances in climate services for monsoon onset predictions to inform planting decisions.

Planting strategies further need to respond to intra-regional differences in climatic and development patterns. Accordingly, the IGP can be roughly grouped into three zones. The contrasting Northwestern IGP and Eastern IGP and the Middle IGP that shares characteristics of both. In the relatively low-yielding Eastern IGP, irrigation is powered mainly by expensive diesel pumps. Many farmers here manage economic risks and production uncertainty by waiting for the monsoon onset before establishing rice nurseries (Mathison *et al* 2018, Urfels *et al* 2021). This practice often results in delayed rice transplanting into late July and early August, causing late sowing of the subsequent wheat crop, thereby shifting maturation into the warmer spring months and reducing wheat yields by around 50 kg ha^{-1} d^{-1} for every day of planting delay beyond the third week of November (Mondal *et al* 2013, Asseng *et al* 2015, Dubey *et al* 2020, Ishtiaque *et al* 2022, McDonald *et al* 2022). Nevertheless, when practiced on a fixed calendar basis, earlier rice establishment may create a different set of production risks by increasing irrigation water requirements at the start of the season if monsoon onset is delayed (Urfels *et al* 2021).

In contrast, the Northwestern IGP is characterized by high-yielding, input-intensive cereal systems and electrically pumped irrigation water is provided at a nominal cost (Shah *et al* 2018). In this region, the sustainability of agricultural production is increasingly jeopardized by groundwater depletion and air pollution from crop residue burning (Famiglietti 2014, Balwinder-Singh *et al* 2019b). Farmers in the Northwestern IGP use groundwater irrigation to plant rice before the onset of the monsoon to ensure timely wheat establishment (Rodell *et al* 2009, Lobell and Gourdji 2012). In line with current state policies that already require farmers to delay rice planting to save water, further delaying rice planting to be in synchrony with the monsoon onset may bring crop water consumption within sustainable boundaries, but productivity impacts at a cropping systems level remain unclear (Humphreys *et al* 2010, Balwinder-Singh *et al* 2019b).

This study explores the impacts of different rice planting strategies on rice-wheat systems across the IGP by deploying a gridded ($0.1 \times 0.1°$) process-based crop model driven by long-term historical weather data with scenarios, medium- and long-duration rice varieties and full and supplemental irrigation schedules. While in-season management decision can close existing yield gaps (Mishra *et al* 2013, Debnath *et al* 2018), the correct planting strategy remains important for achieving maximum potential system-yield levels. Consequently, our main hypothesis is that a climate-responsive planting strategy—e.g. synchronizing rice transplanting with the monsoon—has the potential of improving agricultural productivity, resilience and sustainability in the rice-wheat systems of the IGP (Waha *et al* 2013, Nouri *et al* 2017, Hunt *et al* 2019, Mourtzinis *et al* 2019, Lv *et al* 2020, Urfels *et al* 2021).

We assess (i) caloric systems productivity in terms of average calorific yield levels (DeFries *et al* 2015) while characterizing (ii) agroecosystem resilience, defined as the capacity of the cropping system to maintain productivity despite external shocks (Allen *et al* 2019, IPCC 2022), and (iii) the water resource management implications of different planting strategies. We conclude by providing recommendations for future research and development policy.

2. Methods

2.1. Crop modelling framework

The APSIM model was used to simulate crop growth and productivity of the rice-wheat systems in each cell for the period 1982–2015. APSIM has been extensively calibrated and verified for simulating major cereal cropping systems across Asia including the IGP (Balwinder-Singh *et al* 2011, 2016, 2019a, 2019b, Gaydon *et al* 2017) and has been successfully used in spatial simulations in the region (Azzari *et al* 2017, Jain *et al* 2017). The pSIMS framework was used for running the gridded simulations with minor changes for packages that are no longer supported (Elliott *et al* 2014). A singularity container with the model, any code including the modified pSIMS, and input and output files, and analysis code are available at https://git.wageningenur.nl/urfel001/igp-simulation-setup.

The APSIM model was forced using multiple datasets. We used $0.1° \times 0.1°$ spatial resolution daily meteorological forcing from AgERA5 and most soil parameters from Global Soil Dataset for use in Earth System Models (GSDE) (Shangguan *et al* 2014)—see supplementary methods for more details.

2.2. Crop management

Crop simulations were run without nutrient or water limitation. We did so to isolate the effect of climate on the different planting strategies as a guiding factor for potential yield—with water and fertility management being secondary factors that need further investigation. Crops were harvested at maturity or a late cut-off point and wheat was sown as a function of rice harvest—see supplementary methods for more details.

2.3. Phenology and yield

We focused on the dominant long duration (MTU7092, also called Swarna) and medium duration (Arize6444) rice varieties for which the APSIM model has been extensively calibrated (Balwinder-Singh *et al* 2019a). In line with recent crop modelling advances, we eliminated delays in phenology for temperatures above the optimal by setting the maximum development temperature to an arbitrarily high number (5000 000 °C) (van Oort and Zwart 2018). To ensure that simulated phenology and yield patterns were comparable to those reported elsewhere, we compared the distribution of our results with those of other global and regional datasets (supplementary figures 6–9; incl. GDHY, RiceAtlas, SPAM), showing that our simulations were well within the range of reported planting dates, harvesting dates, and growth duration and yield levels (Monfreda *et al* 2008, Sacks *et al* 2010, Ray *et al* 2012, Laborte *et al* 2017, Iizumi and Sakai 2020, Yu *et al* 2020, MoA 2021).

To compare performance at the cropping systems level (i.e. for combined rice-wheat yield) with reference to potential impacts on food security we focused on the calorific yield, which refers to the annual dietary reference intake (DRI) for an average adult in low-income countries of 2700 kcal day^{-1}, with rice and wheat grain providing 3.60 and 3.34 kcal g^{-1} (DeFries *et al* 2015, FAO 2021).—see supplementary methods for more details.

2.4. Planting strategies

As outlined in the introduction this study considers three planting strategies that correspond to a baseline, fixed date recommendations, and planting at monsoon onset. Farmers' practice baseline was estimated from remote sensing data. Fixed planting date recommendation was taken from state recommendations. Monsoon onset was defined as the agronomic monsoon onset based on ex-post analysis of precipitation patterns—see supplementary methods for more details.

2.5. Scenarios

We ran seven scenarios comprised of a farmers' practice baseline without nutrient and water limitations to understand current limits to potential yield; two scenarios where the planting strategies were changed to understand the potential increase in yield potential; we then introduced a medium duration variety for the fixed date and monsoon onset scenario to see if these can further help to escape temperature stress where needed; and finally two additional scenarios with supplementary irrigation for planting both medium and long duration rice varieties at monsoon onset to explore water-related impacts on yield. The focus of this study rests on potential yields not limited by constraints in nutrients and water.

2.6. Resilience metrics

We focus on yield potential without water or nutrient limitations and define our system at the field level and thus ignore aspects of resilience outside the system (e.g. social protection etc.), assess shocks to yield potential, and focus specifically on the sensitivity and exposure of the system to temperature shocks. Shocks were defined as years where production falls below 80% of the long-term average of that grid-cell. This approach allows for identifying shock years that may be caused by several unknown combinations of climatic factors and considering the inherent variability of the system. Specifically, we focus on (i) sensitivity: the average impact of shocks on yield and (ii) exposure: the number of shock years per number of simulated years.

2.7. Data analysis

Detailed variable explanations can be found in the APSIM documentation. For determining temperature stress, we used the variables *sf1* and *sf2* to track temperature stress in rice and *temp_stress_photo* for tracking heat stress in wheat. We averaged these across growing seasons and reported them as temperature stress factors—see supplementary methods. Water productivity was calculated the ratio between grain yield and the sum of evaporation and transpiration while irrigation use was calculated automatically by APSIM. To interpret the results in an aggregated geographic context, we divided our study area into Northwestern, Middle and Eastern IGP at Longitudes 77° East and 83° East, which roughly aligns with Indian state boundaries and agroecological zones.

3. Results

3.1. Simulated calorific yields for different rice planting strategies

In the Northwestern IGP, the highest system-level calorific yield potential with long duration varieties was an average of 22.5 DRI ha^{-1} yr^{-1} when rice was planted on fixed dates according to state recommendations (figure 2(a) and supplementary figure 1). That is an 12.5% increase (all comparisons relate to typical farmers' practice if not specified otherwise). Areas with lower yield potential in the fixed date scenarios concentrate in the northern-most reaches of the Northwestern IGP where autumn temperatures are lower (figure 2, supplementary figures 2 and 3). Planting of long-duration cultivars with monsoon onset is not a viable option for the Northwestern IGP, because the monsoon arrives latest in this sub-region following its east-west seasonal progression. It is too late for rice planting and reduces system calorific yields to an average 14.4 DRI ha^{-1} yr^{-1}. Adopting medium duration varieties performed overall best with a 2% yield increase for the fixed date scenario and increased simulated yields by 64% when planting at the monsoon onset effectively avoiding temperatures stresses and surpassing the best-performing fixed date scenario with long-duration varieties by 5% (figures 1–3; supplementary tables 1, 2).

In the Eastern IGP, farmers can benefit from synchronizing rice planting with the monsoon onset (figure 2(b)), a strategy that increases system yield

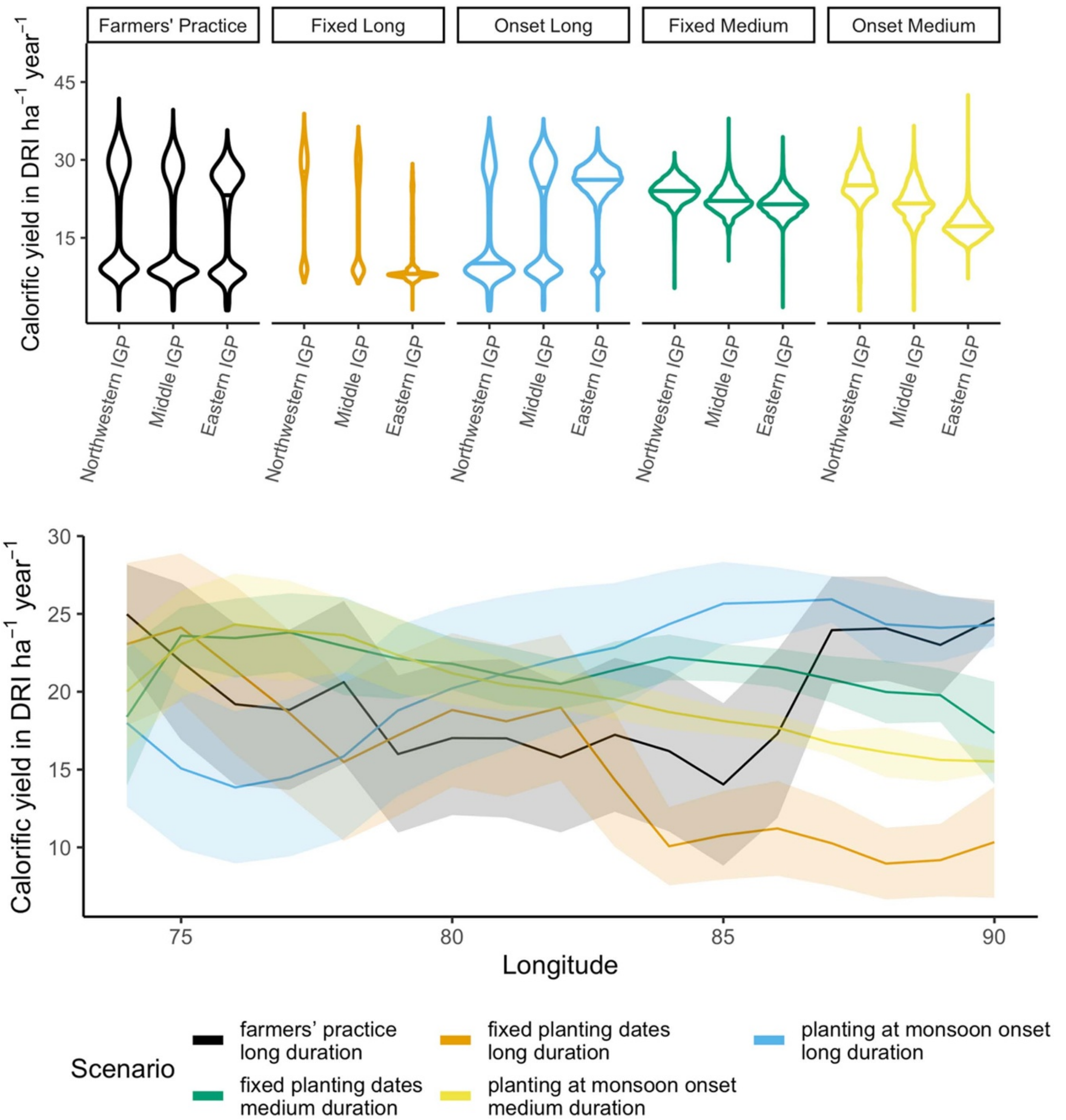

Figure 1. Calorific yield patterns. Top: Violin plots of simulated historical (1982–2015) calorific yield expressed in annual adult DRI ha^{-1} yr^{-1} for the Northwestern, Middle, and Eastern IGP. Horizontal lines show the median calorific yield. Bottom: Longitude-calorific yield graph showing mean yield (lines) and standard deviation (bands) across longitudes and years for each planting date scenario. Long and medium duration refers to rice cultivar's typical growth duration.

potential by 41% to 24.8 DRI ha^{-1} yr^{-1} (see supplementary figure 1). Nevertheless, sub-regional differences remain. With monsoon onset planting, the easternmost region of our study area shows system-level yield reductions caused by low wheat productivity due to low solar radiation (supplementary figures 2 and 3). Fixed calendar date recommendations (10.1 DRI ha^{-1} yr^{-1}) perform overall worse than farmers practice as they increase exposure to temperature stresses for rice and wheat (figures 2 and 3, supplementary figures 2 and 3). Adopting medium duration hybrids in the Eastern IGP increases the average yield by 22% for the fixed calendar date strategy but remains 16% below the monsoon onset planting strategy. Planting medium-duration rice reduces yields for the monsoon onset scenario by 29% (figures 1–3, supplementary tables 1 and 2).

Lastly, in the Middle IGP, both planting on fixed dates and at monsoon onset increase yields by 2% and 13% respectively (see supplementary figure 1). The baseline results in an average system yield potential of 17.4.4 DRI ha^{-1} yr^{-1} while fixed calendar date recommendations reach 17.8 DRI ha^{-1} yr^{-1} and planting at monsoon onset 19.8 DRI ha^{-1} yr^{-1}. However, lower simulated yields are observed in some areas. For the fixed calendar date recommendations, areas of low yield potential are found in the north of the Middle IGP, where winters tend to be colder (figure 2, supplementary figures 2 and 3). Planting at monsoon onset results in lower yield potential over the northwest of the Middle IGP (figure 2), where

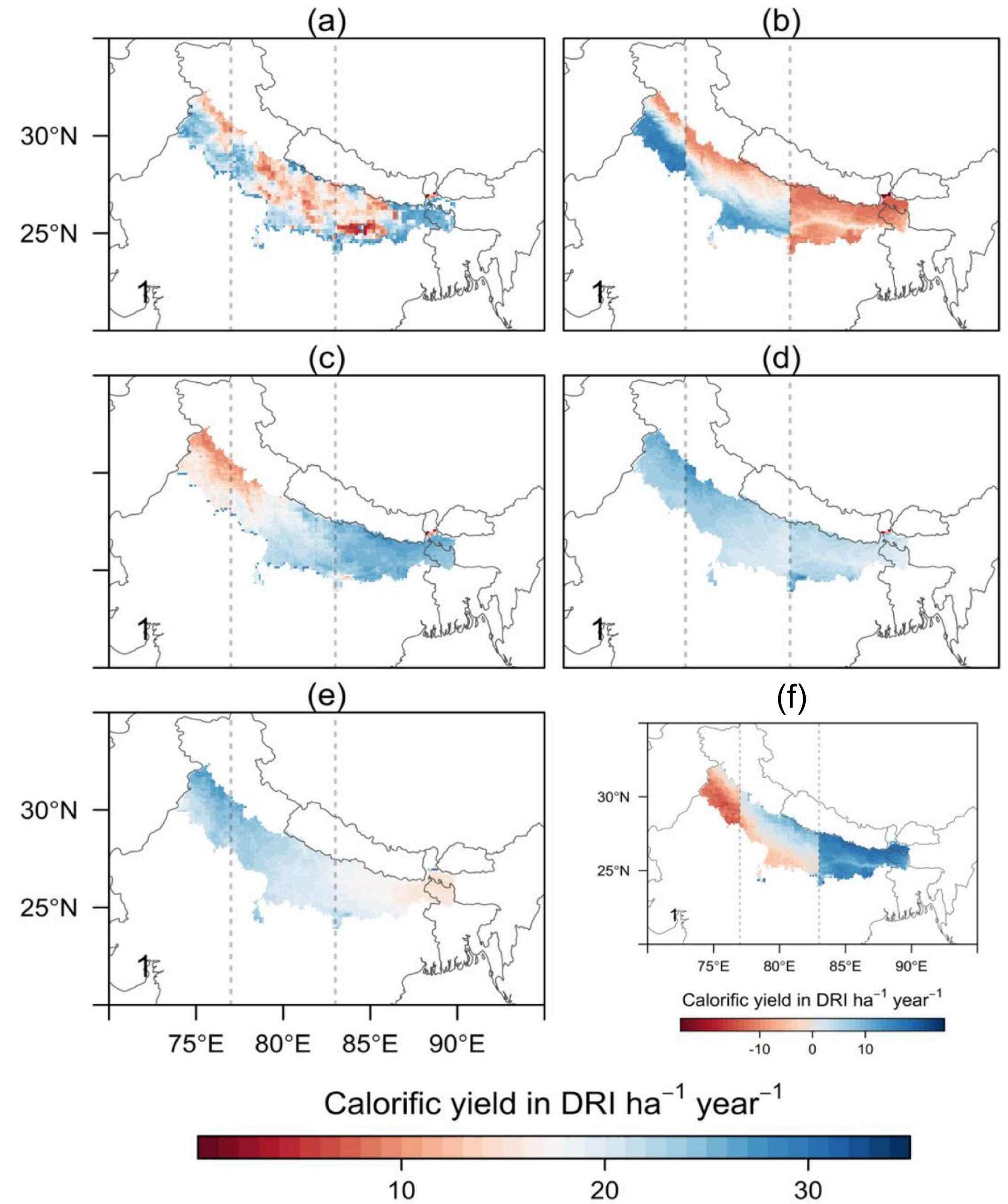

Figure 2. Average simulated historical (1982–2015) combined calorific yield for (a) farmers' practice baseline with long duration rice, (b) planting at fixed calendar date recommendations with long duration rice and (c) planting at monsoon onset with long duration rice, (d) planting at fixed calendar date recommendations with medium duration rice, (e) planting at monsoon onset with medium duration rice, (f) difference between planting at monsoon onset minus fixed calendar date recommendations and with long duration varieties. Dotted lines separate the region into Northwestern, Middle, and Eastern IGP.

the monsoon arrives later (supplementary figures 2 and 3). Medium duration varieties further increases yields to 21.7 and 21.5 DRI ha^{-1} yr^{-1} for fixed and monsoon onset planting—indicating that planting at monsoon onset and especially adopting medium duration varieties are the preferred planting strategies.

3.2. Resilience: yield stability and sensitivity to shocks

Simulated yield stability varies significantly across rice planting strategies (figures 4 and 5). In the Northwestern IGP, the system's sensitivity—i.e. mean reduction of simulated system yield in a shock year—averages at 4.7 DRI ha^{-1} yr^{-1} for the fixed calendar date recommendations with a shock year occurring once every 7–8 years (exposure: 0.13; i.e. fraction of shock years per number of simulated years). The higher yield instability in the northern parts is affected by more frequent crop damage to rice associated with low temperature events (figure 3). In the Middle IGP, yield sensitivity for fixed planting dates (5.1 DRI ha^{-1} yr^{-1}) is lower than planting at

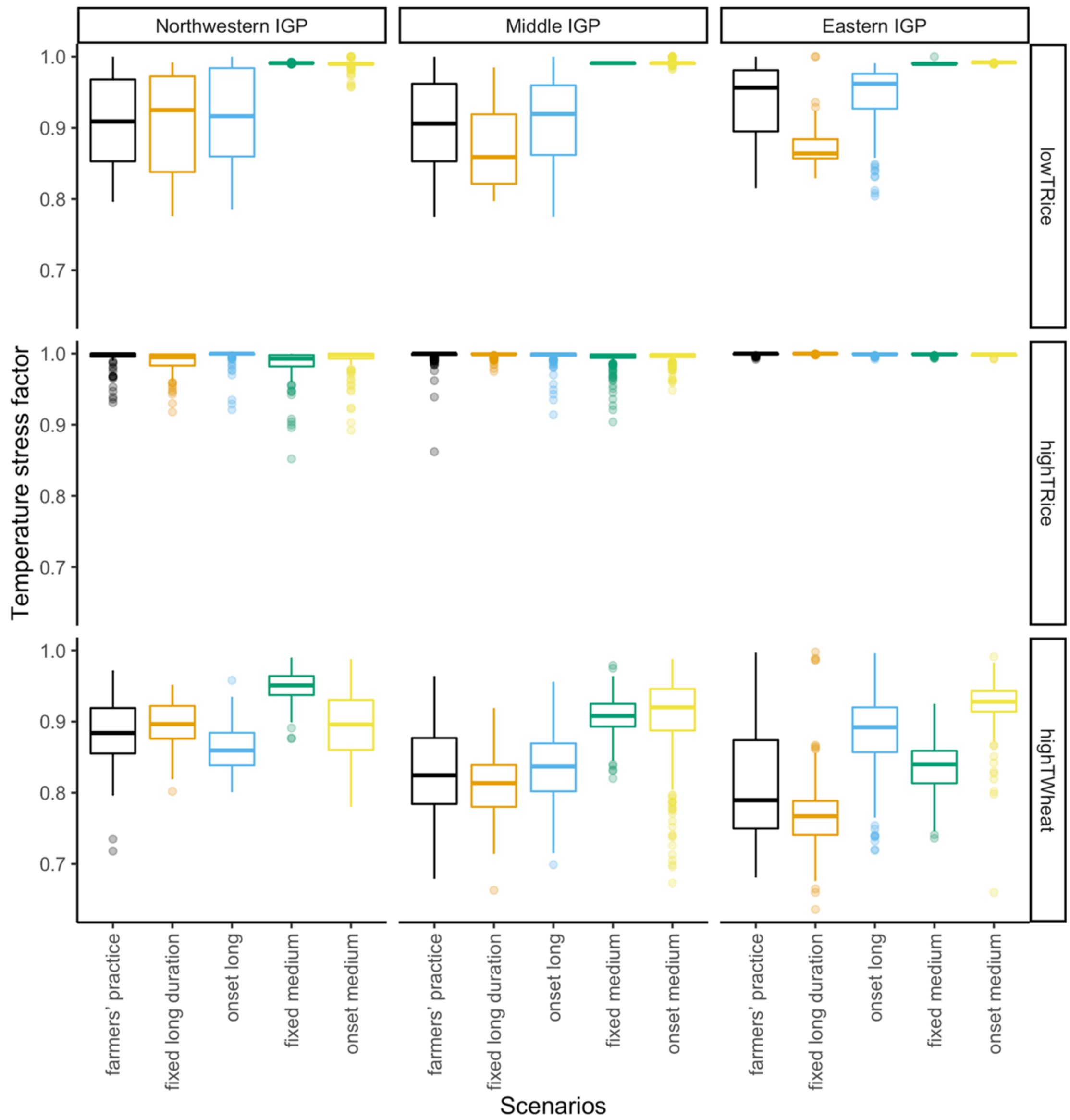

Figure 3. Boxplot of temperature stresses affecting rice-wheat growth across scenarios (1982–2015), years, sub-regions, and stress types. Boxes cover 25th to 75th percentile, horizontal line shows the median, and whiskers extend to 1.5 times the interquartile range with points outside that range marked as dots and representing outliers. 1 indicates no stress (optimal conditions) and 0 indicates severe stress. LowTRice and highTRice refer to low and high temperature stress in rice, respectively, while highTWheat refers to high temperature stress in wheat. Long and medium duration refers to rice cultivar's typical growth duration. Although they incur more stress, long duration varieties in the Eastern IGP outperform medium duration varieties.

monsoon onset (6.5 DRI ha^{-1} yr^{-1}) and have similar exposure score (0.22 vs. 0.23). For the Eastern IGP, planting with monsoon onset displays the lowest sensitivity to shocks with a mean reduction of 3.0 DRI ha^{-1} yr^{-1} in a shock year that occurs, on average, every 11–12 years (0.09). Adopting medium duration varieties effectively reduces the sensitivity and exposure of the rice-wheat to thermal climate hazards, effectively avoiding temperature stresses. In summary, our results show that the fixed calendar date recommendations perform better for the Northwestern and Middle IGP in terms yield stability especially with medium duration varieties, while planting at monsoon onset performs best in the Eastern IGP.

3.3. Environmental trade-offs? Irrigation and water productivity

The simulation results suggest that different planting strategies do not substantially affect irrigation requirements, but that significant differences in rice irrigation requirements exist between sub-regions of the IGP (figure 5, supplementary figures 4 and 5). The average irrigation requirements for rice are highest in the Northwestern IGP for the fixed calendar date recommendations (1391 mm) and lowest in the Eastern IGP for planting at monsoon onset with medium duration varieties (482 mm). Besides, different planting strategies' impact on yields results in large differences in water productivity (figure 5). For instance,

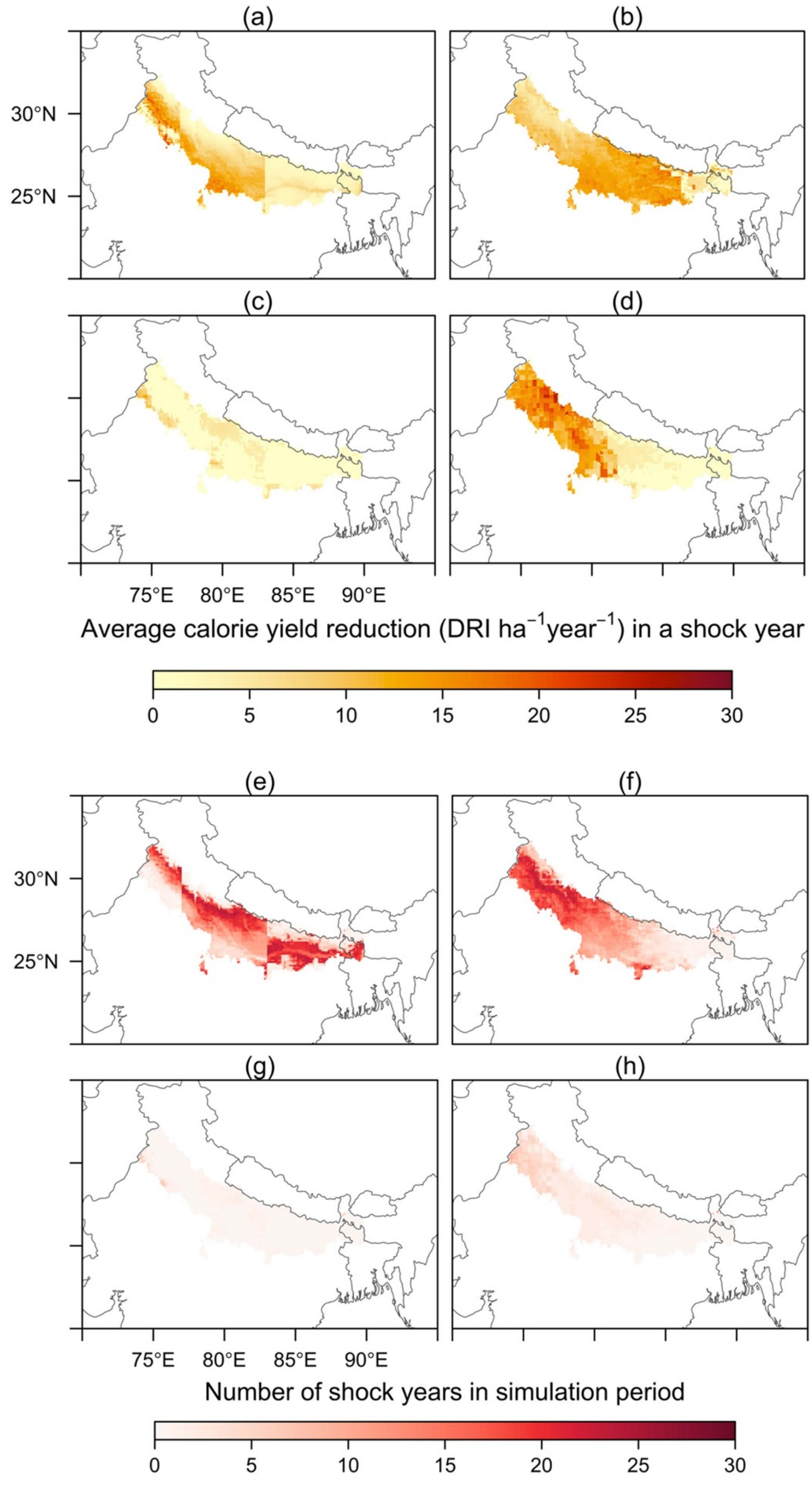

Figure 4. System sensitivity and exposure to shocks. Top: System sensitivity. Bottom: System exposure. Scenarios: (a) and (e) fixed calendar date recommendations long duration rice and (b) and (f) planting at monsoon onset with long duration rice, (c) and (g) fixed calendar date recommendations with medium duration rice, (d) and (h) planting at monsoon onset with medium duration rice.

in the Northwestern IGP, the average water productivity for fixed calendar date recommendations (1.54 DRI cm^{-1}; 0.94 kg m^{-3}; see figure 5 and supplementary table 3) is almost twice as much as when planting at monsoon onset (1.02 DRI cm^{-1}; 0.78 kg m^{-3}, figure 5 and supplementary table 3.

Motivated by the recent groundwater depletion in the Northwestern IGP (Balwinder-Singh *et al* 2019b),

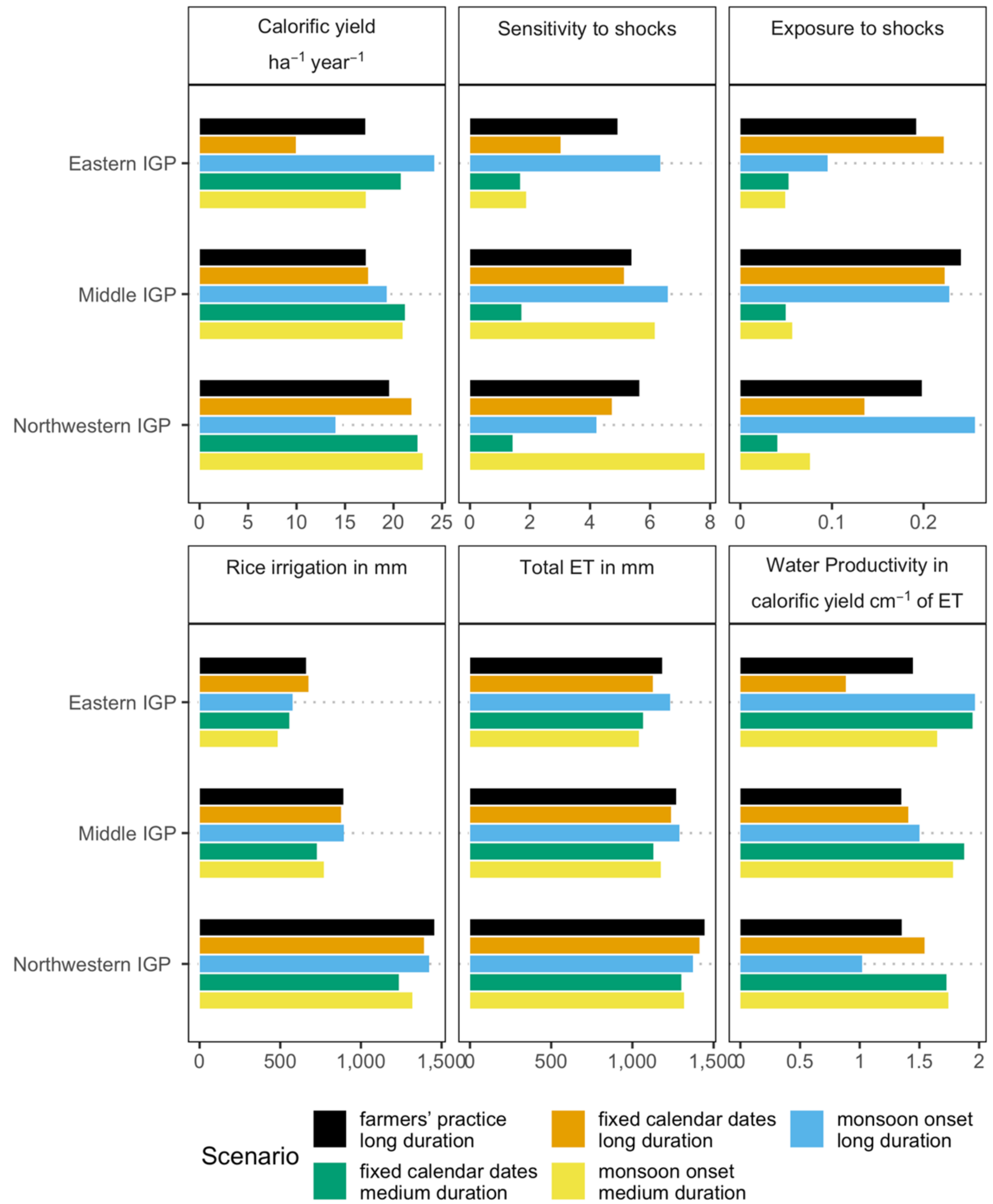

Figure 5. Overview of key system performance indicators across sub-regions of the IGP and rice planting strategies. Bar heights represent mean values of indicator. Calorific yield refers to annual adult DRI ha^{-1} yr^{-1}.

we also tested the use of medium-duration rice varieties planted at monsoon onset with a low-input irrigation schedule where irrigation is supplied only after several days of stress have already occurred (supplementary figure 5). This strategy avoided temperature-induced yield penalties in the Northwestern IGP but irrigation requirements remain substantially higher than in the Eastern IGP. Even if all runoff, drainage, and effective rainfall is captured, the difference between evapotranspiration (ET) and water availability—a rough indicator of irrigation requirements—remains at a substantial 402 mm. Both the late monsoon arrival and early retreat in the Northwestern IGP result in lower overall effective rainfall than in the Eastern IGP, irrespective of planting strategy (supplementary figure 4).

In the Eastern IGP, conversely, planting at monsoon onset allows, on average, the capture 269 mm more effective rainfall (supplementary figure 4). Irrigation requirements are, however, not reduced proportionately—most likely because captured rainwater is lost as percolation beyond the root zone and prolonged in-season dry spells continue to require supplementary irrigation. Planting at monsoon onset would likely also lead to higher irrigation losses in practice than simulated during transplanting due to high percolation losses during land preparation (Bouman and Tuong 2001).

4. Discussion

4.1. Building productive, climate resilient, and groundwater conserving agroecosystems: what is the scope for planting date adjustments?

In the Northwestern and Middle IGP, fixed calendar date recommendations provide the highest system-level productivity and resilience. In these regions, warmer summers and colder autumns and winters combined with shorter rainy seasons restrict the ability to synchronize planting dates with the monsoon onset without incurring yield losses or changing rice varieties. Note that fixed-date planting strategies other than state recommendations may still be superior for any region but were not tested. The water-saving potential of different planting strategies is equally limited as our results suggest only marginal changes in ET among different strategies. These findings align with studies indicating that large improvements in agricultural water productivity are normally caused by yield changes, not water use per se (Perry *et al* 2009). Considering ongoing groundwater depletion (Famiglietti 2014), adaptation strategies to climatic change in the Northwestern IGP should focus on further reducing agricultural water use through shorter duration rice varieties and switching to less water demanding crops such as millet, sorghum, or maize. However, changing varieties or crops may incur yield or profit losses and requires cultural changes in producer and consumer behaviour that are more difficult to achieve than shifting planting dates but would support goals of increasing agricultural and nutritional diversity (Willett *et al* 2019).

In the Eastern IGP, the current rice-wheat system still holds potential for improving yields and resilience within sustainable water use limits. To boost system productivity and resilience, farmers can synchronize rice planting with the monsoon onset to avoid temperature stresses and reduce the risk of increased irrigation requirements for land preparation. Seasonal medium-range climate forecasts are a promising tool for promoting this rice planting strategy as well es bringing planting dates of medium duration varieties closer to the recommendations—as many farmers are likely reluctant to transplant before the monsoon onset. Hypothetically, if the value of such a forecast is the differential in yield over the baseline (7.4 DRI ha^{-1} yr^{-1}), the return would be calorie sufficiency for an additional 24.09 million people a year considering the 3.3 million ha of rice area in Bihar alone. However, errors in seasonal forecasts and establishing their usefulness for informing farmers' agronomic practices remain a key challenge for scaling such approaches and present crucial research frontiers (Hayashi *et al* 2018).

In the Middle IGP, the current rice-wheat system has advantages in its Eastern parts and in years with high rainfall, since earlier and heavier rains complicate cultivating short duration varieties and other crops. A combination of seasonal forecasts coupled to within season and longer-term crop choice advisories is likely most effective for this region.

4.2. Unaccounted factors for crop planting recommendations

Our recommendations for crop planting dates are based on crop model simulations that do not account for several factors such as the likelihood of untimely rains that may obstruct farmers from planting or harvesting (Trnka *et al* 2011, Iizumi *et al* 2019, Jian *et al* 2020). Similarly, farmers are unlikely to adopt timely planting in the presence of delay factors such as unavailability of pre-monsoon irrigation water, lack of reliable electricity access, untimely availability of inputs, labour shortages, and lack of collective action to deter pest and disease pressures; these factors are not explicitly addressed in the models (Bouman and Tuong 2001, Kitoh *et al* 2013, Urfels *et al* 2021). Understanding and mapping these factors remain important research frontiers as untimely transplanting of nurseries can have significant negative consequences for farmers, especially with an increasingly erratic monsoon (Kitoh *et al* 2013). Therefore, current planting advisories should be localized and should target areas with low physical or economic water scarcity and well-established input markets. Furthermore, given the growing rural electrification in the Eastern IGP, planting advisories in this subregion should target areas with electrical irrigation pumping as an enabling factor for adoption.

4.3. Regional influences of low temperature on yield variability

The detrimental effect of low temperatures on rice yields deserves special attention. Low temperatures reduce rice growth in some areas of the IGP in each scenario with marked spatial differences (supplementary figure 2). From a physiological perspective, varieties that are primed to flower in the early morning hours to avoid heat stress (Kadam *et al* 2014) may be counterproductive in environments with low minimum temperature during anthesis such as in the IGP, where flowering during the morning hours can increase exposure to cold stress. In addition, large-scale climatic anomalies induced by La Niña can cause widespread cold waves and increased rainfall and flooding, as was the case in 2020, when minimum temperature in October was below 15 °C (Jin and Wang 2017, Takaya *et al* 2021). Our results also suggest that rice yield response to low-temperature stress exhibits critical thresholds beyond which potential yields decline rapidly. Better tools for communicating such yield risks to farmers are required to support improved farm management decisions.

4.4. Measuring resilience of crop production

Evaluation of farming systems productivity mostly focus on raising average productivity under ideal climatic conditions (Rockström *et al* 2017). Resilience normally characterizes farming systems that must undergo radical transformations such as moving out of agriculture or changing crops (Perez *et al* 2016). But such radical transformation may only be required in 50 years or later and will not affect most crops and locations (Rippke *et al* 2016). We contend that the resilience debate for farming systems should include the system's ability to handle shocks within current systems configurations and climate conditions. This represents the best way to prepare for future stressors that are directionally aligned with contemporary stressors and helps to exploit opportunities by informing contemporary action. We further find measuring resilience helpful and recommend future studies to deploy crop models to better understand and characterize the resilience of agricultural interventions. Moreover, future research on dynamical management decisions induced by a shock year that carry over into the next year represent important steps for better assessing resilience of crop production to climatic shocks.

5. Conclusion

Our work fills a critical gap in studying food production systems between site-specific assessments and global simulations. While global gridded crop models generally do not examine detailed agronomic options, site-based studies suffer from external validity issues due to spatially varying agro-climatic conditions. The regional crop modelling study presented in this article, bridges this gap between global and site-based studies by deploying a long-term, regional modelling study and assesses the impact of rice planting strategies on resource-use trade-offs, and temperature stresses in the IGP.

Our study demonstrates that the performance of rice planting strategies diverges across the IGP. Synchronizing rice planting with monsoon onset improves system productivity and resilience over the Eastern IGP, indicating that monsoon forecasting can be a promising source of information for decision-making by farmers in this sub-region. However, colder winters, hotter summers, and shorter monsoons in the Northwestern IGP restricts the application of this strategy in this region, with limited scope to improve either the productivity or sustainability of the rice-wheat system.

Furthermore, our study shows that cropping systems such as the rice-wheat system must be evaluated as an integrated multi-cropping system so that ex-ante assessments of interventions consider full crop rotations and climatic gradients. Future studies should assess other management factors and consider future climate scenarios. In concert, strengthening the knowledge base on the spatio-temporal interplay of crop systems management and the climate system is critical for transforming food systems in the IGP and elsewhere.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://git.wageningenur.nl/urfel001/igp-simulation-setup.

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Author contributions

A U, C M, B S, and A J M jointly conceived of the study. All authors contributed to the implementation, analytics, and manuscript writing.

Conflict of interest

The authors declare no competing interests.

Ethics statement

This research did not include human subjects, human data or tissue, or animals.

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