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RESEARCH ARTICLE

The challenge of making climate adaptation profitable for farmers: evidence from Sri Lanka's rice sector

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Abstract

Adapting agricultural systems to changes in seasonal precipitation is critical for the agricultural sector in Sri Lanka. This paper presents evidence on the adoption drivers and the welfare impacts of agricultural strategies adopted by Sri Lankan rice farmers to adapt to low rainfall conditions. We estimate the causal impact of adopting different adaptive strategies across three different dimensions: (a) sensitivity to water stress, (b) household productivity, and (c) household livelihood conditions. The results highlight important trade-offs faced by farmers between reducing vulnerability to water stress and maximizing profitability and welfare outcomes. These findings are important for informing policies to support climate adaptation among smallholders, and to build and improve the climate resilience of Sri Lanka's rice sector.

Keywords: adaptive practices; agriculture; climate shocks; productivity; rice; Sri Lanka

JEL classification: Q18; Q13; Q15; N45; O2

1. Introduction

It is projected that climate change will influence the timing and duration of seasonal precipitation in South Asia, and will contribute to a decline in water availability for rice cultivation in the region (Lobell *et al.*, 2011; Kim *et al.*, 2013; Burchfield and De La Poterie, 2018). In Sri Lanka, where rice is both the staple food of the population and the primary crop grown by farmers, reductions in water availability for rice cultivation has serious impacts on farmers' welfare and on national food security (UNESCAP, 2010; Weerakoon *et al.*, 2011). Reductions in precipitation are of particular concern in Sri Lanka's dry zone, which accounts for two-thirds of Sir Lanka's total land and over 70 per cent of paddy production in the country (De Silva *et al.*, 2007).

The adverse impact of low rainfall and low water availability was highlighted during the major drought event that affected multiple farming seasons in Sri Lanka between 2016 and 2017. Reduced rainfall in the primary agricultural season *(maha*) of 2016 and the secondary *yala* season of 2017 severely affected water availability for agricultural production. The World Food Programme estimated that as a result of the drought, reservoirs were on average at just 18 per cent of their capacity and 45 per cent of communities reported that their closest reservoirs were empty (WFP, 2017). This led to a significant drop in crop production and a rapid increase in food insecurity among rural households. In total, 900,000 households were negatively affected by the drought (WFP, 2017).

The *Overarching Agricultural Policy* in Sri Lanka recognizes the importance of adapting and building resilience to climate events such as drought in order to achieve national development and food security objectives (Government of Sri Lanka, 2021). A key policy thrust within the agricultural policy framework is to address emerging climate change impacts by supporting the adoption of suitable agricultural strategies and practices by farmers. Detailed empirical evidence on the impacts of adopting climate adaptive agricultural practices under conditions of climate shocks, and the socio-economic and institutional factors that influence their adoption, is required to help guide efforts for translating these policy objectives into effective actions.

In the economic literature, structural Ricardian models are often used to understand how farmers adapt to climate change and the implications of this adaptation on farm outcomes (Seo *et al.*, 2005; Kurukulasuriya and Mendelsohn, 2008; Seo and Mendelsohn, 2008; Di Falco and Veronesi, 2013; Di Falco, 2014). This approach utilizes a two-stage framework, where the first stage models farmers' selection of multiple adaptation strategies, and the second stage models the impacts of adopting the considered practices on farm-level outcomes (Di Falco, 2014). Using this empirical framework, economists have provided important insights on the stand alone and complementary impacts and adoption drivers of adopting climate adaptive practices (Hassan and Nhemachena, 2008; Di Falco *et al.*, 2011; Kurukulasuriya *et al.*, 2011; Asfaw *et al.*, 2016; Abidoye *et al.*, 2017; Gorst *et al.*, 2018; Etwire *et al.*, 2019). In this article, we contribute to the literature on the impacts of climate shocks and adaptive practices by using a normalized inverse probability weights procedure to inform a simultaneous estimation of a weighted system of partially recursive equations. Our approach expands the existing literature on climate adaptation through a mediation analysis, which allows us to disentangle the direct impact of climate adaptive practices from the indirect impacts associated with reductions in sensitivity to climate shocks.

Our analysis makes use of a unique dataset of 1,100 rice producing households in the Anurādhapura district of Sri Lanka covering the agricultural seasons 2017–2018. With these data, we assess the impacts of six different climate adaptation practices, which are further disaggregated by the agricultural field types (upland/lowland) and agricultural seasons (*maha*/*yala* seasons) that they are implemented in. Because the survey reference period coincides with an exceptionally dry period, we are able to disentangle the causal impacts of adopting these practices on farmers' sensitivity to water stress, measured as the probability of having experienced crop losses due to wilting; their impacts on farm productivity, proxied by total harvest value; and their impacts on the household's income. This multidimensional approach allows us to identify important trade-offs and complementarities between the reduction in the sensitivity of farm systems to weather shocks and profit maximization objectives that farmers navigate when

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adopting a particular adaptation practice.[1] Finally, we complement the analysis by examining the socio-economic and institutional factors that are associated with the adoption of these practices.

The results show that while a number of the practices considered are effective at reducing sensitivity to water stress, these benefits rarely lead to improvements in agriculture profitability and household income. The reasons are practice-specific, but are linked to high opportunity costs of labour for Sri Lankan farmers, poor development of output markets for crops other than rice, and management constraints that may arise from their adoption. The results suggest that agricultural research and extension should be bundled with farm service and output market development programmes in order to make these climate adaptive practices more productive and welfare enhancing. Bridging the divide between the climate adaptation benefits of the practices and their profitability is essential in order to foster widespread adoption of adaptive practices, and greater overall resilience to climate change in the Sri Lankan agricultural sector.

The remainder of the article is organized as follows. In section 2, background is provided on the study location and the practices under consideration. In section 3, a description of the conceptual model is presented, which is followed by a description of the empirical strategy in section 4. Section 5 provides information on the data set and key variables used for the analysis along with descriptive evidence from the sample population. Sections 6 and 7 present the results from the quantitative analyses considering the impacts on water stress sensitivity and welfare, and the adoption determinants of selected practices, respectively. Finally, in section 8, concluding remarks and policy implications are discussed.

2. Background

2.1 Study location

The Anurādhapura district is located in the North Central Province and dry zone region of Sri Lanka. It is one of the most important rice producing districts of the country, accounting for the largest share of paddy area extent (over 11 per cent of the country's total rice area extent) and the second largest number of producers (Government of Sri Lanka, 2021).

Sri Lankan agricultural production occurs under three primary water access systems. Major irrigation systems are those having a command area of more than 80 hectares and where water supply comes from a major tank, a river or a major stream diversion.[2] In total, there are nearly 400,000 hectares of land supplied by major irrigation systems in the country, which is equivalent to 44.8 per cent of the total extent of paddy land in the country. Of this, 30,619 hectares of major irrigated land are found in the Anurādhapura

[1] It is important to note that because our data were collected during an abnormally low rainfall year, we are unable to assess the impacts of these practices under normal rainfall conditions. Since these practices are promoted as adaptations to low rainfall conditions, we anticipate that the welfare impacts of the practices are highest under drought conditions, implying that the estimated impacts of adoption on harvest value and income are upper bound estimates.

[2] Administratively, major irrigation systems are maintained by either the Department of Irrigation or Mahaweli Authority of Sri Lanka. This study distinguishes the areas in which irrigation water for farm activities is provided by the Mahaweli Development Project from other major irrigation systems. This is because Mahaweli is the largest multipurpose national development programme in Sri Lanka, and a number of peculiarities motivate the choice.

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district. Minor irrigation systems are characterized by a command area smaller than 80 hectares where water is supplied by small tanks or stream diversions. Minor irrigated paddy lands cover 237,000 hectares of land in Sri Lanka (roughly 27 per cent of all paddy land). The Anurādhapura district has a high concentration of minor irrigated paddy land, covering a total of 56,111 hectares of land. Water stress episodes in these systems are expected to be more frequent and severe as a result of widespread reductions in tank capacity due to silting. Finally, rain-fed production systems are highly dependent on precipitation levels for cultivation. In Sri Lanka, 256,000 hectares of paddy land are managed under rain-fed conditions. In the Anurādhapura district, 16,000 hectares of land are classified as rain-fed paddy land (Shand, 2002).

Farmland in Sri Lanka is also distinguished as being in upland or lowland areas. In most cases, farmers operate both type of fields. Upland fields are typically rain-fed or irrigated with agrowells, lift-irrigation systems and surface tanks (*Pathas*). Consequently, they are more exposed to the risk of agronomic water stresses than lowland fields. Paddy production is concentrated in irrigated lowland fields, where water stress risks are driven by aggregate rainfall levels and the conditions of reservoir and canal systems.

Finally, variability exists between the dominant farming seasons. In Sri Lanka, there are two farming seasons, which are driven by two distinct monsoon rainfall patterns and associated inter-monsoon seasons. The main cultivation season is known as *maha* and begins in October and ends in March. The secondary season, known as *yala,* begins in April and lasts until September (Zubair, 2002). Rice cultivation during the *yala* season is increasingly infeasible in most rain-fed and minor irrigated systems because of changes in rainfall patterns. During the *maha* season, there is typically enough rainwater for paddy cultivation, although dry periods routinely pose challenges to rice production in rain-fed and minor irrigation systems (Chithranayana and Punyawardena, 2014).

As a result, appropriate adaptive practices and levels of sensitivity to water stress are likely to vary between upland and lowland fields as well as between seasons and irrigation systems. Accordingly, this analysis disaggregates adaptation practices and water stress impacts between upland and lowland fields and estimates the impacts of these practices during the *maha* and the *yala* seasons separately, controlling for the type of irrigation system at a field level.

2.2 Farming practices to reduce water stress sensitivity

In Sri Lankan rice systems, there are a variety of practices that are promoted to help reduce the sensitivity of production to water stress, and to foster improved household productivity and welfare. These practices vary in terms of the relative intensities of land, labour, capital and knowledge they require to implement, and the potential risks they may entail to household productivity and welfare. We focus on six unique practices, which are disaggregated into 12 field type and season-specific practices in the analysis. The selection of these practices is based on two criteria. Firstly, they are included in policy frameworks and extension guidelines in Sri Lanka to support climate adaptation in the agricultural sector. Secondly, there are sufficient observations and variability in the data to conduct a meaningful empirical analysis.[3] The practices selected are: (1) the adoption

[3]In particular, practices that are not widely adopted are excluded from analysis, using a threshold of 10 per cent of adoption at field type and season levels. Similarly, in order to ensure sufficient variability for the analysis, we also exclude practices that are adopted by more than 90 per cent of farmers.

of short-duration rice seed varieties on lowlands during the *maha* and *yala* seasons; (2) planting other field crops on lowland fields during the *yala* season and on uplands during the *maha* season; (3) planting maize on uplands during the *maha* season; (4) retaining trees on lowlands during *yala* and on uplands during both the seasons; (5) using soil erosion barriers on uplands during both the *maha* and *yala* seasons; and (6) residue retention on lowlands during both the seasons.

The adoption of short-duration rice varieties is being promoted in Sri Lanka as a strategy to manage reductions in precipitation and increases in evapotranspiration, which may become particularly acute in the months of January and February under future climate scenarios (De Silva *et al*., 2007).

The cultivation of other field crops is an important adaptation strategy for water scarcity in Sri Lanka (Handawela and Kendaragama, 1995). It is emphasized in the National Climate Change Adaptation Strategy as a means of reducing the adverse impact of declining agricultural water availability (Imbulana, 2006). The crops cultivated as other field crops include chili, maize, green gram, cowpea and onions. Maize has been specifically identified as a growth sector by the government of Sri Lanka, due in part to rising demand for animal feed, which has increased Sri Lanka's import requirements. We, therefore, treat this crop separately in the analysis. Key constraints to the adoption of other field crops are that they often require more labour-intensive production techniques than standard rice production, the prices are more volatile, and inputs more limited (Burchfield and De La Poterie, 2018).

Intensive agroforestry practices, such as planting wind breaks or integrating leguminous tree species into farm systems, are not common in dry land systems in Sri Lanka (Mahendrarajah, 2003). This is particularly true in lowlands, where agroforestry can compete with paddy field operations on the thin bunds between fields. However, retaining trees on fields is a common *passive* agroforestry strategy used by farmers to reduce soil moisture loss in crop fields (Kumara and Bandara, 2002). Therefore, this analysis focuses on the impacts of trees already established in fields.

Building soil erosion barriers to reduce runoff velocity is likely to affect farmers' sensitivity to water stress in countries like Sri Lanka where the soil erosion hazard is high. Soil erosion risk in Sri Lanka is not only due to the actual magnitude of the erosion, but more importantly to the thin layer of reddish-brown earth that sits atop a layer of gravel (IUCN, 2016). As a result, even a small amount of erosion rapidly degrades the productivity of soil. In addition, many interrelated socio-economic factors, such as fragmentation of lands due to increase in population and encroachment into sensitive crown lands, also contribute to soil erosion (Nayakekorala, 1998). Establishment of soil erosion barriers in Sri Lanka can be observed only in uplands and, being a labour-intensive practice, it is expected to be more widespread among farmers with greater labour endowments or less opportunity for off-farm income activities.

The retention of crop residues or use of mulch is practiced to reduce soil moisture evapotranspiration and to build up soil organic matter over time. Most rice producers in Sri Lanka practice some form of residue retention on their lowland fields. Mulching and residue retention generate the highest benefits during low rainfall conditions and may have minimal direct impacts on yields under normal conditions. Residues on many Sri Lanka paddy fields are retained as a consequence of combine harvesting, which leaves residues in the field. The practice can be improved by adding urea or water to hasten decomposition. Because basic residue retention is practiced on the vast majority of paddy fields, the analysis focuses specifically on these '*improved*' residue management

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strategies. Furthermore, as the agronomic benefits from the practice are expected to accrue after multiple years of consecutive adoption, this analysis focuses on adopters that have retained residues in the field for five consecutive years.

3. Conceptual framework: linking water stress sensitivity, household welfare, and adaptation choices

The conceptual framework used for this study accounts for the complex interplay between household-level socio-economic characteristics, the factor intensities and bio-physical attributes of the farming practices, and heterogeneous production environments within which they are implemented (upland/lowland fields, *maha/yala* seasons, and irrigation system).

Our starting point is that climate change in Sri Lanka's rice systems will increase the probability of low rainfall events and the risk of crop loss due to water stress (Madduma and Wickremagamage, 2004; De Silva *et al.*, 2007). As farmers' perceptions of climate risk change, the expected utility derived from the adoption of practices to mitigate this risk increases (Deressa *et al.*, 2009, 2010). However, farmers face a utility optimization problem, as they are unable to predict if, in any given season, water stresses will occur. This optimization problem is further confounded by uncertainties and opportunity costs associated with climate adaptation practices themselves and the alternative risk management strategies that households have at their disposal. Therefore, whether or not the adoption of a practice promoted to reduce sensitivity to water stress achieves this objective, relative to conventional practices, depends on a wide range of factors. This includes how well the practice was implemented, the duration of implementation, and the appropriateness of the practice to the local environment, among many others (Molua, 2002; Imbulana, 2006; Esham and Garforth, 2013).

Moreover, even if the adoption of a practice does reduce the sensitivity of a system to water stress, this may not necessarily contribute to improvements in productivity and economic welfare gains relative to non-adopters (Reardon *et al.*, 1998; Barrett *et al.*, 2001, 2008). There are several reasons for this. First, the choice to adopt one practice over others entails trade-offs between the allocations of production factors and their opportunity costs. For example, the choice to adopt a labour-intensive adaptation practice, such as building erosion control structures, will divert labour away from other income opportunities; therefore the opportunity costs of this investment choice are potentially high (Deininger *et al.*, 2007). If the positive effect on water stress sensitivity is not sufficient to compensate for reductions in off-farm income resulting from this investment choice, the net income effect of the practice will be negative. Second, trade-offs can also exist between the overall impact of a practice on productivity and its impact on reducing water stress sensitivity. For example, some practices can reduce losses from wilting, but may also reduce overall productivity by lower planting densities or increased weed pressure relative to alternative practices. Finally, practices that entail changes in cropping systems, for example the cultivation of crops less exposed to water scarcity, may reduce sensitivity to water stress, but also expose farmers to more thinly traded, less competitive market conditions than those in rice markets.

Given these reasons, the empirical approach adopted for this study distinguishes between the productivity and welfare impacts derived indirectly through a reduction in water stress sensitivity from those obtained directly through productivity gains and improvements in factor allocations. The combination of these two impact pathways shapes the net impact of the practice. Disentangling these two impact pathways provides insights into the complementarities and trade-offs between the objectives of increasing the climate resilience and improving household livelihood conditions.

The final element of our conceptual framework seeks to understand factors associated with the adoption of the adaptive practices under consideration. In the context of partial or incomplete markets, where production choices are linked to consumption outcomes, as is the case for many producers in Sri Lanka, investments that reduce risk are often prioritized over profitability maximizing activities (Holden and Binswanger, 1998). This is further conditioned by a range of socio-economic and institutional factors, which affect households' ability and willingness to cope with production-related risks, and their capacity to allocate production factors to a practice, relative to alternative investment options. As a result, our empirical approach must account for this heterogeneity, in order to reduce concerns over endogeneity due to self-selection into the treatment and to identify the constraints and the barriers to the adoption of practices.

These characteristics include farmers' human capital endowments (education) and physical assets (land, wealth and livestock), which influence the propensity of households to adopt practices with different capital, land or labour factor intensities. In addition, variations in off-farm income earning opportunities[4] and their associated effects on the opportunity costs for household labour are likely to be important (Deininger *et al.*, 2007). Farm households that derive a large share of their income from off-farm sources are in a better position to invest in capital-intensive farm technologies and practices and are relatively less prone to adopt relatively labour-intensive practices. Moreover, access to off-farm income may, in principle, help to spread the livelihood risks associated with climate- or market-induced volatility in the farm sector. The type and share of irrigated land controlled by a household is also a potential determinant in the choice of adaptation strategy, as this mediates the relative risk of water stress that a household is exposed to. Finally, access to institutional support systems such as input subsidies, concessionary production loans, and insurance is also likely to shape heterogeneous adaptive strategies among the farmers. These programmes mediate farmers' risk exposure and thus their propensity to adopt risk mitigating practices.

4. Estimation strategy

The estimation procedure used in this analysis relies on an inverse weighted probability simultaneous equations model (Hirano *et al.*, 2003; Bang and Robins, 2005). This approach is expected to address selection bias through a doubly robust estimation procedure of the effects of adopting a specific adaptation strategy on sensitivity to water stresses, measured as the probability of experiencing crop wilting; a productive indicator, namely the total value of the harvest (net and gross); and a welfare indicator, namely the gross household income, measured as the sum total value of the crops sold plus off-farm income, and income from cash and commodities received by the household from third parties. During the agricultural season considered for this study, the Anurādhapura district was hit by a severe drought which affected water availability and created conditions for agronomic water stress in all the farm households involved in the rice sector. As a result, water stress is considered exogenous to all farms and farm plots in the district. However, whether or not a plot has experienced yield losses as a

[4]Off-farm opportunities are particularly relevant in Sri Lanka as they produce approximately 80 per cent of agricultural GDP (Deininger *et al.*, 2007).

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result of this widely covariant shock depends on the sensitivity of the production system to water stress. We define this sensitivity as a latent variable, which is determined by individual-level and plot-level attributes, such as access to irrigation and position on the irrigation canal, as well as by the adoption of the adaptive strategies considered in the analysis.

4.1 Addressing self-selection to measure the effect of practices on water stress sensitivity

This analysis controls for endogeneity related to the adoption of practices through a propensity score method (Rosenbaum and Rubin, 1983). In our framework, each treatment regime has been defined with a binary variable *T* which is equal to 1 if the household adopts the strategy and 0 otherwise. Participation in the treatment is estimated using the vector of pre-exposure characteristics, *W*. In particular, we estimate the weights used to mitigate the selection bias taking advantage of the vector of observable characteristics, *W*, which includes human capital endowments (proxied by the household head education), physical assets (proxied by the amount of the available land used for cultivation, a dummy variable identifying the household's sole ownership of the largest field, a wealth index including all the agricultural assets, and a dummy variable taking value one if the household owns livestock), household's available workforce and off-farm income earning opportunities (proxied by family size and a dummy variable identifying off-farm employment), type and share of irrigated land controlled by a household (proxied by a dummy variable identifying the irrigation system type and a continuous variable indicating the share of land under irrigation), access to institutional support systems (such as input subsidies, concessionary production loans, and insurance) and a number of dummy variables indicating the availability of information related to the improved seeds and other innovative technologies. Although it is not possible to rule out the possibility that the selection is also based on other unobservable characteristics, the doubly robust procedure relaxes the concerns about estimating unbiased result even though the selection model has not been perfectly specified. Another (somewhat related) issue that is not possible to rule out with the identification strategy used for this study is the existence of reverse causality among the choice of the production system (the adoption of specific technologies and/or management practices) and the sensitivity to water stresses. In fact, household farmers could adopt practices or management practices in response to the onset or anticipation of water stresses.[5] However, the concerns are relaxed by the fact that the infrastructural and institutional constraints which determine the adoption of a specific production system in the Sri Lanka rice sector framework are quite irreversible in the short term and make the households' choice extremely unlikely to be modified in response to and/or anticipation of sporadic water stresses.[6]

[5]It is worth highlighting that this caveat does not apply to the adoption of practices which have been defined across multiple years (i.e., retaining trees on the field and improved residue retention over the last five agricultural seasons).

[6]However, in order to relax these concerns, the robustness of all the results has been tested (and confirmed) using a different empirical approach which endogenizes adoption choice into the model basing the identification strategy on additional exclusion restrictions (see Robustness Check IV in online appendix D).

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Once the selection model has been estimated, the predicted probabilities have been inverted and normalized[7] to obtain a vector of weights, w, for the sub-sample of households on *common support*.

Formally the probability of treatment given the pre-exposure covariates is:

$$e(W) = P(T = 1|W) = E\{I(T = 1)|W\} = E(T|W). \tag{1}$$

This has been first modelled using a binomial logit function such that:

$$P(T = 1|W) = (W, \beta) = \frac{exp(\beta_0 + W^T\beta_1)}{1 + \exp(\beta_0 + W^T\beta_1)}. \tag{2}$$

The intuition behind this approach consists of estimating the average treatment effect, Δ , through the difference of the inverse propensity score weighted averages between treated and control groups (Lunceford and Davidian, 2004):

$$\widehat{\Delta_{IPW}} = n^{-1}\sum_{i=1}^{n}\frac{T_iY_i}{e(W_i, \widehat{\beta})} - n^{-1}\sum_{i=1}^{n}\frac{(1 - T_i)Y_i}{1 - e(W_i, \widehat{\beta})}, \tag{3}$$

where Y_i is the outcome variable of the unit of analysis, i, and T is the treatment status.

4.2 Estimate the direct, the indirect and the impact of practices on productivity and welfare

Once having estimated the normalized inverse probability weights, the empirical strategy relies on simultaneous estimation of a weighted system of partially recursive equations.[8] Empirically, the re-weighting procedure creates a pseudo-population in which measured confounders can be equally distributed between treatment and comparison groups, thus relaxing concerns of endogeneity. Furthermore, the simultaneous estimation of the two outcome equations is expected to accommodate the correlation among the error terms, and to control for a wide set of additional covariates. Importantly, the doubly robust procedure ensures the consistency of the estimator when either the propensity score or the outcome model are mis-specified, thus addressing a crucial shortcoming of the propensity score models (Robins *et al.*, 1994).

As sensitivity to water stresses is assumed to be a latent variable, S_i^*, it is proxied by an observed binary outcome S_i which is equal to 1 when farmers harvest an area smaller than the area planted because of wilting and 0 otherwise,

$$S_i = \begin{cases} 1 & if\ S_i^* > 0 \\ 0 & \text{otherwise} \end{cases}. \tag{4}$$

[7]The normalization of the vector of weights relaxes the concerns about the finite sample performance of the inverse probability weighting (IPW) methods, reducing the variance of the estimated treatment effect due to extreme weight. A robustness check with weights obtained by excluding the treated households with low conditional probability of adoption and control household with high probability of adoption from the sample is reported in online appendix D, Robustness Check II).

[8]The tables and the figures containing the diagnostic and the tests of the balancing properties of the inverse weighted samples of treated and control are fully reported in online appendix B.

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The weights are integrated into the simultaneous linear estimation of the following system of two equations[9]:

$$\begin{cases} S_{I,j} = \beta_0 + \beta_1 T_{ij} + \beta_i W_i + u_{1\ I,j} \\ Y_{I,j} = \beta_0 + \beta_1 \hat{S}_{I,j} + \beta_2 T_{I,j} + \beta_i X_i + u_{2I,j} \end{cases}, \tag{5}$$

where S_{ij} represents the observed proxy for sensitivity of the household i due to the adoption of the practices j; T_{ij} is a dummy variable that is equal to 1 if household i adopts practice j, and 0 otherwise; W_i is a vector of exogenous household and farm characteristics (which includes all the variables shaping the selection into the treatment constituting the vector W in the equation (2)); and $u_{1\ i,j}$ represents the random error term that is assumed to be uncorrelated with the explanatory variables, but correlated with the error term $u_{2\ I,j}$ of the second equation of the system. Moreover, $Y_{I,j}$ is the selected outcome for household i depending on the estimated sensitivity to water shock $\hat{\mathbf{S}}_{I,j}$, the direct effect of the adoption of the practice $T_{I,\ j}$ and a vector of household characteristics X_{2i}, including all the household variables included in W_i and a number of additional variables which are assumed to influence the outcomes but excluding field level ones (in order to ensure the identification of the system).

This estimation procedure allows for a mediation analysis to disentangle the direct impact of the adoption on productivity and welfare (the partial derivative of the outcome relative to the adoption of the practice $\Delta Y_j / \Delta T_j$) from the indirect impact through the sensitivity (the product of the partial derivative of the outcome and the partial derivative of the sensitivity $(\Delta Y_j / \Delta \hat{S}_j) * (\Delta S_j / \Delta T_j)$). Finally, the net effect is obtained by adding the impacts from the direct and indirect channels (i.e., $(\Delta Y_j / \Delta \hat{S}_j) * (\Delta S_j / \Delta T_j) + (\Delta Y_j / \Delta T_j)$, the partial derivative of the outcome of a reduced form specification).

4.3 Estimate the determinants and the barriers to the adoption of adaptive strategies

In order to investigate the barriers to and the determinants of the adoption of adaptive practices, this analysis takes advantage of a random utility framework. Assuming that the utility difference from the adoption of the practice relative to the alternatives is a latent variable U_j, farmers select the strategy when the expected utility from adoption is higher than that from alternative strategies ($U_j > 0$).

Formally, the adoption model is:

$$T^*_{ij} = X_i \beta_i + \upsilon_{ij}, \quad j = 1, \ldots, J \quad \text{and} \quad i = 1, \ldots, N, \tag{6}$$

where T^*_{ij} is a latent variable capturing the demand and/or preference of farm household i for strategy j; X_i is a vector of field and household sociodemographic, infrastructural and institutional characteristics affecting the adoption of strategy j; and υ_{ij} is a stochastic error term (Kassie *et al.*, 2013). We assume that the latent variable T^*_{ij} is the utility difference between adopting a practice or not, and if the difference is positive the farmer will

[9]We acknowledge that using a linear estimator for both the equations, regardless of the binary nature of the variable proxying the farmers' sensitivity to water shock, is a second-best choice. It is used to facilitate the decomposition of the net treatment effect in the two constituting components (direct and indirect). However, in order to test the robustness of the results, a specification considering the binomial nature of the dependent variable in the first equation has been also estimated. The results are largely consistent with those presented for this analysis and are available upon request.

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adopt the practice in question. The latent variable is proxied by the following observed binary outcome T_{ij} which is

$$T_{ij} = \begin{cases} 1 & \text{if } T^*_{ij} > 0 \\ 0 & \text{otherwise} \end{cases}. \quad (7)$$

Also in this case, the probability of the treatment has been modelled using a binomial logit function such that:

$$P(T = 1|X) = (X, \beta) = \frac{exp(\beta_0 + X^T \beta_1)}{1 + \exp(\beta_0 + X^T \mathrm{B}_1)}. \quad (8)$$

5. Data sources and descriptive evidence

The analysis takes advantage of a unique dataset of rice-producing households in Anurādhapura district, Sri Lanka. The data were gathered as part of a joint effort between the Economic and Policy Analysis of Climate Change unit of the FAO-UN and the Environmental and Water Resources Management Division of Hector Kobbekaduwa Agrarian Research and Training Institute (HARTI). A Multistage Stratified Random Sampling procedure was used to ensure the representativeness of the sample at the district level, as well as the proportional random selection of farmers from each of the four irrigation systems in Sri Lanka.[10] The number of farm households within each Divisional Secretariat and within each irrigation system was used to draw a proportional random sample of 11 Divisional Secretariats and 110 farmers organizations from which 1,100 households (corresponding to 3,954 seasonal fields) have been interviewed (details on the sample design and the geographic distribution of the households interviewed are in online appendix A).

The dataset is multilevel, and includes modules at the household, individual, field, activity, and crop level. At the field level, detailed information about all the plots owned or used by the household during the 2017/18 agricultural year, including owned cultivated parcels, sharecropped, or rented parcels, and other pieces of land (such as home gardens, orchards, fallow fields, virgin lands) is collected. To capture variations in seasonal practices, the questionnaire contains separate modules for the 2017/2018 *maha* season, the 2018 *intermediate* season, and the 2018 *yala* season. The questionnaire distinguishes lowlands from uplands, and captures specific seasonal information on agricultural activities, from land preparation to harvesting. It also captures annual information about orchards and home gardens activities. Additional modules have been designed to gather information on input and output market behaviours, input use, livestock holdings and sales, institutional access, assets, and off-farm income.

5.1 Descriptive evidence

This section provides the descriptive statistics at the household (online appendix table A1)[11] and field levels (table A2) on the main variables included in the empirical analysis. In what follows, for the sake of parsimony, only selected relevant statistics will be commented upon.

[10] Even though a Mahaweli system could be considered a major irrigation system, for the study purpose it is considered as a separate system because of its different management aspects and objectives.

[11] All the tables for this paper are available in the online appendix.

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At the household level, the average gross income of households is 832,270 rupees (US$4,600), however there is a large difference between the top and the bottom quintiles of the distribution (1.9 million rupees or US$10,500). This suggests significant socio-economic heterogeneity among rice farmers in the district. On average, 44.3 per cent of the total gross income comes from off-farm sources, while the share from agricultural activities (including harvest and livestock) is 48 per cent of total gross income. The remaining 7.4 per cent comes from cash or in-kind transfers, which highlights the important role of the public sector in supporting agriculture in Sri Lanka, as well as the relevance of remittances from internal and external migrants.

At a field level, the data show significant variations between the farm practices, technologies, input use, crop choice, and productivity between field types and season. On average rice producers in the district cultivated 2.2 acres in the lowlands and 2.5 acres in the uplands during *maha* season. This reduces to about 1.9 acres in the lowlands and 2.47 acres in the uplands during *yala,* when rains are less consistent and the season is shorter. Rice is almost exclusively cultivated on lowlands and more intensively during the main season (*maha*). Accordingly, the average productivity on lowlands is about 1,700 kg per acre during the *maha* season and about 1,670 kg per acre during the *yala* season. Rice productivity is negligible on uplands during both the seasons, which is a function of the agroecological conditions of uplands and because the government does not provide any support for paddy cultivation on uplands.[12]

The reference period used for this analysis was characterized by a below-average rainfall during the *maha* 2017/18, coupled with low irrigation water availability, which resulted in significant cuts in the area planted (FAO, 2020). Water availability started to recover during the *yala* season 2018, but was still below the historical average. As a result, all the farmers in the district operated under conditions of water stress during the reference period, and their ability to cope with this was likely linked to some combination of household characteristics as well as to the implementation of different adaptation practices. The descriptive data show that during the *maha* season 24.4 per cent of lowland fields and 41.4 per cent of upland fields experienced crop wilting that resulted in farmers harvesting less of their field than was planted. In the *yala* season, conditions improved, but crop loss due to wilting was still reported in 10.7 per cent of lowland fields and 14.4 per cent of upland fields.

Levels of crop diversification vary between season and field types. Rice is the dominant crop in lowland fields during *maha* season, with more than 95 per cent of fields dedicated to rice. However, due to seasonal reductions in water availability during the *yala* season, many lowland fields shift out of rice to produce other field crops. In total, 21 per cent of the lowland fields in the *yala* are used to produce other crops, with maize accounting for 5 per cent of the cases. In the uplands, where water for irrigation is limited to agrowells, more than 85 per cent of the fields are devoted to the cultivation of other crops which have lower water requirements. On these fields during *maha* season, maize is a dominant crop, and is cultivated on 53.4 per cent of the fields, while during the *yala* other crops are prevalent. The use of short-duration rice varieties is not widespread. The data collected shows that they are used exclusively in lowland fields and most predominantly in the *maha* season (36.4 per cent compared to 26.4 per cent during *yala*). Agroforestry in the district is primarily passive, and involves retaining beneficial trees

[12]These figures are almost 25 per cent smaller than the official estimates for the Anuradhapura district from the paddy statistics of the department of census and statistics of Sri Lanka.

in fields, not establishing new agroforestry systems. In cultivated upland fields, trees are found on over 20 per cent of fields, and on about 10 per cent of lowland fields.[13] The figure shows that cultivated fields having soil erosion barriers are exclusively on uplands, with roughly 15 per cent of upland fields having soil erosion barriers. Crop residues are retained on more than 95 per cent of the lowland fields, regardless of the season. The percentage decreases to 70 per cent for uplands but is still very high. Improved residue retention, which involves long duration of adoption and the use of urea or water to speed decomposition, is less widespread, but is sufficiently adopted to enable an empirical analysis. In total, 11.8 per cent of lowlands during *maha* and 12.5 per cent of lowlands during *yala* have been managed through improved residue retention practices. It is important to note that, given the widespread adoption of residue retention, the interpretation of the impacts of improved residue retention is relative to basic residue retention.

6. Empirical results: impacts on water stress sensitivity and welfare

In this section we examine the impacts of adopting the identified practices on water stress sensitivity, value of harvest and household income, while differentiating between the direct, indirect, and net impacts of the practice on the welfare indicators. Table A3 reports only the estimated marginal effects of each of the selected adaptive strategies at the field level.[14] Of the 12 field- and season-specific practices considered, four are found to significantly reduce sensitivity to water stress. Famers retaining residues and enhancing their decomposition rate (i.e., improved residue retention) on lowland fields during *maha* are about 14.8 per cent less likely to experience production loss due to wilting than non-adopters.

Growing other field crops reduces sensitivity to water by 18.7 per cent on uplands during *maha* and 9.3 per cent on lowlands during *yala*. However, farmers cultivating maize on uplands during the *maha* season are more prone to water stresses (+16.4 per cent). All else equal, using short-duration seed on lowland during the *yala* season reduces water stress sensitivity by 5.3 per cent on lowland. Despite the positive impacts of the practices on reducing water stress sensitivity, the impact on productivity and welfare is limited.

Retaining the residues on lowland during *maha* has a positive direct effect on the value of the crop harvest (+28.6 per cent) that almost doubled (+53.5 per cent) considering the net effect (i.e., direct effect on the gross value of the production plus the indirect effect through the reduction of the sensitivity). Such positive impacts persist, after netting out the cost related to input and labour (+27.4 per cent). However, it does not result in a statistically significant impact on the gross household income. The direct effect of this practice on the household welfare is confirmed on the lowland fields cultivated during the *yala* season that is associated to a productivity increase (both gross +42.9 and net +39.5 per cent) and to a higher household income (+18.1 per cent). However, there is no evidence of an effect through a sensitivity reduction and in the positive impact of

[13] It is worth noting that the number and type of fields cultivating across season vary. Given that, the incidence of the permanent practices is also changing across seasons and not only across type of land. Coherently with the rest of the analysis, some of these practices have been excluded from the empirical analysis when the adoption rate is below the 10 per cent threshold (e.g., retaining trees on lowland during the *maha* season). These results are available upon request.

[14] The complete results are available upon request.

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implementing this practice regardless of the season considered. It is important to note that conventional residue retention is widespread in Sri Lanka. Therefore, these results show the impact of improved residue management practices relative to conventional residue retention practices.

Cultivating other crops on upland during *maha* is found to generate positive indirect effects through the channel of the reduction of the sensitivity to water stresses on the value of crops harvested (+23.6 per cent). However, this indirect effect does not produce a statistically significant positive net effect on any outcomes. Weaknesses in markets for other field crops likely explain why reduced sensitivity to water stress does not lead to a net improvement in both the value of crops harvested (gross and net) and the household gross income.

Adopting soil erosion barriers on upland during *yala* is associated with an increase in the gross value of the harvest (+ 29.8 per cent), which persists after netting out the input costs (+ 29 per cent), but disappears when we consider the household income as outcome. Again, these results are likely to be due to the opportunity cost of the labour applied on upland during the short agricultural season (*yala*).

Overall, the mismatch between productivity and welfare outcomes is likely due to the labour intensiveness of many of the practices considered, which diverts labour from off-farm income generating activity. This assumption is further supported by the descriptive data presented in table A4, which reports the average number of person days employed on the fields by adaptive strategy. It is apparent that fields on which diversification strategies are adopted employ, on average, the highest number of person days. It is worth highlighting that most of the heterogeneity among different strategies is due to the household labour, which supports the interpretation that high opportunity cost for labour related to the adoption influences the practice's impact on household income.

Another potential bottleneck emerging from the analysis is related to the weakness and the fragmentation of markets for crops other than rice. Sri Lankan farmers cultivate other crops preferably on upland during the *maha* season and on lowland during the *yala*. In the previous case, the indirect effect of the practice on the sensitivity to water stresses is transmitted to all the agricultural outcomes but does not produce a significant increase in the gross income. In the latter case, the results point out that the gains in the wake of a shock are eroded by issues with the commercialization of this product. Moreover, when we focus on the cultivation of maize on upland during *maha*, a greater sensitivity to water stresses associated with this strategy negatively affects farm-level productivity and the profitability.

All together these results suggest that planting other crops is likely to be a residual strategy to preserve the fertility of the soil for the subsequent agricultural season on lowlands and/or a way to produce food for self-consumption rather than an adaptive strategy on uplands.[15]

These findings highlight the challenges faced in Sri Lanka in terms of addressing emerging climate vulnerabilities, which are likely to become more pronounced in the future. Consistently with other recent contributions on the same topic (e.g., Gorst *et al*., 2018), the results of this analysis highlight that the current practices promoted to reduce drought sensitivity are not very effective in translating the reductions in water stress sensitivity into measurable productivity and welfare gains, particularly in terms of profitability and gross income.

[15] These assumptions are supported by the results in Robustness Check I in online appendix D.

7. Adoption determinants of selected practices

In this section, the factors associated with the adoption of each adaptive strategy at the household level are explored, focusing specifically on those practices that were found to reduce sensitivity to water stress.[16] The first notable result in table A5 is that the factors explaining adoption are highly specific to the practice selected.

The gender and the age of the household head is found to reduce the probability of cultivating other crops on upland during *maha*, holding other factors constant. In addition, cultivation of other field crops in the upland during *maha* is positively associated with the household head's level of education. This is likely driven by structural inequalities between men/women and young/old headed households in terms of mobilizing labour and accessing capital required to adopt these practices.

The age of the head of household is also found to be negatively associated with the adoption of other field crops in *maha* upland and *yala* lowland fields, while family size is positively associated with the latter practice.

Looking at the household agricultural assets' endowments, diversification on lowland during the short season (*yala*) is positively associated with the normalized agricultural wealth index. Conversely, the index is negatively associated with the probability of cultivating crops other than rice on upland during the main season (*maha*), although households cultivating larger fields are more prone to diversify the upland fields during *maha*.

Taken together, the results suggest that the promotion of crop diversification is often a knowledge-intensive strategy limited by the capacity to mobilize labour, and the nature of the labour force employed. These findings highlight the importance of addressing labour constraints to achieve widespread adoption of these strategies.

Moreover, the asset endowments of households that diversify their cultivation differ with the season/land type considered. During the *maha* season, the diversification on upland fields is an option for less endowed households to reduce their sensitivity to water stresses. This indicates that wealthier farmers, who may have lower subjective risk levels, are less likely to diversify their production during *maha* and are more likely to concentrate their efforts on the lowland rice production (Kim *et al*., 2014). During the short season (*yala*), relatively more capital- and labour-endowed households are more likely to diversify their production on lowland field. However, in this case the diversification is not an adaptive strategy to reduce the sensitivity to water shock, but rather a way to preserve the fertility of the field for the next agricultural season instead of leaving it uncovered. Further evidence based on panel data is required to disentangle these puzzling results, although our conjectures are supported by findings on the adoption of mutual combinations of practices (online appendix D), which show that the effect on the sensitivity of the *stand-alone* adoption of this strategy turns out to be positive when the benchmark is composed of a sub-sample of the population not adopting any practices.

The sole ownership of the largest field reduces the probability of adopting improved practices on lowlands (short-duration rice seeds during the *yala* season and improved residue retention during the long season). In fact, the farmers renting the fields have more incentives to increase the productivity as the harvest must be sufficient to compensate the rent of the land.

[16]The results for all the practices analysed in this study are available in online appendix C.

As for the available infrastructure in the field, the larger is the field area covered by agro-wells, the higher is the probability of adopting improved residue retention technique on lowland and cultivating maize on upland during the long season (*maha*).

Fertilizer and other input subsidies reduce the probability of crop diversification on lowland during *yala*. Although subsidies are given to both rice and other field crop producers in lowlands, the results suggest that the subsidies are associated with increased incentives for rice cultivation.

An important finding is related to the risk management tools available. Participating in crop insurance schemes increases the probability of adopting short-duration rice seeds on lowland during the *yala* season and reduces the probability of adopting other risk reducing strategies on these fields, such as diversifying the cultivation during *yala* or retaining residues and enhancing their decomposition during *maha*.

As the distance from the fertilizer's retailers increases, the probability of using improved seed on lowlands during *yala* decreases while that of retaining residues on these fields and enhancing their decomposition during *maha increases*. For the latter practice, a negative association has been found with the distance from the agrarian service centre. These results are likely to reflect the trade-offs between boosting the productivity through a greater availability of chemical fertilizers and other improved inputs and implementing alternative sustainable management of natural resources, promoted by the Ministry of Agriculture through the agrarian services centres, when these chemicals became less available.

The availability of water, measured as the share of irrigated land and the irrigation type, is associated with the adoption of short-duration rice seeds on lowlands during *yala*. This relationship is likely driven by the fact that rice production during the *yala* season is of short duration and is concentrated in irrigated farm systems.

Finally, it is worth highlighting the existence of substantial peer effects within farmers' organizations for all the practices considered. Leveraging these positive peer effects through group-level extension approaches can generate positive adoption impacts.

Overall, the results from the analysis highlight that the adoption of climate adaption strategies is conditioned on the interlinked relationships between factor intensities of the practices and the factor endowments of the households, and complementary/alternative risk management tools available to the household, as well as peer effect within the community.

8. Conclusions

This paper has analysed the impacts of the adoption of several farm management practices on the sensitivity of farm systems to water stress and household welfare in the Anurādhapura district. The study highlights the existence of potential trade-offs between reducing vulnerability to water stress and maximizing profitability and welfare outcomes. The analysis shows that a number of factors enable or constrain the adoption of climate adaptive practices including: significant opportunity costs for farmers related to off-farm income opportunities, the existence of alternative or complementary risk management tools, the degree of market development, and the peer effects at the community (farmer organization) level.

Several important policy recommendations come out of this analysis. First, building and improving the resilience of Sri Lanka's agricultural sector and farmers' welfare to climate shocks requires the development of strategies to replace labour with capital, including through the development of service markets or mechanization options.

Second, the development and the strengthening of markets for other crops is crucial to support increased diversification of the agricultural production. Making the cultivation of crops other than rice profitable for farmers requires supporting private investments in input and output markets for these crops.

A note of caution is due here since the empirical results refer to an anomalous dry agricultural season. We acknowledge that the practices analysed may perform differently under 'normal' rainfall conditions and the empirical results on the effectiveness of the practices should be interpreted as an upper bound. Moreover, the identification strategies used for this analysis relax some concerns about the endogeneity related to a non-random treatment assignment, but some bias may still arise if the farmers' adoption is shaped by unobservable characteristics.

Ultimately, the findings from this study highlight the challenges faced by Sri Lanka's extension services and agricultural research institutions. They demonstrate that developing and promoting practices and technologies is necessary to reduce the adverse impacts of water stress, but not sufficient to achieve widespread adoption, and more profitable and productive farm-level outcomes.

To address these issues, research and extension must look beyond field experiments and trials and explore options to bundle together the promotion of better practices with complementary support to market institutions, such as appropriate mechanization services, value chain support for other field crops, and input supply systems. In this way, farmer-friendly packages of technologies that support climate risk reduction and lead to more profitable farm-level outcomes can be achieved.

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