**Risk-based evaluations of competing agronomic options for climate adaptation: The case of rice planting strategies in the Indo Gangetic Plains**

# Abstract

Adjusting crop planting dates and variety durations is emerging as a crucial climate change adaptation strategy for many cereal systems. Such strategies include, for example, harmonizing crop planting with the onset of the rainy season or planting at specific recommended calendar dates. Evaluations of these strategies mostly consider yield and yield variability, but focus less on financial risks associated with different planting strategies. However, choosing recommendations amongst competing levels of yield and yield stability is not straightforward as preferences for yield increases and stability might differ. Here, we present a novel framework that uses a computational spatial economics approach for evaluating which planting strategies work best where. To demonstrate our approach – we evaluate readily available gridded crop simulation outputs for various rice crop planting strategies for the rice-wheat systems of the Indo-Gangetic Plains. Our findings provide quantitative evidence to the previous conclusion that harmonizing the planting dates of long-duration varieties at the monsoon onset works best in the Eastern IGP, this strategy fail and is clearly outperformed by planting rice at state-recommended planting dates in most of the Western and Middle IGP. Importantly, our risk-based assessment shows that the results are not as clear cut in the northern Middle IGP where farmers appear to have more flexibility to achieve comparable outcomes. In conclusion, our approach provides a useful and novel tool for comparing different agronomic climate adaptation strategies from an economic risk perspective in a spatial framework.

# 1. Introduction

Climate change is predicted to have a largely negative impact on the agricultural systems of low-income countries (IPCC, 2022). To adapt, farmers and policy makers must choose between several competing agronomic response options. Researchers usually evaluate these options based on average yield levels, water use, and income across years with varying weather conditions and provide subsequent recommendations. However, comparing these different indicators and assessing acceptable levels of variability is not straightforward resulting in recommendations based on qualitative expert judgement. This is especially the case for risk averse smallholder farmers that seek to minimize any losses they may have to incur. How, for example, shall one evaluate an adaptation strategy that, across several years, has been shown to require an average of 50mm additional water use to gain 300 kg of yield, 10% more income and increase yield variability by 5%?

Deriving recommendations for rice planting in the rice-wheat cropping systems of the Indo-Gangetic Plains (IGP) is a case in point. In the IGP, rice is planted in the monsoon season from June to October (also called kharif) while wheat is grown as an irrigated crop in winter season from November to April (also called rabi). Climate impacts on agricultural systems of the IGP are amongst the most severe globally (IPCC, 2022), as, e.g., late monsoon onsets delay rice sowing in the Eastern IGP and push wheat crops into periods of high terminal heat stress – while farmers in the Western IGP use free electricity to plant their rice crops early in the hot summer months and contribute to groundwater depletion. Recent compelling evidence (e.g., McDonald et al 2022, Urfels et al 2022, and Montes et al 2022) suggests that advancing the planting date of rice to match the monsoon onset is one of the viable adaptation options for farmers in the Eastern IGP – and might help to alleviate groundwater depletion in the Western IGP. To test this hypothesis, Urfels et al (2022) and Montes et al (2022) used gridded crop simulations for the Indo-Gangetic Plains to investigate the impact of different rice planting strategies (combining sowing dates, variety duration and irrigation) on system level productivity, resilience, and environmental benefits. However, most farmers are risk averse and not only interested in long-term profit maximization and yield outcomes. It is thus important to consider economic risks and not just average yield and yield variability as critical for evaluating agronomic adaptation strategies. For example, recent studies (see, Hurley et al 2018, Suri 2011) have shown that year to year variation in economic returns to adopting technologies can result in lower levels of adoption of generally profitable agricultural innovations – but approaches for evaluation agronomic strategies from a risk perspective remain scarce.

To address this knowledge gap, we develop a robust and risk-oriented framework to select suitable adaptation strategies for risk-averse farmers. To demonstrate our approach, we extend the evaluation of the crop modelling results for different rice planting strategies across the IGP of Urfels et al. (2022) and evaluate them through our novel risk-oriented framework.

This paper contributes to two strands of literature. The first strand of literature is on stability analyses of agricultural technology benefits based on ex-ante cropping system assessments (e.g., Urfels et al 2022, Montes et al 2022). Montes et al (2022) used inter-annual standard deviation to analyze the stability of the planting date scenarios. Urfels et al (2022) used deviation from the mean caloric yield for each of the years when a shock occurred as a measure of yield instability. These measures of yield stability while a step better than mean comparisons, they do not consider robustness of the optimal decision to risk aversion of the farmers. In addition, these measures do not consider higher order moments beyond mean and variability that may matter for distributional comparisons. In addition, we argue that stability analyses just as comparisons of means do not consider the trade-offs of achieving the highest returns with the lowest uncertainty. While uncertainty of modelling has been addressed by, for example, using model ensembles or monte carlo simulations, these only allow for stronger confidence in the mean and variation around it – but do not take into account farmers’ risk preferences.

These limitations are addressed in the second strand literature which focuses on the spatial risk assessment of economic benefits of agricultural innovations (e.g., Nalley and Barkley 2010, Hurley et al 2018). This literature attempts to optimize on the trade-offs of achieving the highest return and lowest uncertainty therefore allows one to choose strategies that are more robust. Using modern portfolio theory (Markowitz 1959) which suggests that a strategy to maximize average returns may be a suboptimal strategy, Nalley and Barkley (2010) used a mean-variance analysis to optimally select wheat varieties that achieve highest return and lowest risk. This strategy still suffers from the limitation of using a subset of moments (mean and variance) of the distribution. The stochastic dominance approach was developed to resolve these concerns in selecting robust strategies (Levy 2016). Using long term weather data, crop simulation model results (APSIM), spatially explicit observed maize prices, and fertilizer prices; Hurley et al (2018) simulates whether weather risk affects the adoption of fertilizer and improved maize seeds. They use heterogeneity in soils and climate in a calibrated crop growth model to simulate the distributions of yields across adoption of fertilizer and improved maize seed scenarios.

We specifically follow the approach proposed by Hurley et al (2018) to estimate willingness to pay bounds for a risk averse farmer to likely adopt an alternative rice planting date strategy. We depart from their approach in two substantial ways. First, instead of fertilizers and improved varieties, we consider multiple management changes including sowing dates, irrigation amounts, and varieties differing on duration to maturity. Second, we consider a rice-wheat multi-crop system unlike Hurley et al (2018) who focus on maize only. Our application shows how this risk-assessment framework can handle increasingly complex decisions.

The rest of the paper is organized as follows. We present next the methods focusing on the computational risk assessments. In section 3 we present results and discussion of the yield and economic benefits of alternative planting date strategies. We finally conclude in section 4.

# 2. Methods

To present our risk-assessment framework for comparing different adaptation options for risk-averse farmers, we use the gridded APSIM simulation outputs from Urfels et al. (2022). We then compare the different options regarding their economic performance and riskiness. To assess economic returns, we multiply the simulated yield outcomes with spatially explicit price data for rice and wheat. Since the only variable cost of in the simulation is irrigation amount, we consider their impact on the outputs and calculate partial profits using common irrigation cost of US$1.26 per m3 and multiply it with the total irrigation amount required in each simulation. Next, we use a novel method to estimate willingness to pay bounds through a stochastic dominance approach to determine which rice planting strategies are both economically beneficial and least risky. The remainder of this Methods section provides an overview of (i) the input data and (ii) our risk assessment approach.

## 2.1. APSIM spatially gridded crop model scenarios

The data used in this paper was based on gridded APSIM crop growth simulation model results for climate variables for the period 1982-2015 reported in Urfels et al (2022) and Montes et al (2022).[[1]](#footnote-2). We use seven scenarios from crop simulation results reported in Urfels et al (2022). The scenarios correspond to variation in irrigation, varietal duration and the planting of rice at the onset of the monsoon. Table 1 shows the details for the scenarios.

Table 1: Scenarios

|  |  |  |
| --- | --- | --- |
| Scenario number | Rice planting strategy | Description |
| S0 | Farmer practice | Farmers’ practice baseline without nutrient and water limitations to understand current limits |
| S1 | Fixed long (baseline) | Planting long duration variety at a fixed recommended date (state recommendation) |
| S2 | Fixed medium | Planting medium duration variety at a fixed recommended date |
| S3 | Onset long | Planting long duration rice variety at the onset of monsoon |
| S4 | Onset long supp | Only providing supplementary irrigation for planting long duration varieties at monsoon onset |
| S5 | Onset medium | Planting medium duration variety at monsoon onset |
| S6 | Onset medium supp | Supplementary irrigation for planting medium varieties at monsoon onset |

We supplement the APSIM model results with spatially gridded rice and wheat prices from the Landscape Crop Assessment Survey (LCAS; <https://systems-agronomy.github.io/lcas/>) data interpolated using a random forest model and back of the envelope spatially gridded irrigation costs.

## 2.2. Computational spatial ex-ante economic model under risk aversion

Our framework uses a two-step approach, first evaluating systems-level yield risks and subsequently systems level economic risks. For both yield risks and economic risks, we assess adaptation options through a willingness to pay (WTP) lens that considers both economic performance and riskiness. The guiding question is: How much would a farmer be willing to pay for an adaptation option and still be clearly better off than with the baseline? To assess this, we assume that an adaptation option is suitable for risk averse farmers if the distribution (not just the average) of yield and economic outcomes supersedes the baseline. Using the so called ‘second order stochastic dominance’ (SOSD) – a well-established measure in decision theory for comparing the riskiness inherent in two distributions – we assess whether the adaptation option is less risky than the baseline (i.e. negative outcomes less likely).Below we provide an overview of how SOSD works for our case. For more details regarding SOSD and risk aversion, please see Levy (2016) and Meyer (1977) for a detailed explanation.

### 2.2.1. Comparing the riskiness of two agronomic adaptation options

To evaluate the riskiness of an adaptation option regarding either yield or economic returns, we compute spatially explicit willingness to pay bounds in rice and wheat yield equivalents that define, for a risk averse farmer, whether that farmer would adopt a technology or not. While SOSD provides an estimate of which option is risker – we use Hurley et al.’s (2018) approach to further assess how much better it is. In principle, the WTP bounds indicate (i) how much the cumulative distribution of the adaptation option can be shifted to the left (i.e. the benefits uniformly reduced) and still outperform the baseline (lower bound), and (ii) how much the cumulative distribution function can be moved to the right (i.e. the benefits uniformly increased) before it is entirely on the right side of the baseline (upper bound).

To demonstrate this approach, we use a hypothetical experiment shown in Figure 1. Based on mean comparisons, is clearly better than and . If we think in terms of distributional differences, is clearly better than because the cumulative distribution curve of is wholly to the right of . This is also called first order stochastic dominance. Consider the next case, where and are having crossing cumulative distribution functions. Visually, it can be assessed that has a higher mean and much lower likelihood of low performing outcomes. G has a higher mean and is less risk. This is, G second order stochastically dominates . Since the cumulative distribution function of G and F are crossing each other, neither distribution first order stochastically dominates the other.

Lastly, consider the case of and , they are crossing each other and have the same mean. It is difficult to visually assess which one is more risky – i.e. determine the second order stochastic dominance ordering for these technologies.

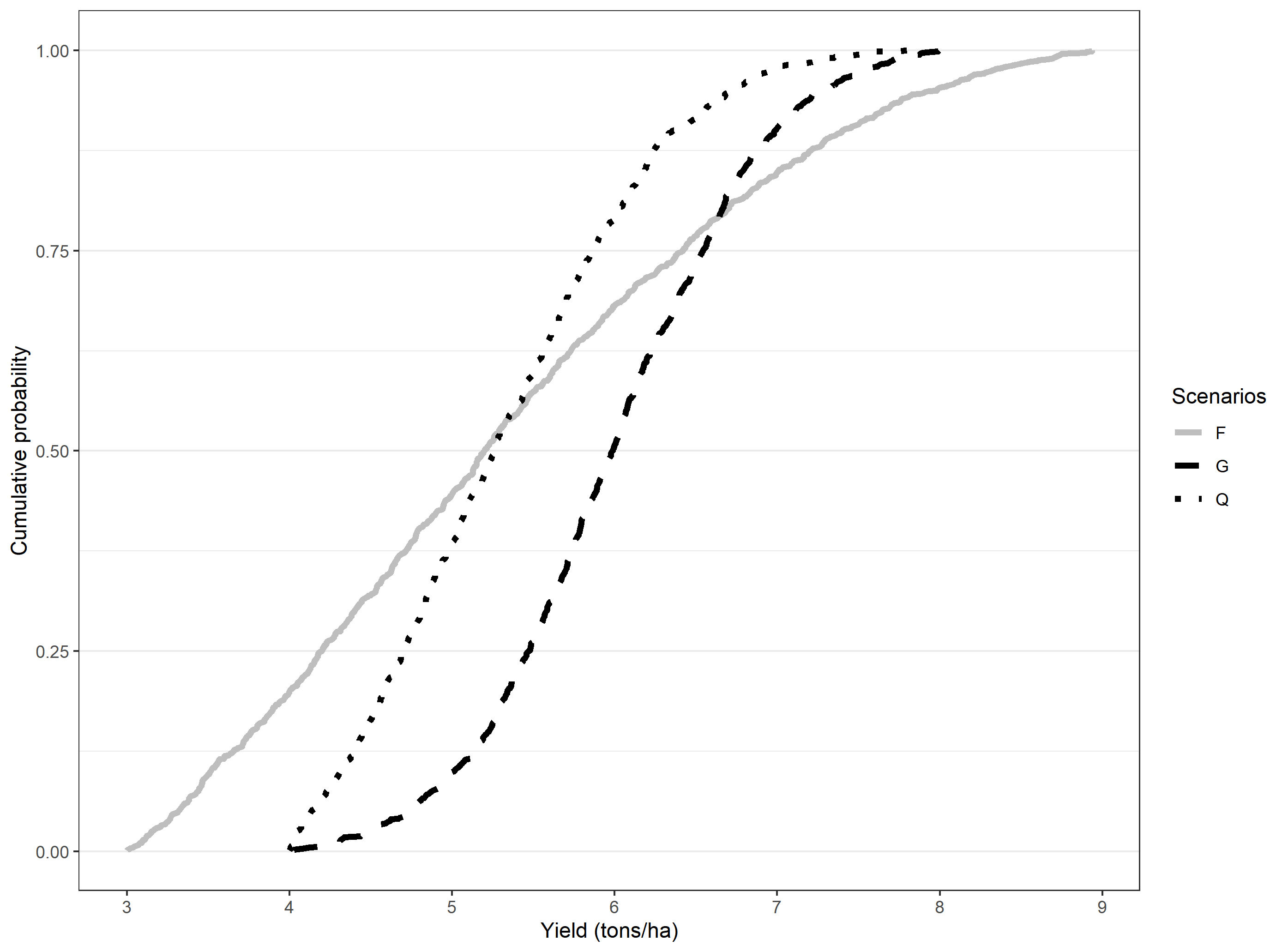


Figure 1: Hypothetical stochastic dominance assessment

***Note:*** We use a truncated normal distribution with four parameters: minimum (a), maximum (b), mean, and standard deviation (sd). The parameters used for each of the scenarios are as follows: G= rtruncnorm (n=1000,a=4,b=8, mean=6,sd=0.8), Q=rtruncnorm (n=1000,a=4,b=8, mean=5,sd=1), F=rtruncnorm (n=1000,a=3,b=9, mean=5,sd=2).

The lower WTP bound that makes any risk-averse farmer prefer new technology (in this case scenarios other than the baseline) can be derived using second order stochastic dominance (see Hurley et al 2018 for detailed derivations). If both lower bound and upper bound are positive, then any risk averse farmer will prefer the new technology. Conversely, if both lower bound and upper bound are negative, then any risk averse farmer will stick to the old technology. If however, the lower bound is negative and the upper bound is positive, then it is requires an explicit understanding of risk preferences—information not easily available—to determine which distribution is preferred. We use Octave for the computational analyses.

Proceeding with the hypothetical distributions, we show in table 2 results from using our approach to compute upper and lower willingness to pay bounds. The WTP bounds are positive for the comparison between Q and G as well as F and G.

Table 2: Hypothetical distributions and willingness to pay bounds

|  |  |  |  |
| --- | --- | --- | --- |
| Panel (a): Truncated normal distribution parameters for the hypothetical distributions | | | |
| Truncated normal parameters | G | Q | F |
| N | 1000 | 1000 | 1000 |
| Min=a | 4 | 4 | 3 |
| Max=b | 8 | 8 | 9 |
| Mean | 6 | 5 | 5 |
| SD | 0.8 | 1 | 2 |
| Panel (b): Willingness to pay bounds from computational second order stochastic assessment | | | |
|  | Q(base)  vs G | Q vs F | F vs G |
| WTP lower bound (t/ha) | 0.036 | 0 | 0.499 |
| WTP upper bound (t/ha) | 0.763 | 0.218 | 1.384 |
| Interpretation | G F/SOSD Q | Not clear | G SOSD F |

The sign for the WTP bounds gives the evaluation of the benefits of the technology for a risk averse farmer. If both upper and lower bounds are positive, the farmer is willing to pay for that strategy. The upper bound is the amount of money that would pay just to stay with the new technology, while the lower bound is the amount that would pay just to be indifferent between the new strategy and the base strategy. For negative WTP for upper and lower bound, it shows that they would need to be paid to accept the proposed strategy. Lower bound is the amount of money that they would accept to abandon their existing strategy. Upper bound is the amount of money that they would accept just to be indifferent between the new strategy and their existing strategy.

### 2.2.3. System economic benefits under risk

For cropping system assessment, we focus on the revenues and partial profits (revenue-cost of irrigation) derived from both rice and wheat. Willingness to pay is therefore in monetary terms rather that quantity terms. We use the same approach as stated above to determine if it is beneficial for a risk averse farmer to adopt the planting date strategy. When the revenue WTP is compared to cost of production differences between the baseline and the proposed strategy, we get the profit potential for the farmers in each grid cells.

# 3. Results

Here we present our results to evaluate the yield and economic risks associated with different rice planting strategies that were simulated across the Indo-Gangetic Plains. We first present results for rice and wheat yields and subsequently assess the performance for system level economic returns and their risks. We use the state recommended calendar dates for rice planting as a baseline (not the farmers’ practice) as it is a more clear-cut strategy than the remotely sensed farmers’ practice.

## 3.1. Yield benefits over baseline for risk averse farmer

Our results provide a strong overview where, from a risk perspective, one strategy outperform another. While the results generally corroborate the findings from the previous crop simulations reported in Urfels et al. (2022), our risk-based framework allows as to identify spatially demarcated zones where risk averse farmers might want to switch strategies and where multiple strategies can work similarly well for risk averse farmers.

### 3.1.1. Rice

Table 3 shows the descriptive statistics on the willingness to pay bounds (ton/ha) in rice yield equivalent for the planting date scenarios in comparison to the fixed date with long duration variety planting strategy. The WTP summary rows show the percentage of farmers who are more likely to (a) benefit, (b) be worse off or (c) be indifferent between the planting date strategies. Only 31% of the farmers would find the planting long duration rice varieties at the monsoon onset as beneficial followed by planting medium duration varieties at the recommended calendar dates medium (30%). For farmer practice, the average and median WTP bounds (both lower and upper) are negative implying that farmers are overall worse off using their current rice planting strategies.

Table 3: Rice WTP bounds with fixed long as baseline, IGP

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Bound | Statistics | S0-S1 | S2-S1 | S3-S1 | S4-S1 | S5-S1 | S6-S1 |
| Upper bound | Mean | -1.03 | 1.90 | 0.76 | 0.41 | 1.32 | 1.01 |
| Std.Dev | 1.36 | 1.75 | 2.50 | 2.38 | 1.79 | 1.76 |
| Min | -5.65 | -2.47 | -5.58 | -5.65 | -4.23 | -4.38 |
| 10th percentile | -2.17 | -1.60 | -2.26 | -2.35 | -1.65 | -1.53 |
| 25th percentile | -1.85 | 1.32 | -0.58 | -0.88 | 0.66 | -0.47 |
| Median | -1.33 | 2.48 | 0.04 | -0.30 | 1.77 | 1.53 |
| 75th percentile | -0.45 | 3.04 | 3.18 | 2.86 | 2.38 | 2.20 |
| 90th percentile | 0.15 | 3.52 | 4.11 | 3.68 | 3.06 | 2.93 |
| Max | 5.92 | 5.64 | 5.73 | 5.65 | 10.95 | 8.90 |
| Lower bound | Mean | -3.53 | -0.73 | -1.42 | -2.02 | -1.27 | -1.49 |
| Std.Dev | 1.68 | 1.73 | 2.60 | 2.47 | 1.78 | 1.68 |
| Min | -7.83 | -4.69 | -7.02 | -6.16 | -7.02 | -7.20 |
| 10th percentile | -5.53 | -2.47 | -5.13 | -5.19 | -2.75 | -3.20 |
| 25th percentile | -4.62 | -2.03 | -3.76 | -4.41 | -2.28 | -2.52 |
| Median | -3.71 | -1.15 | -0.71 | -1.87 | -1.51 | -1.82 |
| 75th percentile | -2.32 | 0.35 | 0.18 | -0.14 | -0.34 | -0.54 |
| 90th percentile | -1.89 | 1.92 | 1.90 | 1.18 | 1.16 | 0.73 |
| Max | 4.84 | 5.05 | 4.79 | 4.66 | 8.50 | 6.49 |
| WTP summary | Clearly better (share) | 0.02 | 0.30 | 0.31 | 0.21 | 0.21 | 0.18 |
| Not clear (share) | 0.11 | 0.52 | 0.21 | 0.19 | 0.59 | 0.53 |
| Clearly worse (share) | 0.87 | 0.18 | 0.49 | 0.60 | 0.21 | 0.29 |
| Number of cells | 17411.00 | 17412.00 | 17420.00 | 17421.00 | 17421.00 | 17421.00 |

Note: The number of cells are lower for S0-S1, S2-S1 and S3-S1 due to missing information in some of the grid cells.

Figure 2 shows for which grid cells the proposed planting strategy is clearly better, clearly worse, or neither better or worse than the state recommended planting dates with long duration varieties. Among these, planting with monsoon onset with a long duration strategy seems to provide much advantage in the eastern part of IGP. The western part seems to benefit more from the fixed date recommendation with long duration variety. The yield trends have been discussed in Urfels et al. (2022), pointing out the Middle IGP is a transition zone. Our risk-based approach corroborates these findings and provides additional insight into the transition areas where it clearly demarcates where one strategy supersedes the other, and where several strategies provide comparable benefits (e.g. see Figure 2c).

A collage of maps

Description automatically generated

Figure 2: Willingness to pay **(rice yield t/ha)** for the strategy against a fixed long duration variety reference strategy using second order stochastic dominance

### 3.1.2. Wheat

Like in rice, our results for wheat show how rice planting strategies affect the wheat crops – which is grown directly after rice harvest and its planting date thus strongly dependent on the rice planting date. Table 4 shows descriptive statistics of the willingness to pay bounds in wheat yield equivalent (t/ha) for the scenarios in comparison to fixed date recommendation with long duration rice variety rice planting strategy (here after called fixed long strategy). Column (S0-S1) shows the comparison between farmer practice and fixed long strategy. It is apparent from the lower bound estimates, almost 90% of farmers have negative WTP lower bound for the farmer practice strategy when compared with the fixed long strategy. For about 25% of these, even the upper WTP is negative. Farmer practice is a good strategy for risk averse farmers for only about 4% of the grid cells. For wheat the best strategy seems to be planting medium duration varieties and state recommended calendar dates in that most of grid cells (86%) will benefit with higher wheat yields as compared to the fixed long rice planting strategy.

Table 4: Wheat WTP bounds (ton/ha) with fixed date-long variety scenario as baseline, IGP

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Bound | Statistics | S0-S1 | S2-S1 | S3-S1 | S4-S1 | S5-S1 | S6-S1 |
| Upper bound | Mean | -0.50 | 1.00 | 0.22 | -0.88 | 0.17 | -0.65 |
| Std.Dev | 0.83 | 0.46 | 0.64 | 1.19 | 0.70 | 1.14 |
| Min | -5.47 | -0.08 | -1.16 | -4.06 | -1.56 | -4.19 |
| 10th percentile | -1.89 | 0.28 | -0.58 | -2.55 | -0.76 | -2.19 |
| 25th percentile | -0.71 | 0.71 | -0.18 | -1.78 | -0.42 | -1.63 |
| Median | -0.29 | 1.09 | 0.08 | -0.79 | 0.20 | -0.50 |
| 75th percentile | 0.00 | 1.34 | 0.54 | -0.06 | 0.75 | 0.29 |
| 90th percentile | 0.28 | 1.53 | 1.28 | 0.77 | 1.11 | 0.75 |
| Max | 1.59 | 1.99 | 2.05 | 1.91 | 1.78 | 1.61 |
| Lower bound | Mean | -1.94 | 0.49 | -0.37 | -1.69 | -0.37 | -1.62 |
| Std.Dev | 1.45 | 0.37 | 0.83 | 1.45 | 0.79 | 1.47 |
| Min | -7.00 | -0.55 | -2.29 | -6.67 | -2.29 | -6.67 |
| 10th percentile | -3.88 | -0.02 | -1.49 | -3.69 | -1.50 | -3.65 |
| 25th percentile | -3.15 | 0.27 | -0.90 | -2.97 | -1.01 | -2.83 |
| Median | -2.14 | 0.49 | -0.37 | -1.64 | -0.21 | -1.70 |
| 75th percentile | -0.58 | 0.70 | 0.15 | -0.52 | 0.28 | -0.17 |
| 90th percentile | -0.04 | 1.07 | 0.79 | 0.29 | 0.47 | 0.24 |
| Max | 1.34 | 1.34 | 1.62 | 1.49 | 1.35 | 1.23 |
| WTP summary | Clearly better (share) | 0.04 | 0.86 | 0.28 | 0.15 | 0.40 | 0.20 |
| Not clear (share) | 0.20 | 0.12 | 0.35 | 0.09 | 0.19 | 0.14 |
| Clearly worse (share) | 0.75 | 0.01 | 0.37 | 0.76 | 0.41 | 0.66 |
| Number of cells | 17421.00 | 17421.00 | 17421.00 | 17421.00 | 17421.00 | 17421.00 |

However, there is a clear spatial structure to these results. Figure 3 shows the spatial distribution of willingness to pay classifications categorizing strategies on wheat yield whether they are worse, better or worse, and better than the fixed long rice planting strategy. Fixed planting of a medium duration rice variety seems to be the best strategy to ensure higher wheat yields across most locations in IGP except the northwestern side where one would be indifferent (12%). Besides, the Eastern IGP also performs well with planting long duration varieties at the monsoon onset, which is much earlier in the Eastern IGP than in the Western IGP.

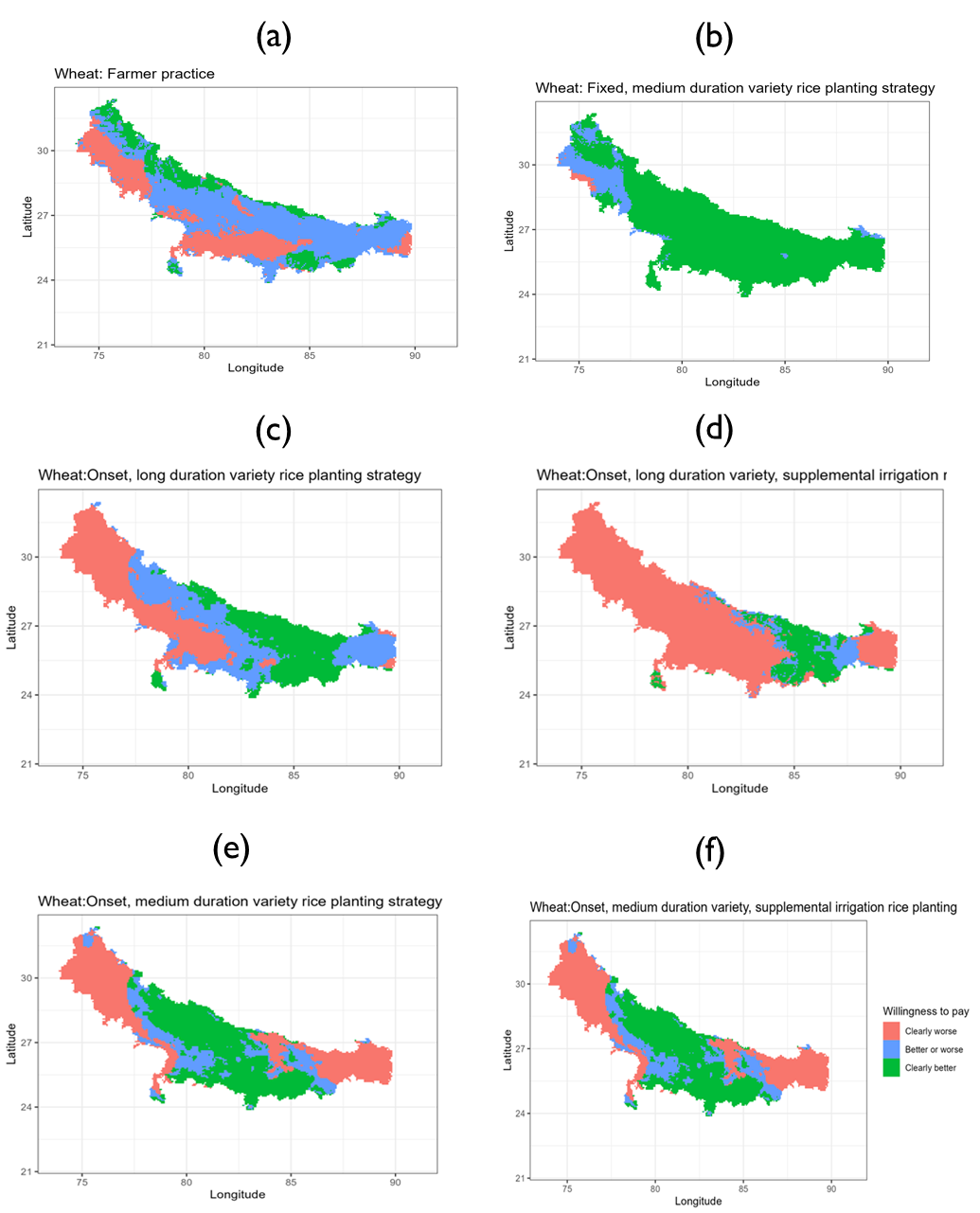


Figure 3: Willingness to pay (wheat yield t/ha) for the strategy against a fixed long duration variety reference strategy using second order stochastic dominance.

## 3.2. System-wide economic benefits for a risk averse farmer

The above yield-based risk assessment likely matter most to subsistence farmers. Most farmers in the IGP, however, sell some parts of their produce. Fully evaluating the system level risks thus requires an economic evaluation across both crops. We first provide an overview of the revenue and associated risks, followed by a more profit-oriented analysis that includes partial costs incurred for irrigation to estimate – as this is the only cost variable that varies across our scenarios.

### 3.2.1. System revenues

To calculate system revenues, we used grid cells level prices of rice and wheat to compute the revenues of following each of the scenarios. The grid cells level prices are obtained by interpolating prices from the Landscape Crop Assessment Survey (LCAS) for 2017/18 season. We then use these economic indicators in the stochastic comparisons. Table 5 shows the descriptive statistics for the willingness to pay bounds. Starting with the percentage of grid cells that would benefit from each of the scenarios as compared to the baseline, the WTP summary rows show that farmers’ practices is the worst performing strategy across the IGP (column 3) with 78% losing compared to the state recommended planting dates. This is followed by planting medium duration varieties at the monsoon onset with constrained irrigation (column 8) that results in 52% of cells clearly worse off than the baseline.

Table 5: Gross revenue WTP (thousand rupees/ha) bounds with fixed long as baseline

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Bound | Statistics | S0-S1 | S2-S1 | S3-S1 | S4-S1 | S5-S1 | S6-S1 |
| Upper bound | Mean | -23.99 | 34.99 | 8.37 | -14.67 | 14.30 | 1.49 |
| Std.Dev | 25.96 | 28.30 | 41.11 | 47.53 | 29.59 | 31.35 |
| Min | -144.09 | -28.54 | -84.72 | -125.24 | -64.90 | -89.49 |
| 10th percentile | -56.03 | -15.52 | -45.24 | -74.99 | -26.87 | -37.83 |
| 25th percentile | -39.27 | 22.03 | -19.37 | -51.28 | -4.45 | -19.90 |
| Median | -24.18 | 41.04 | 1.34 | -18.60 | 15.28 | -1.92 |
| 75th percentile | -12.33 | 56.10 | 39.14 | 20.11 | 36.06 | 25.19 |
| 90th percentile | 1.85 | 66.82 | 69.81 | 56.16 | 53.93 | 45.26 |
| Max | 87.55 | 91.16 | 96.57 | 86.07 | 132.20 | 108.48 |
| Lower bound | Mean | -73.43 | -1.39 | -18.36 | -43.68 | -16.67 | -28.19 |
| Std.Dev | 36.34 | 25.91 | 43.02 | 49.08 | 28.35 | 30.59 |
| Min | -177.76 | -59.94 | -123.07 | -139.93 | -119.55 | -151.45 |
| 10th percentile | -113.83 | -28.09 | -77.92 | -109.68 | -46.58 | -65.46 |
| 25th percentile | -94.35 | -20.99 | -53.41 | -86.66 | -30.70 | -43.60 |
| Median | -72.95 | -6.29 | -13.44 | -42.45 | -19.58 | -29.30 |
| 75th percentile | -56.20 | 16.31 | 10.49 | -3.30 | -1.85 | -11.96 |
| 90th percentile | -29.14 | 36.79 | 37.99 | 22.05 | 20.96 | 11.44 |
| Max | 83.40 | 69.35 | 87.03 | 76.56 | 113.90 | 83.34 |
| WTP summary | Clearly better (share) | 0.02 | 0.42 | 0.36 | 0.23 | 0.23 | 0.16 |
| Not clear (share) | 0.09 | 0.42 | 0.16 | 0.14 | 0.44 | 0.32 |
| Clearly worse (share) | 0.89 | 0.16 | 0.48 | 0.63 | 0.32 | 0.52 |
| Number of cells | 17456.00 | 17456.00 | 17456.00 | 17456.00 | 17456.00 | 17456.00 |

These results show that there is no one size fits all strategy and we further investigate the spatial structure to better understand the performance of different rice planting strategies across the IGP. Spatially, there are pockets for which a risk averse farmer would not switch to the recommended fixed date with long duration variety strategy especially in the central grid cells of Bihar. Again, the spatial structure of the results shows where, due to interannual weather risks, farmers may fare best to choose one specific strategy and where they might be similarly well off with more than strategy.

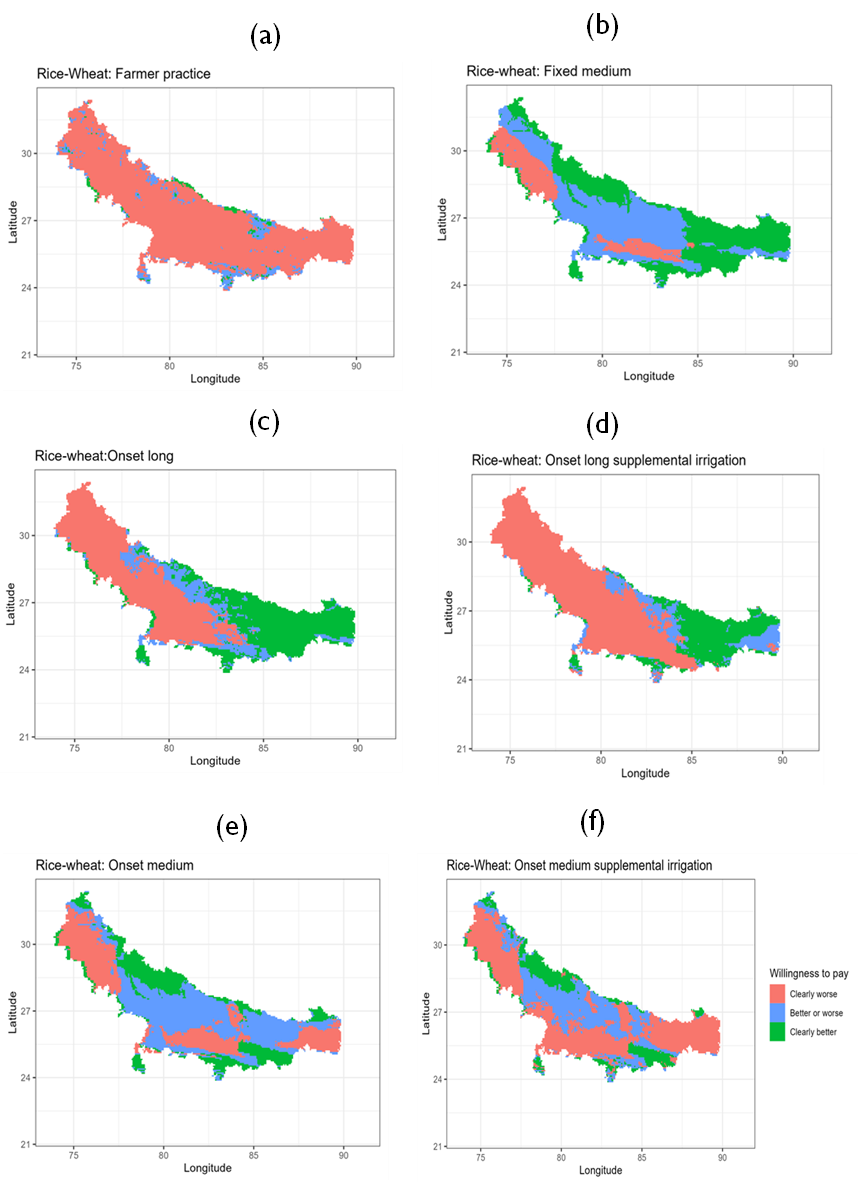


Figure 4: Spatial distribution of revenue WTP (where to target the scenarios)

### 3.2.2. System partial profits

When considering partial profits as incurred by the varying irrigation costs, the results again show that there is no one size fits all solution for the IGP with no single rice planting strategy outperforming others. Table 6 shows descriptive statistics for willingness to pay for partial profits (revenue-irrigation costs) for each of the planting date strategies as compared to fixed date-long duration rice variety strategy. As with productivity and revenue comparisons, farmer practice is a worse strategy for about 85% of the grid cells in IGP. None of the strategies dominate across the entire IGP.

Table 6: Partial profits WTP (thousand rupees/ha) descriptive statistics

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Bound | Statistics | S0-S1 | S2-S1 | S3-S1 | S4-S1 | S5-S1 | S6-S1 |
| Upper bound | Mean | -15.31 | 40.40 | 12.30 | 7.84 | 23.80 | 25.40 |
| Std.Dev | 22.82 | 28.98 | 42.88 | 46.27 | 31.34 | 34.62 |
| Min | -97.77 | -25.01 | -80.65 | -95.69 | -62.89 | -82.90 |
| 10th percentile | -36.40 | -10.73 | -42.52 | -49.44 | -21.58 | -17.54 |
| 25th percentile | -26.88 | 24.88 | -16.26 | -27.25 | 7.19 | -1.91 |
| Median | -18.74 | 47.15 | 2.00 | 1.43 | 24.04 | 23.22 |
| 75th percentile | -8.09 | 62.14 | 48.44 | 41.74 | 48.21 | 52.55 |
| 90th percentile | 6.10 | 72.21 | 77.33 | 79.22 | 63.93 | 74.15 |
| Max | 99.85 | 96.57 | 103.13 | 112.42 | 137.49 | 129.42 |
| Lower bound | Mean | -50.40 | 3.51 | -16.12 | -24.19 | -8.78 | -5.70 |
| Std.Dev | 26.63 | 25.83 | 44.08 | 47.57 | 28.33 | 32.81 |
| Min | -126.29 | -54.20 | -115.70 | -112.73 | -103.66 | -118.82 |
| 10th percentile | -79.57 | -23.43 | -73.37 | -82.82 | -38.10 | -47.72 |
| 25th percentile | -66.27 | -16.27 | -54.83 | -66.11 | -23.19 | -23.23 |
| Median | -52.75 | -0.94 | -13.87 | -28.33 | -12.87 | -6.43 |
| 75th percentile | -35.94 | 20.98 | 16.24 | 13.97 | 6.85 | 12.31 |
| 90th percentile | -21.19 | 41.44 | 44.49 | 43.67 | 29.05 | 36.92 |
| Max | 89.66 | 76.40 | 90.44 | 97.08 | 120.33 | 99.99 |
| WTP summary | Clearly better (share) | 0.02 | 0.49 | 0.37 | 0.31 | 0.32 | 0.38 |
| Not clear (share) | 0.13 | 0.37 | 0.18 | 0.21 | 0.48 | 0.35 |
| Clearly worse (share) | 0.85 | 0.14 | 0.45 | 0.48 | 0.21 | 0.27 |
| Number of cells | 17420.00 | 17420.00 | 17420.00 | 17420.00 | 17420.00 | 17420.00 |

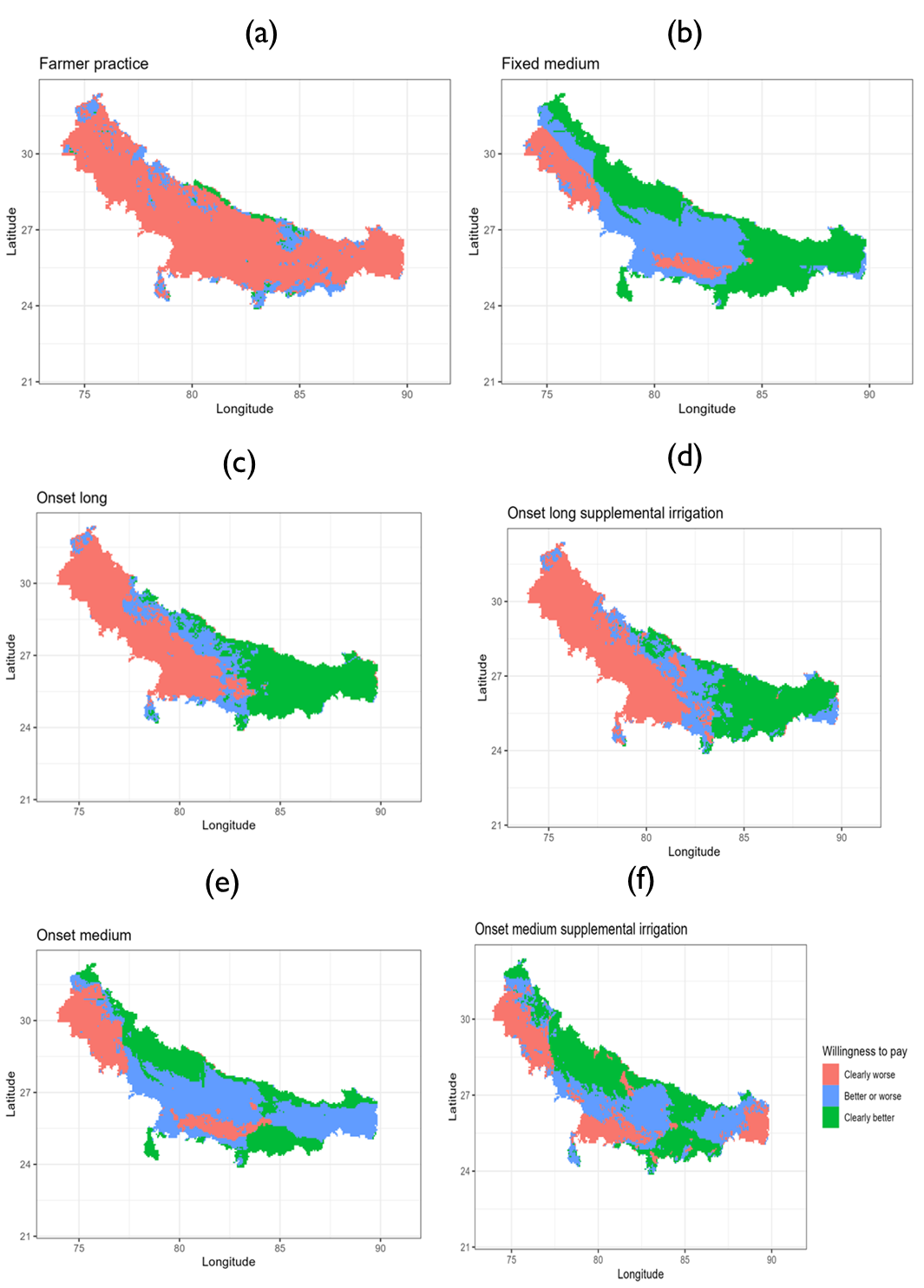


Figure 5: Spatial distribution of partial profit WTP (where to target the scenarios)

# 4. Recommended rice planting date strategy per grid cell

Lastly, our risk-based evaluation approach allows us to compare all of the rice planting strategies against each other and identify which strategy performs clearly better and with less risks involved than any other strategy and where several competing strategies might result in similar economic benefits as well as risks. In other words, the foregoing analyses has made binary or pairwise comparisons – while the most important question is which strategy should be recommended where? To derive this optimal scenario, we calculate the maximum upper bound WTP among the scenarios and the maximum lower WTP. If one single scenario clearly pay more and clearly induces less risks than the others, we select that scenario for that particular grid cell. As a result, Figure 6 shows the optimal rice planting date strategy. Importantly, in addition to the findings of Urfels et al. (2022), our framework shows that, for example, in parts of the Eastern Gangetic Plains providing only supplemental irrigation rather than full irrigation is economically beneficial from a risk perspective. While the same is true for some areas in the northern parts of the Middle and Western IGP – indicating that climatic and soil variability in the Northern and Southern parts of the Western and Middle IGP produce substantially different outcomes – but also indicating that in these areas multiple rice planting strategies perform equally well and farmers have more flexibility to choose amongst various options for similar results.

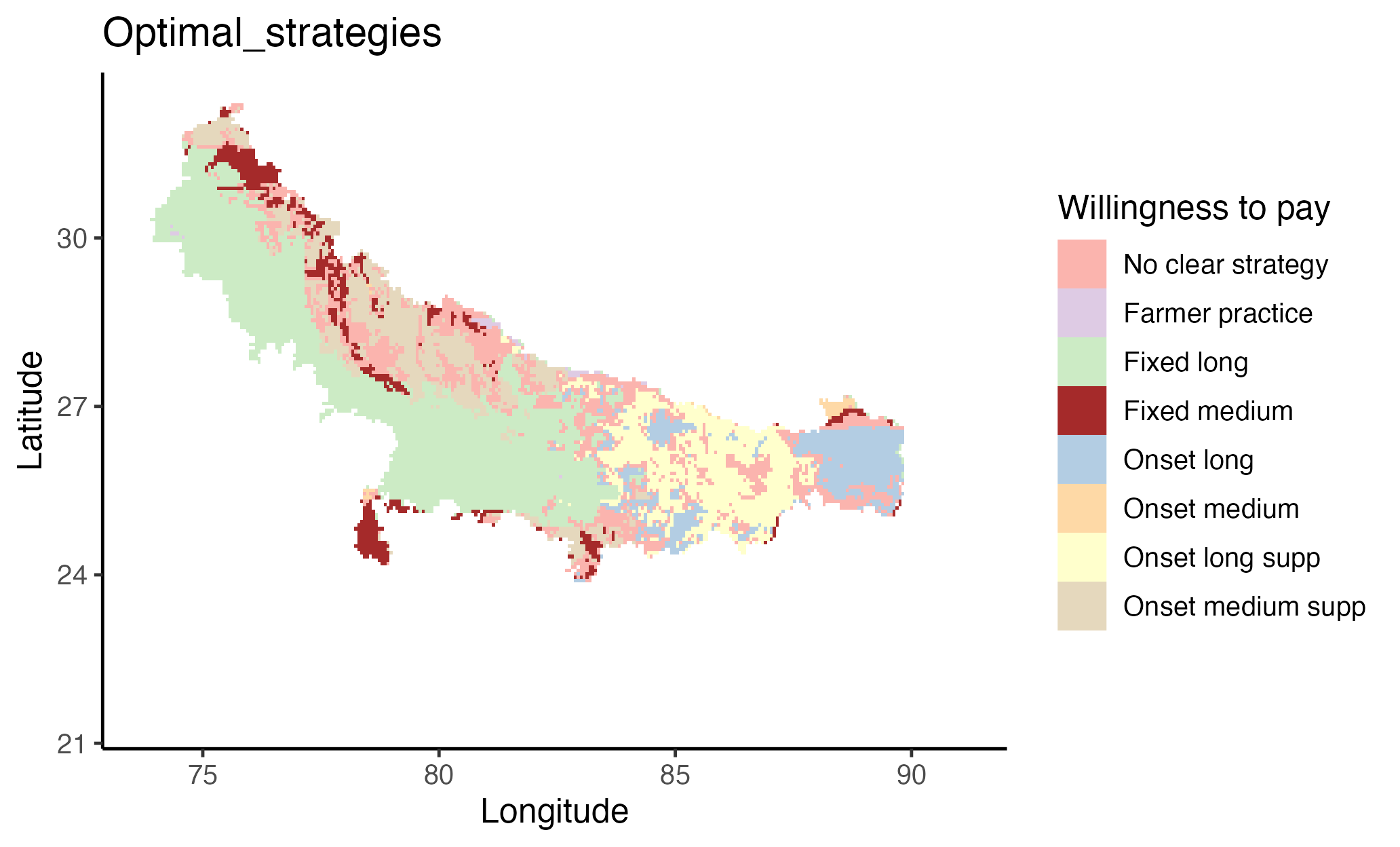


Figure 6: Optimal rice planting date strategy

# 5. Conclusion

We have shown in this article how a spatially explicit risk-assessment framework can provide evidences on how different agronomic climate adaptation strategies can be adequately evaluated for risk averse farmers. Our work builds on aand usesOur results for the IGP provide further evidence that early sowing of long duration rice is a suitable strategy for risk averse farmers of the rice-wheat rotation system in Bihar – while planting at state recommended dates and growing medium duration varieties is a better option in the Western and Middle IGP. Importantly, we also show that farmers in the Middle IGP have more flexibility to choose amongst competing options without jeopardizing incomes or increasing risks. With weather variability expected to further increase, our risk-assessment approach can provide a robust framework for evaluating various competing climate adaptation options for risk averse smallholder farmers that not only benefit from higher long term gains – but also seek to minimize losses in any given year.

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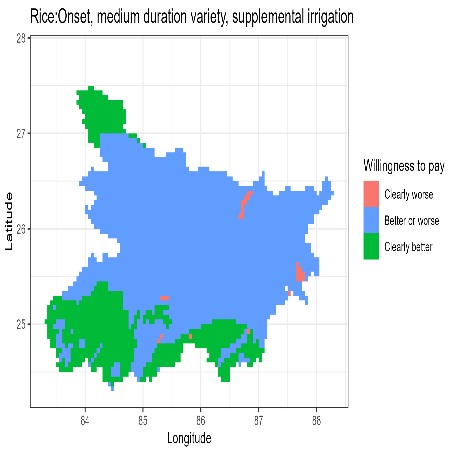
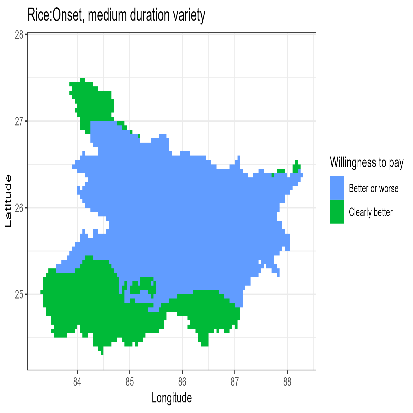
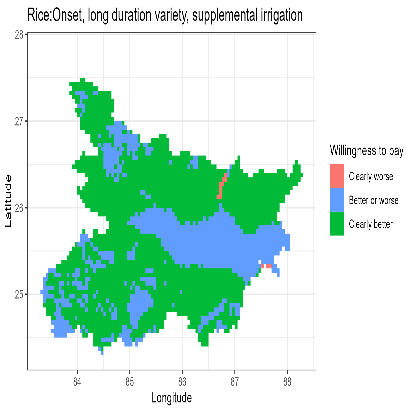
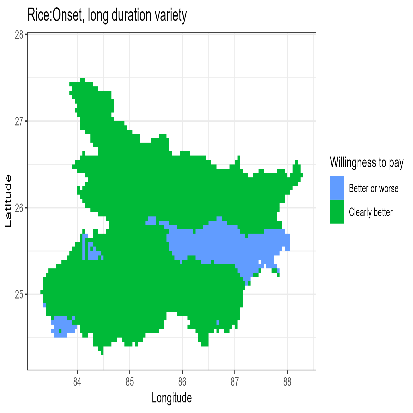
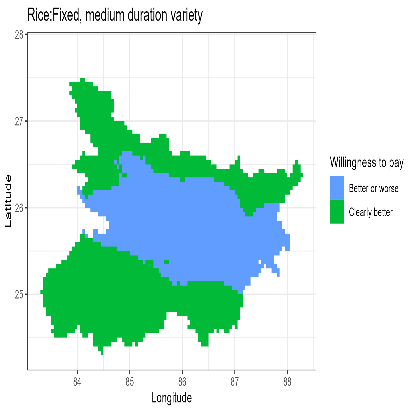
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# Appendices

## Appendix A: Fixed long as baseline with zero yield entries, Bihar



a

b

c

d

e

f

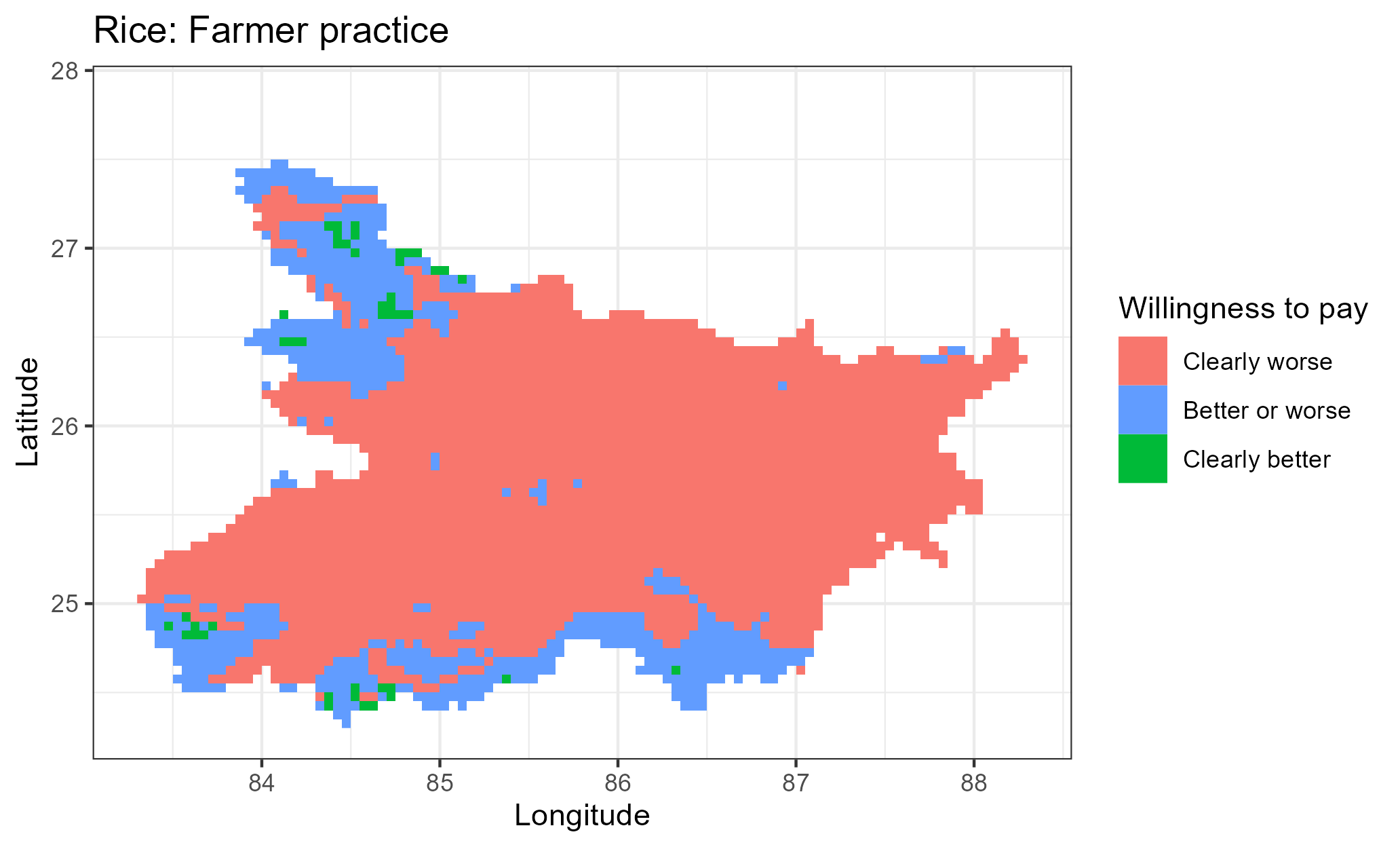


Figure A1: Rice WTP decisions as compared to fixed long strategy

a

b

c

d

e

f

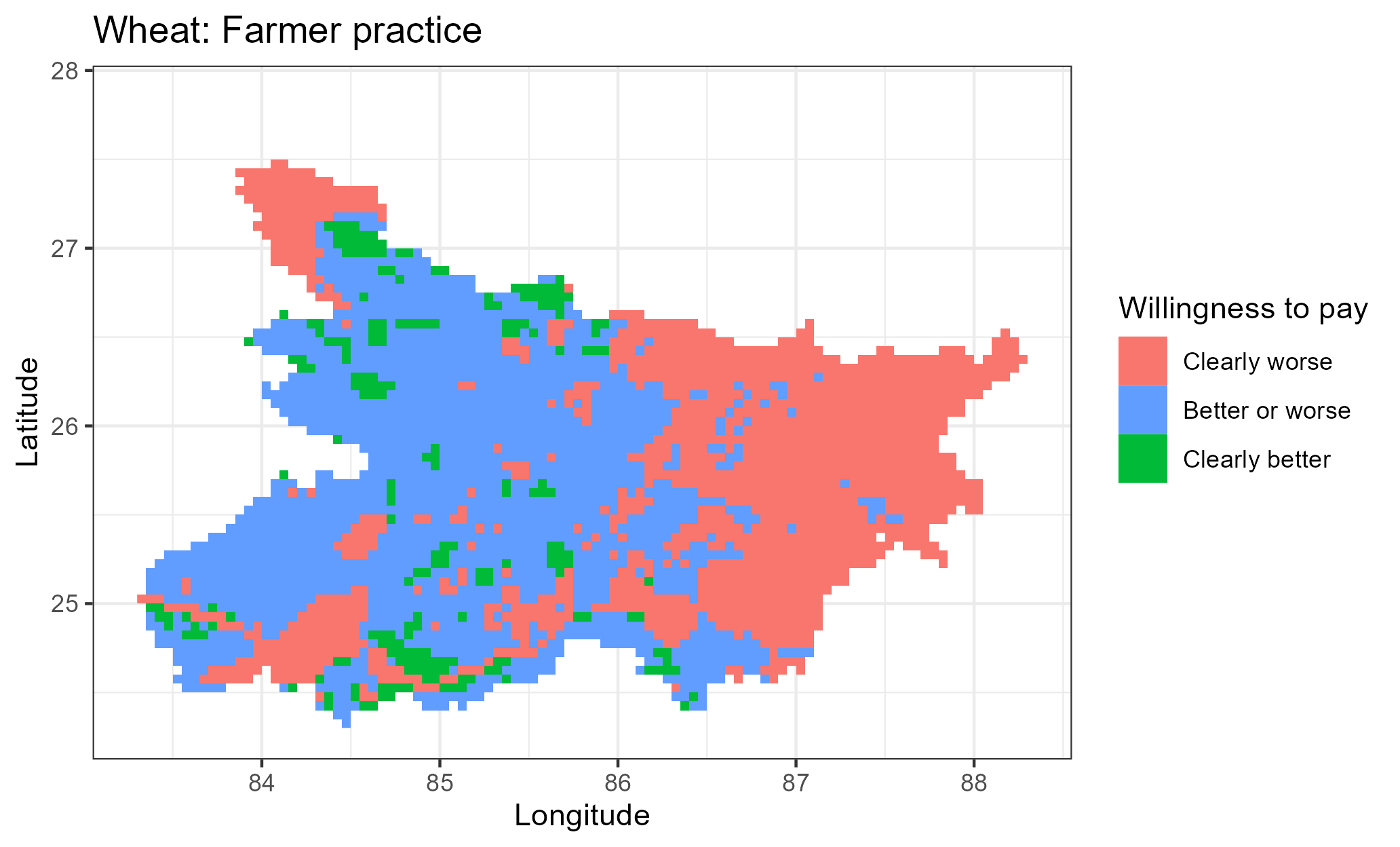
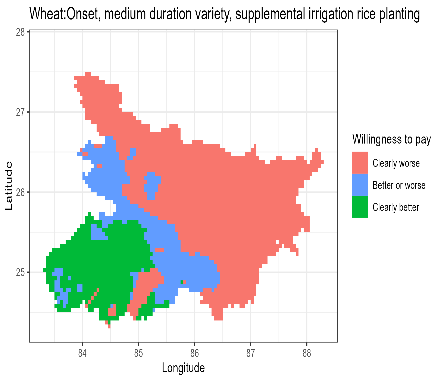
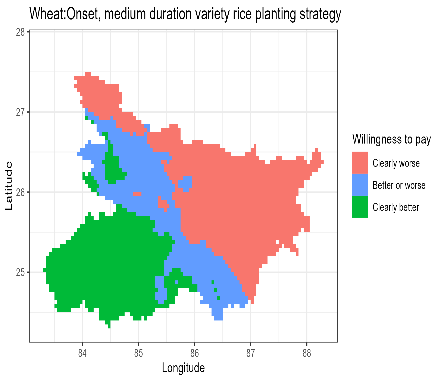
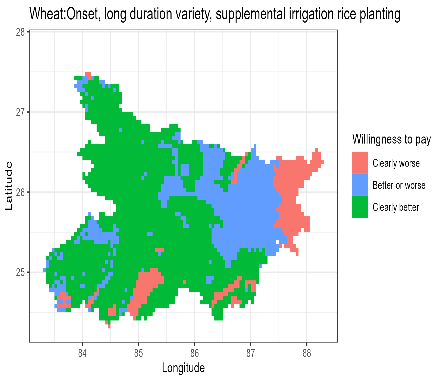
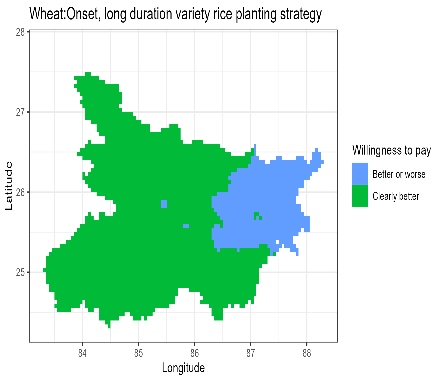
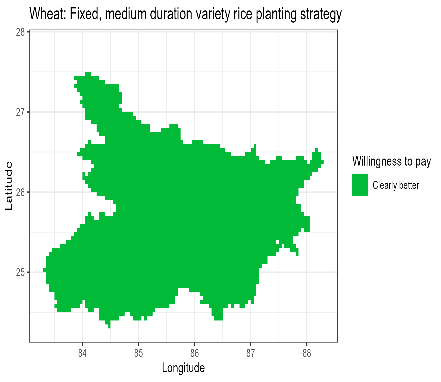


Figure A2: Wheat WTP decisions as compared to fixed long strategy

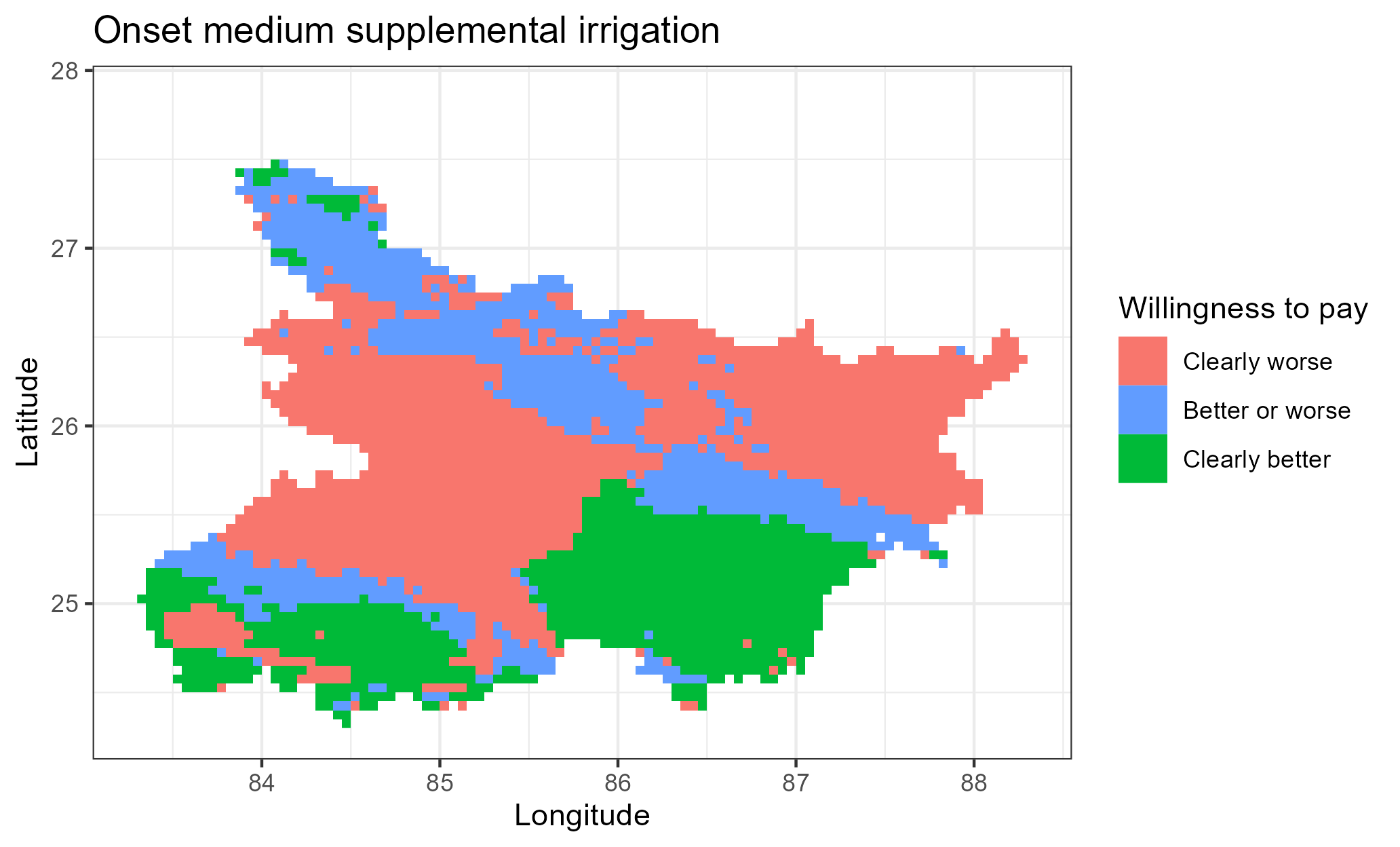
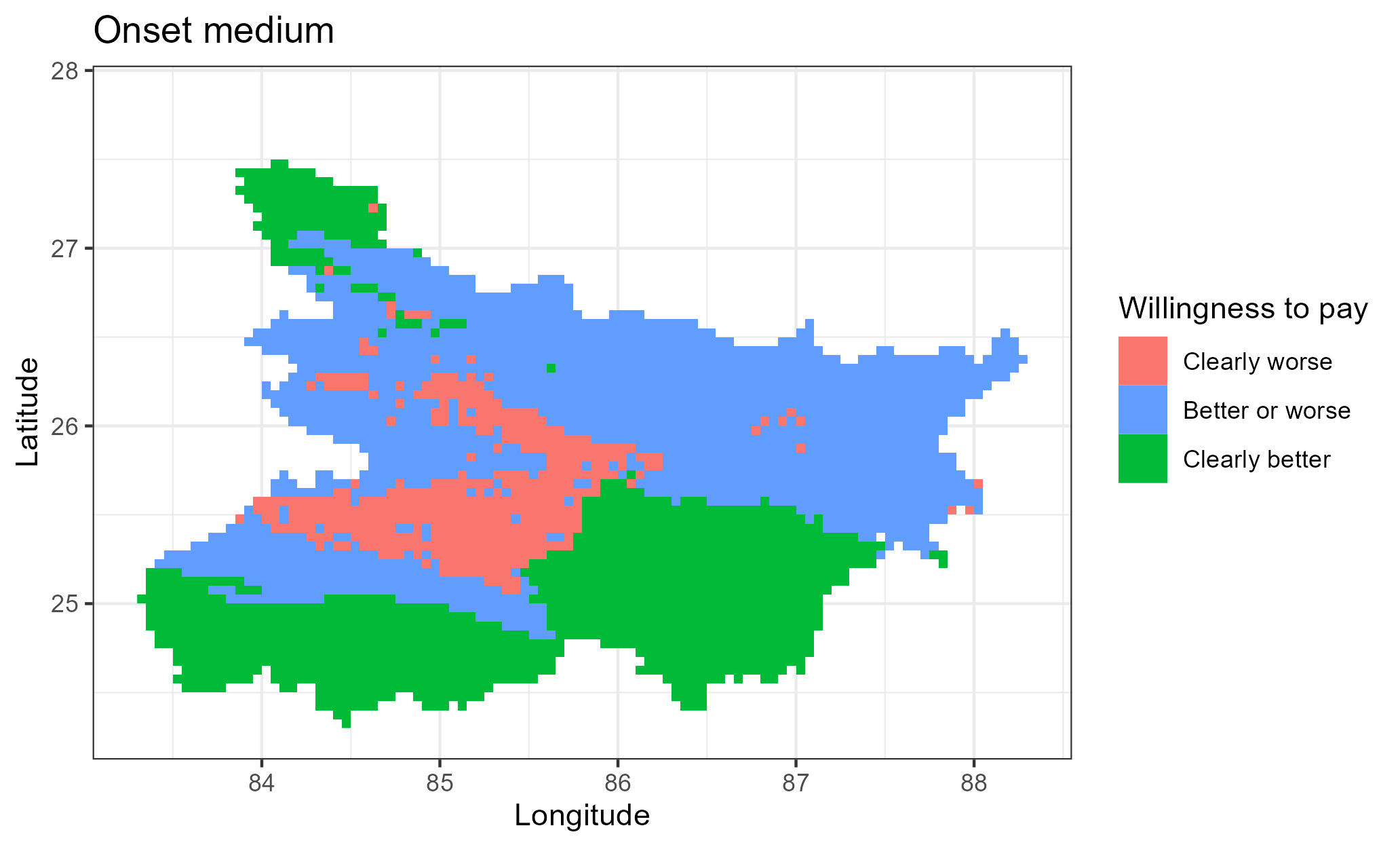
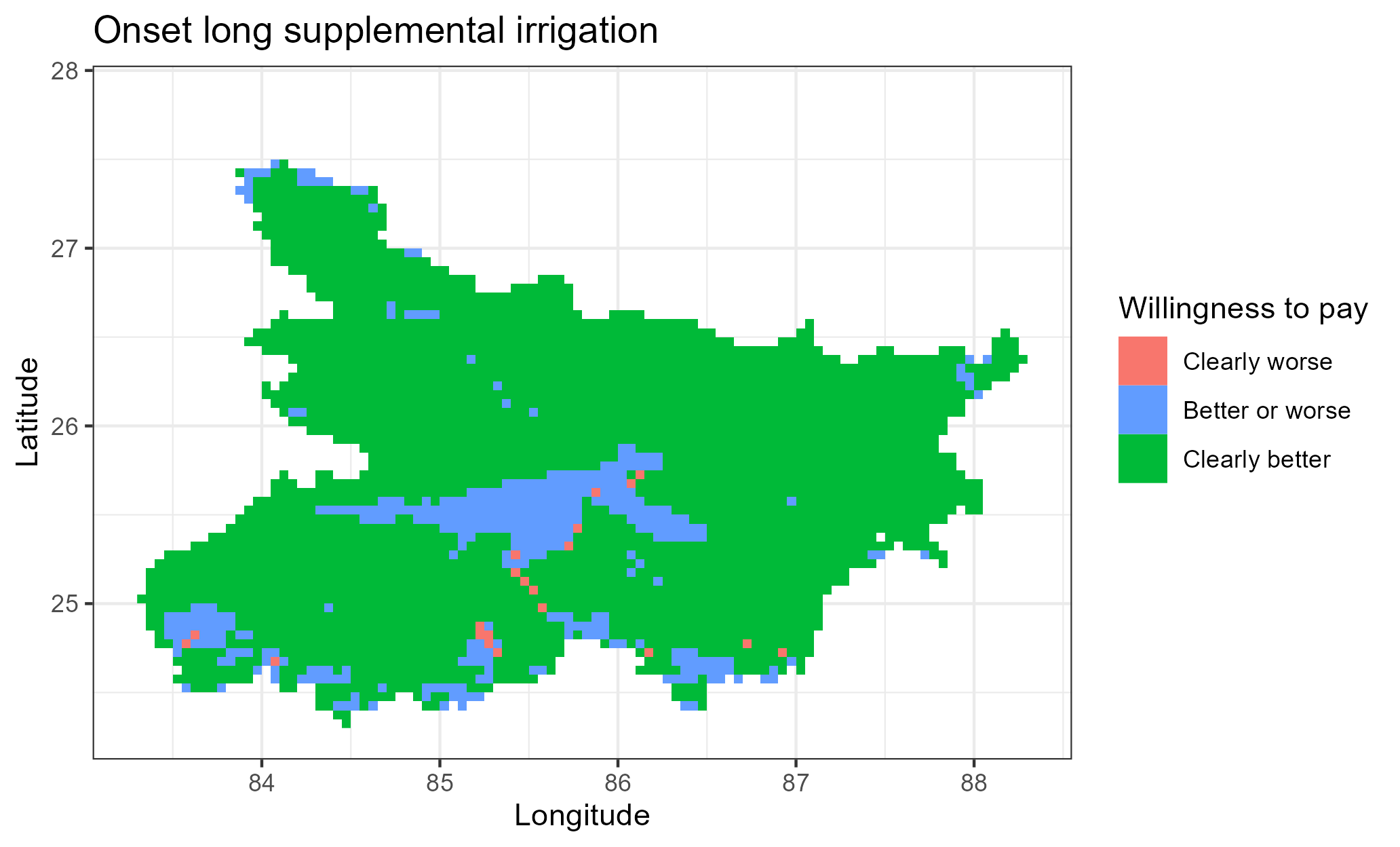
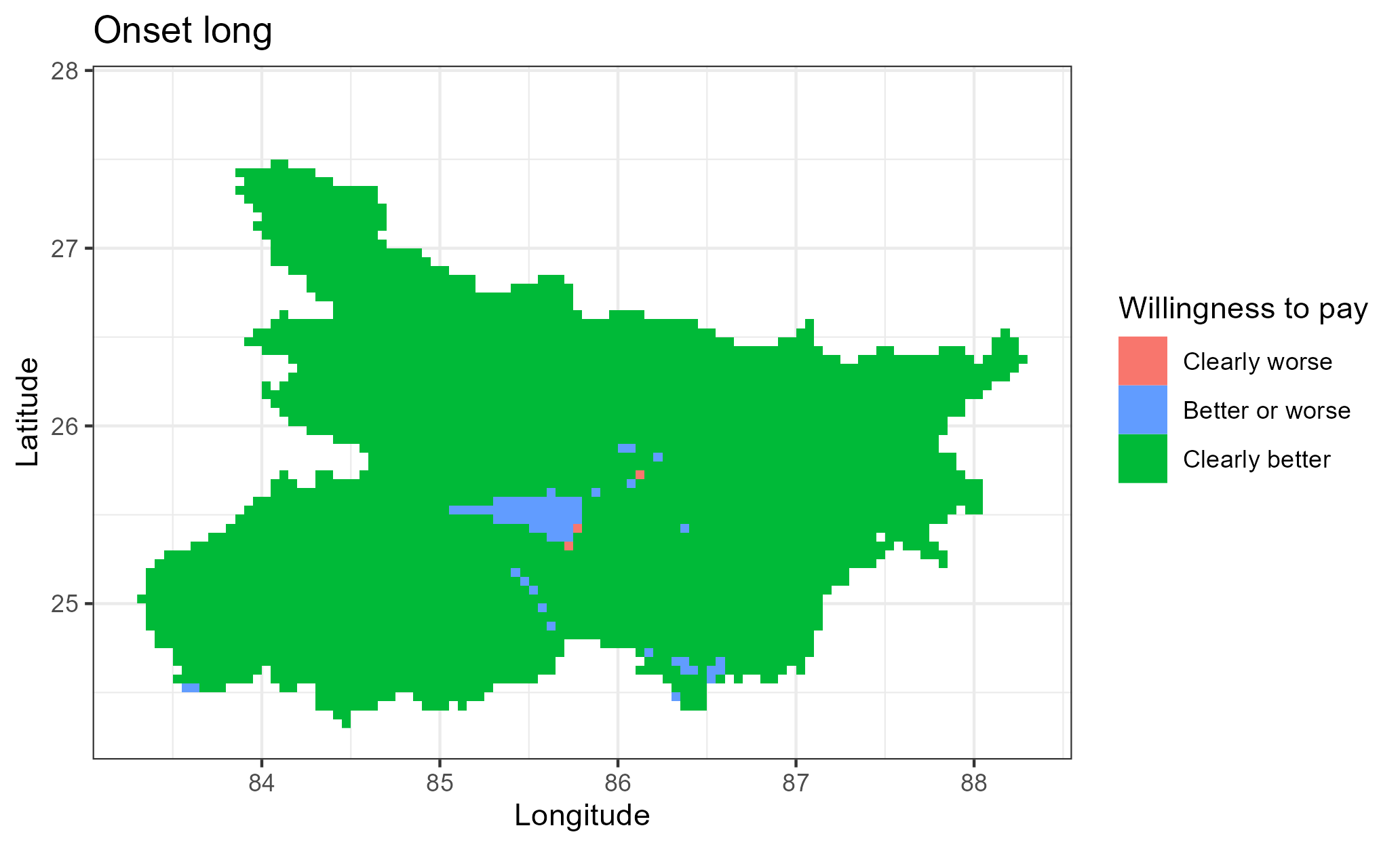
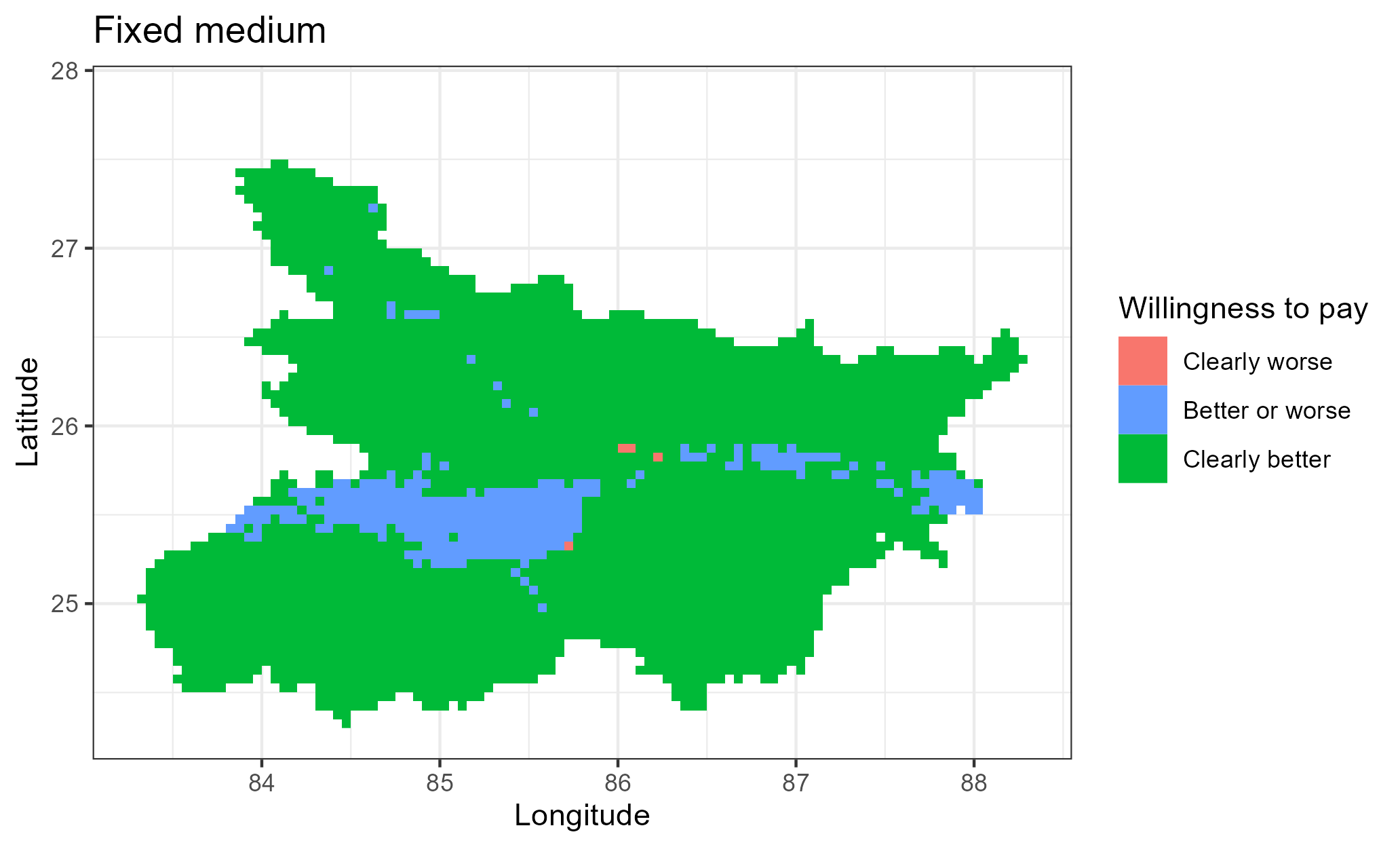
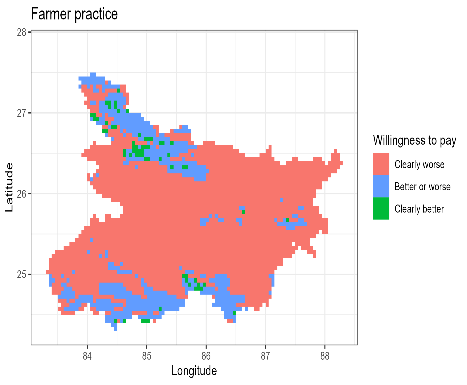


Figure A3: Revenue WTP decisions as compared to fixed long strategy

Table A1: Rice WTP bounds with fixed long as baseline [with zero yield entries], Bihar

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Bound | Statistics | S0-S1 | S2-S1 | S3-S1 | S4-S1 | S5-S1 | S6-S1 |
| Upper bound | Mean | -0.84 | 2.92 | 3.95 | 3.57 | 1.91 | 1.80 |
| Standard deviation | 1.57 | 0.41 | 0.62 | 0.63 | 0.35 | 0.45 |
| Min | -2.20 | 2.27 | 2.89 | -1.75 | 1.29 | -1.95 |
| 10th percentile | -1.92 | 2.50 | 3.18 | 3.03 | 1.55 | 1.45 |
| 25th percentile | -1.87 | 2.61 | 3.44 | 3.20 | 1.64 | 1.60 |
| Median | -1.69 | 2.79 | 3.85 | 3.48 | 1.84 | 1.79 |
| 75th percentile | -0.41 | 3.18 | 4.40 | 3.95 | 2.13 | 2.03 |
| 90th percentile | 1.86 | 3.49 | 4.85 | 4.37 | 2.40 | 2.31 |
| Max | 4.88 | 4.19 | 5.73 | 5.33 | 3.12 | 2.97 |
| Lower bound | Mean | -3.21 | 0.44 | 1.43 | 0.73 | -0.61 | -0.86 |
| Standard deviation | 1.44 | 1.38 | 1.23 | 1.18 | 1.33 | 1.28 |
| Min | -6.59 | -1.73 | -1.71 | -3.91 | -2.66 | -3.04 |
| 10th percentile | -5.31 | -1.31 | -0.10 | -0.44 | -2.24 | -2.29 |
| 25th percentile | -4.28 | -0.66 | 0.43 | -0.12 | -1.68 | -1.91 |
| Median | -3.08 | 0.25 | 1.29 | 0.57 | -0.84 | -1.14 |
| 75th percentile | -2.06 | 1.37 | 2.27 | 1.47 | 0.28 | -0.08 |
| 90th percentile | -1.82 | 2.68 | 3.25 | 2.39 | 1.49 | 1.20 |
| Max | 0.76 | 3.69 | 4.79 | 4.37 | 2.45 | 2.35 |
| WTP summary | Clearly better (share) | 0.01 | 0.57 | 0.87 | 0.69 | 0.29 | 0.24 |
| Not clear (share) | 0.19 | 0.43 | 0.13 | 0.30 | 0.71 | 0.75 |
| Clearly worse (share) | 0.79 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Number of cells | 3386.00 | 3386.00 | 3386.00 | 3386.00 | 3386.00 | 3386.00 |

Table A2: Wheat WTP bounds with fixed long as baseline, Bihar

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Bound | Statistics | S0-S1 | S2-S1 | S3-S1 | S4-S1 | S5-S1 | S6-S1 |
| Upper bound | Mean | -0.34 | 1.28 | 1.23 | 0.64 | 0.20 | -0.37 |
| Standard deviation | 0.98 | 0.12 | 0.38 | 0.69 | 0.76 | 1.03 |
| Min | -2.60 | 0.60 | 0.18 | -2.39 | -1.11 | -2.39 |
| 10th percentile | -1.98 | 1.15 | 0.64 | -0.09 | -0.80 | -1.78 |
| 25th percentile | -1.16 | 1.23 | 0.98 | 0.48 | -0.37 | -1.22 |
| Median | 0.05 | 1.30 | 1.29 | 0.75 | 0.11 | -0.36 |
| 75th percentile | 0.32 | 1.37 | 1.50 | 1.04 | 0.82 | 0.47 |
| 90th percentile | 0.59 | 1.40 | 1.65 | 1.25 | 1.32 | 1.10 |
| Max | 1.59 | 1.53 | 2.05 | 1.91 | 1.69 | 1.61 |
| Lower bound | Mean | -1.71 | 1.03 | 0.66 | 0.04 | -0.24 | -1.15 |
| Standard deviation | 1.23 | 0.12 | 0.61 | 0.90 | 0.78 | 1.10 |
| Min | -3.72 | 0.38 | -0.89 | -3.47 | -1.42 | -3.72 |
| 10th percentile | -3.13 | 0.88 | -0.26 | -1.04 | -1.08 | -2.18 |
| 25th percentile | -2.64 | 0.98 | 0.23 | -0.34 | -0.87 | -1.88 |
| Median | -2.11 | 1.06 | 0.78 | 0.25 | -0.47 | -1.60 |
| 75th percentile | -0.01 | 1.11 | 1.17 | 0.64 | 0.36 | -0.49 |
| 90th percentile | 0.00 | 1.15 | 1.34 | 0.93 | 1.07 | 0.81 |
| Max | 1.34 | 1.24 | 1.62 | 1.49 | 1.35 | 1.23 |
| WTP summary | Clearly better (share) | 0.06 | 1.00 | 0.80 | 0.64 | 0.31 | 0.19 |
| Not clear | 0.52 | 0.00 | 0.20 | 0.25 | 0.25 | 0.19 |
| Clearly worse (share) | 0.42 | 0.00 | 0.00 | 0.11 | 0.44 | 0.62 |
| Number of cells | 3386.00 | 3386.00 | 3386.00 | 3386.00 | 3386.00 | 3386.00 |

Table A3: Revenue WTP descriptive, Bihar

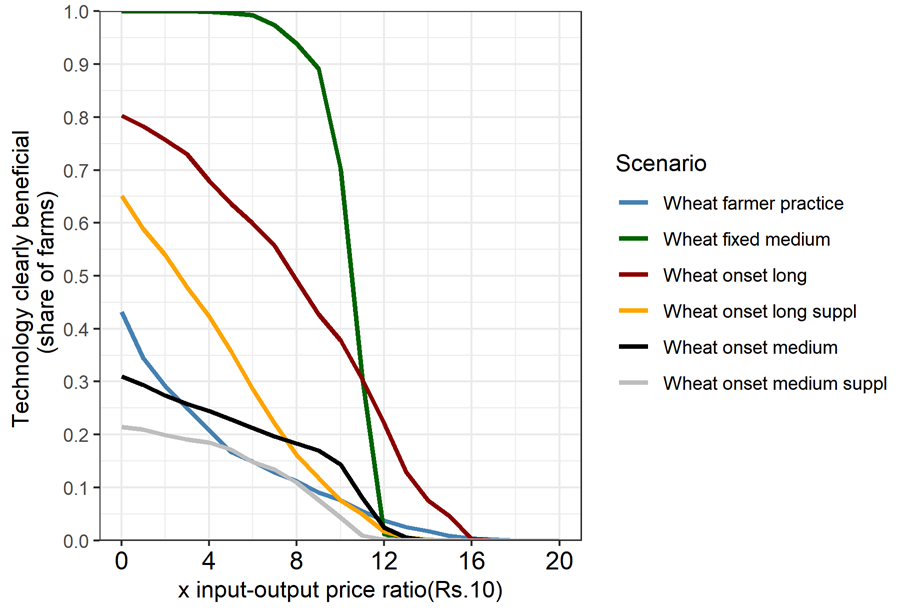
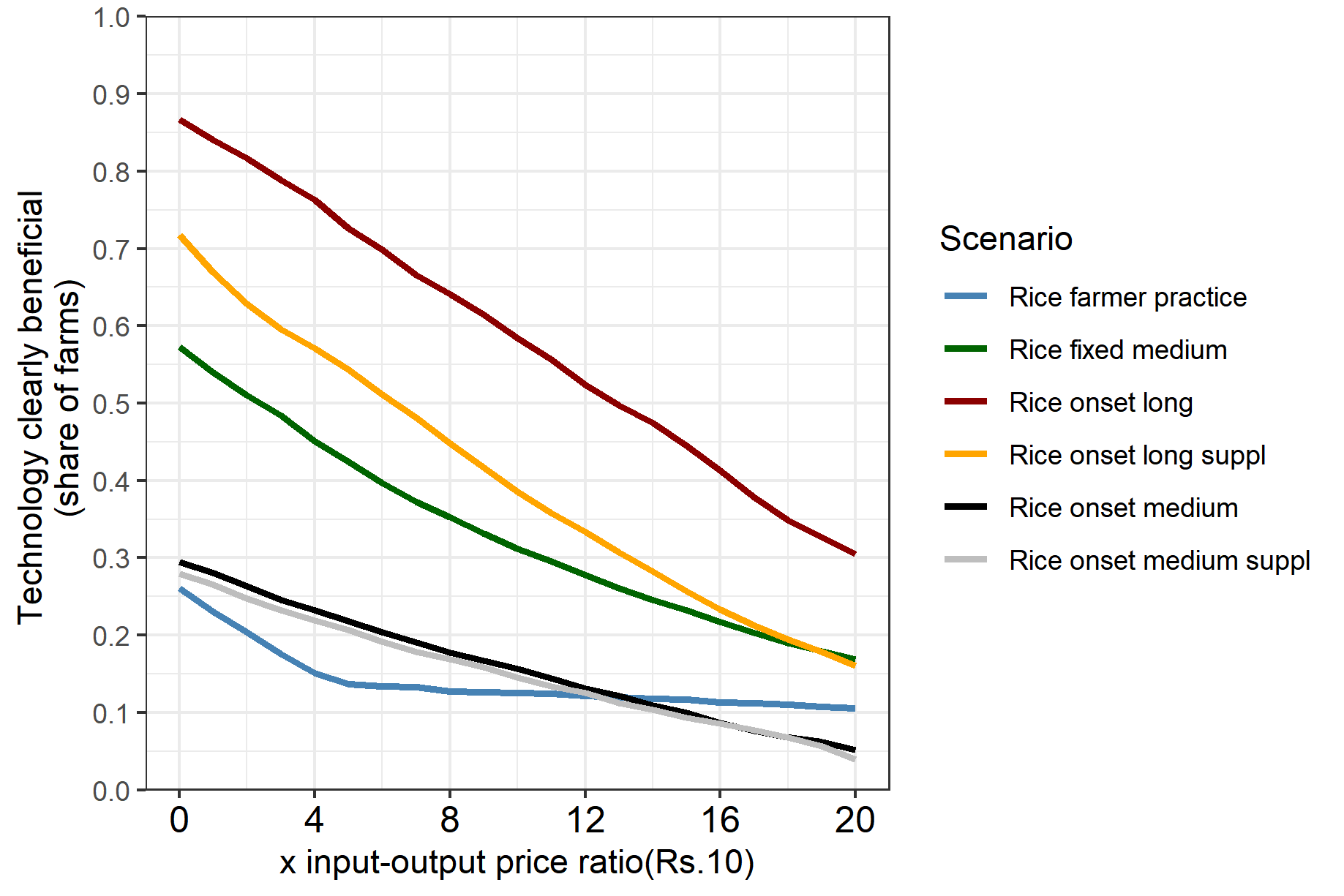
|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Bound | Statistics | S0-S1 | S2-S1 | S3-S1 | S4-S1 | S5-S1 | S6-S1 |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Upper bound | Mean | -20013.05 | 55883.71 | 63616.27 | 49155.51 | 20429.77 | 7515.66 |
| Standard deviation | 32655.19 | 9074.47 | 17482.79 | 18110.54 | 18591.31 | 22571.44 |
| Min | -95787.35 | -10517.52 | -4369.18 | -19391.88 | -39021.17 | -50886.52 |
| 10th percentile | -59656.73 | 43928.94 | 38320.78 | 24205.65 | -867.53 | -16172.84 |
| 25th percentile | -51206.99 | 49765.59 | 49675.54 | 36655.93 | 4862.05 | -10466.29 |
| Median | -20973.23 | 56612.31 | 66844.77 | 52036.13 | 17028.43 | 228.33 |
| 75th percentile | -4138.39 | 62657.69 | 77845.09 | 63242.54 | 35833.15 | 26593.53 |
| 90th percentile | 24233.15 | 66609.76 | 85588.52 | 70133.90 | 49660.69 | 43570.32 |
| Max | 81513.61 | 77485.07 | 99480.34 | 88532.49 | 65034.09 | 61649.20 |
| Lower bound | Mean | -65401.51 | 22156.76 | 34908.06 | 19381.06 | -5512.13 | -15873.31 |
| Standard deviation | 30942.86 | 18377.46 | 19462.07 | 19031.29 | 24394.58 | 25250.42 |
| Min | -155222.24 | -30504.21 | -22649.54 | -49949.50 | -50621.89 | -67245.17 |
| 10th percentile | -106733.31 | 181.31 | 10065.78 | -2004.77 | -35187.29 | -46957.71 |
| 25th percentile | -89550.75 | 8369.37 | 20432.33 | 8001.31 | -24179.36 | -35355.27 |
| Median | -66430.47 | 19168.12 | 33537.89 | 18166.67 | -11178.09 | -19318.34 |
| 75th percentile | -44071.09 | 34650.94 | 48244.30 | 30751.22 | 13467.91 | 1582.32 |
| 90th percentile | -22426.40 | 50199.19 | 62462.09 | 45209.79 | 30279.24 | 19949.24 |
| Max | 77859.21 | 67605.46 | 84539.77 | 74983.11 | 55539.64 | 52194.78 |
| WTP summary | Clearly better (share) | 0.02 | 0.90 | 0.98 | 0.88 | 0.37 | 0.26 |
| Not clear (share) | 0.20 | 0.09 | 0.02 | 0.12 | 0.51 | 0.24 |
| Clearly worse (share) | 0.78 | 0.00 | 0.00 | 0.01 | 0.13 | 0.49 |
| Number of cells | 3429.00 | 3429.00 | 3429.00 | 3429.00 | 3429.00 | 3429.00 |

## Appendix C: Price sensitivity, Bihar

The analyses so far have focused on productivity gains to rice planting date adjustment. However, cost of production may also be affected by these adjustments. The changes in the cost of production may be due to direct changes in the inputs (e.g., alternative variety may be more expensive, sowing labor or hired machinery may be costly during the proposed sowing dates or irrigation may be costly). The changes may also be due to indirect changes in the production system. For example, sowing a long duration variety may require more irrigation which then increases irrigation costs. There are no studies that compute these costs comprehensively. We therefore test the robustness of the decisions on which strategy is beneficial to the farmers by using multiple of cost-output price ratios.

To test the robustness of the willingness to pay measures, we conduct a simple sensitivity analysis in which we vary the differential input price ratio of cost of the proposed rice planting strategy to the output prices. This is given by

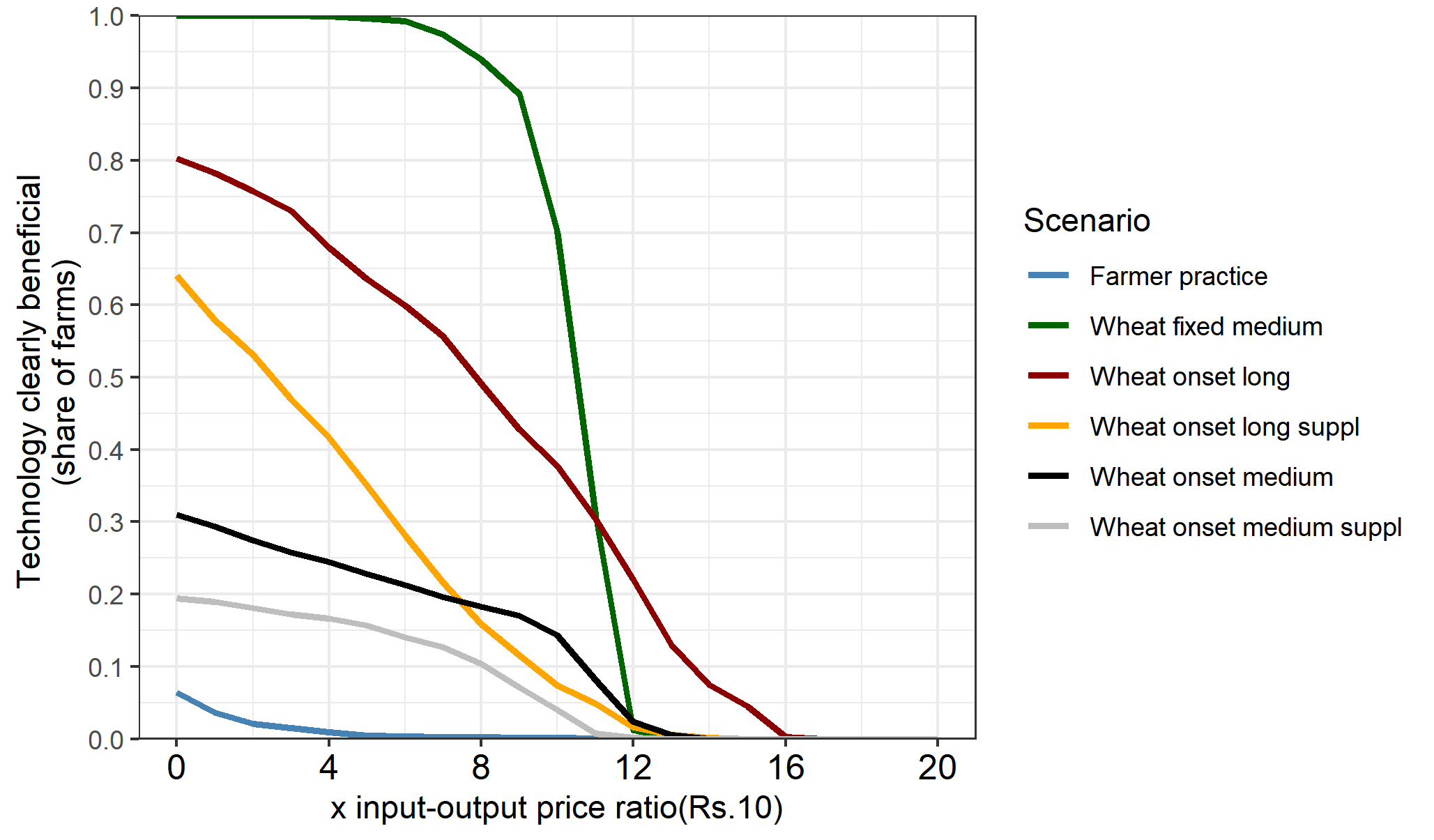
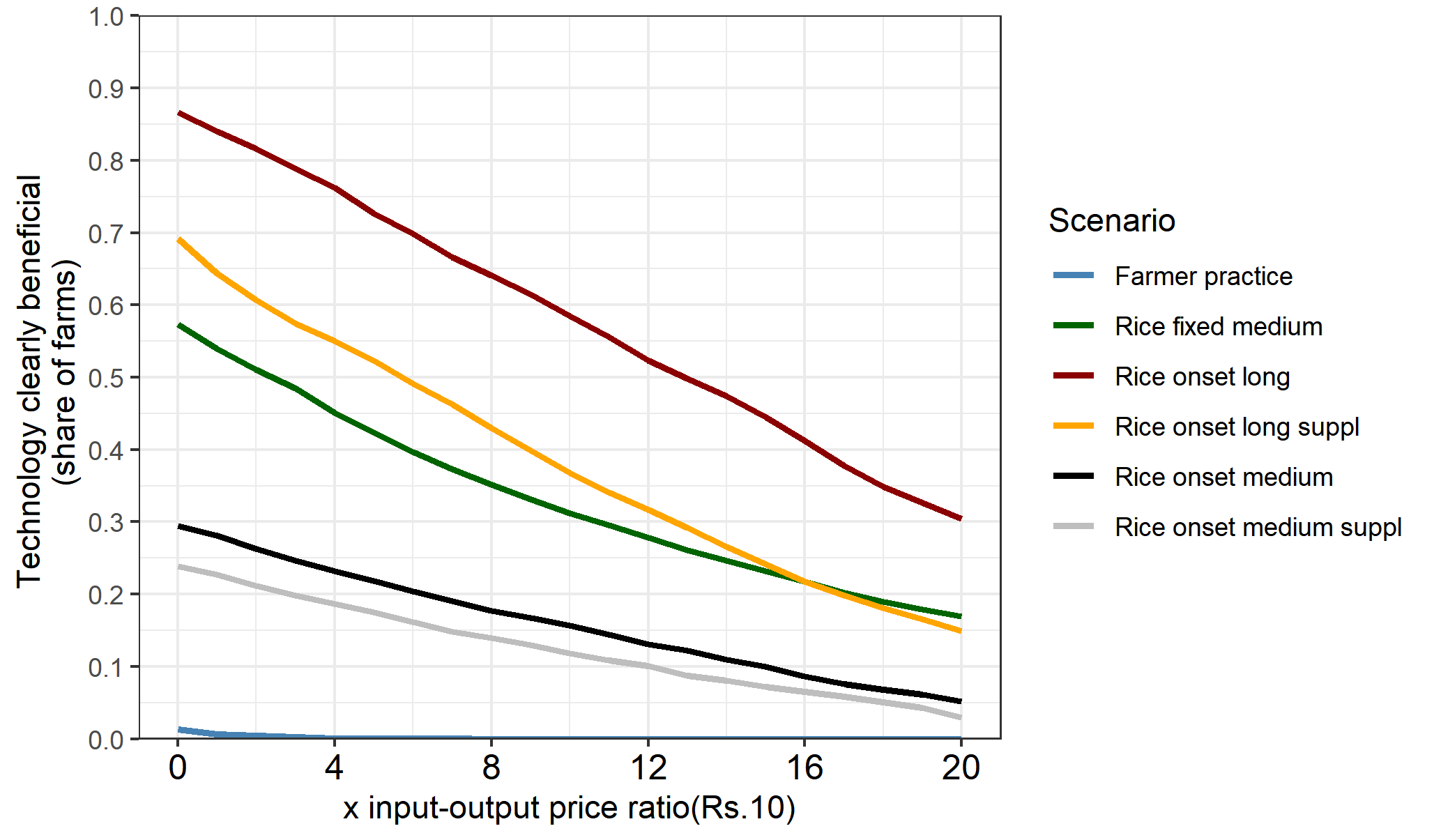
Figure C1 shows the percentage distribution of risk averse farmers who would prefer that strategy as compared to the fixed long rice planting given increase input cost-output price ratio. At zero input cost changes, the percentage of farmers who prefer the corresponding strategies are as in table 2 and table 3. Panel (a) of Figure 4 shows that wheat is more responsive to changes in the costs of production as compared to rice. Overall, the ordering of the strategies remains intact with constant changes in costs of production except for implausibly high costs of production.



a. Without zero yield entries

Rice

Wheat



b. With zero yield entries

Rice

Wheat

Figure C1: Price sensitivity

1. The gridded APSIM crop simulation model setup and results are available here: <https://git.wageningenur.nl/urfel001/igp-simulation-setup>. [↑](#footnote-ref-2)