Growing More Rice with Less Water: The System of Rice Intensification and Rice Productivity in Vietnam

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Abstract

We study the effects of a large-scale System of Rice Intensification (SRI) program on the water productivity of rice in Vietnam by exploiting the provincial and time variations in SRI uptake and irrigation water supply over the period 2000–2012. Our findings document that the world's second-largest rice exporter could produce four million tons of more rice with same water supply in the reasonably achievable case of 20% SRI uptake across its provinces. In addition, we find that SRI increases the output of other crops too, due at least partly to its possible water savings and soil nutrition preservation in rice production. Moreover, we show that SRI is more likely to be adopted in provinces with stronger quality of provincial institutions and weaker agricultural capital base. Numerous selectivity and randomization tests affirm that the water productivity effect of SRI is robust to selection in SRI uptake at province and district levels and addressing potential unobservables and omitted variables problems.

JEL classification: O13; O33; Q18; Q25.

Keywords: Agricultural Technology; SRI; Impact Evaluation; Water Productivity.

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Abstract

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1. Introduction

The recent resurgence in attention to agriculture stems not only from concerns over how nine billion people are to be fed by 2050, but also from a recognition of the substantial role that agriculture plays in poverty alleviation, economic growth, and long-term development (see Bustos et al., 2016, and Pham et al., 2021). However, agriculture is an input-intensive sector, meaning that improving productivity without compromising resources and the environment is a major challenge. In particular, water – one of the most important inputs (along with seed variety and fertilizer) for boosting cereal productivity (McArthur & McCord, 2017) – is set to become a scarce resource due to an increase in food demand, and greater competition from other sectors. Especially, climatic shocks with droughts occurring more frequently at global scale has endangered agricultural production and food security (Peck & Adams, 2010; Baldos & Hertel, 2014).[1] Moreover, most new methods of crop cultivation, such as intensive irrigation and water management methods, have failed to deliver the desired outcomes, with any reductions in water usage coming at the expense of the crop yield (Carrijo et al., 2016).

In this context, the System of Rice Intensification (SRI) has arisen as a new agricultural practice that arguably boosts rice production while decreasing the water usage. SRI differs from conventional rice production methods in several respects, including its water usage, labor intensity, and seedling planting techniques (Thakur & Uphoff, 2017). By 2012, SRI had reached more than 51 countries (see Online Appendix A Table 1). From a global sustainability perspective, SRI has been reported to save significant amounts of water (25–67%) in rice production in various countries, including China, Cambodia, Philippines, Indonesia, and Sri Lanka. Some early studies reported water productivity improvements even reaching 100% (Satyanarayana et al., 2007). Field experiments and on-station trials have shown that rice grows better under the intermittent water management of SRI than under traditional flooded irrigation (Thakur et al., 2011; Suryavanshi et al., 2013; Kahimba et al., 2014).[2]

However, there are important issues that need attention in the literature. First, plot-level findings from field experiments (mostly relying on small samples) have raised concerns about the generalizability of SRI's benefits. Second, cross-sectional trials provide limited information regarding temporal effects on soil quality and nutrient preservation of the agronomic practice that (arguably) relies on less water. Third, SRI uptake not only remains very low in many countries (Barrett et al., 2004), but also exhibits a myriad of selection issues at the province, district, and farmer levels. For example, Barrett et al. (2004) posits that the farmers who are commonly the first to adopt the SRI are also those who are more skilled, and that these farmers are more likely to be successful with any technology. Moreover, they tend to implement the SRI on their best plots. Furthermore, we believe that the levels of SRI adoption are not independent of province-level institutions that allocate funding for farmer training and provincial infrastructure that shapes the agricultural activity. Thus, the observed gains from the SRI may not be attributable to the new method directly, but instead, may reflect several observed and unobserved characteristics at the province, farmer, or plot levels.

In this connection, it must be acknowledged that recent randomized controlled trials have strong potential to provide causal evidence of some of the SRI's benefits and individual adoption (e.g., Barrett et al., 2021). However, it is also crucial to understand the extent to which the SRI uptake is affected by provinces' institutional and infrastructural set-up and whether aggregate policy conclusions can be derived about SRI's benefits. In addition, the nutrient-preservation effects of SRI over time remain in question until randomized controlled trials can be scaled up in several directions. Taken all together, without an analysis of large-scale implementations, it difficult to determine the factors behind the SRI uptake as well as its water productivity benefits for the agricultural sector.

The key objective of this study is to bridge this gap by examining the effects of SRI on water productivity of rice in Vietnam using province-level longitudinal data on large-scale SRI implementations. Our investigation exploits data on the year and intensity of SRI adoption in 23 of Vietnam's 64 provinces over the period 2000–2012. In addition, we investigate whether implementing SRI fully (all SRI procedures are followed) or partially (some but not all components of SRI are practiced) makes a difference to water productivity. Moreover, we examine the longer-term yield effects of the SRI beyond the contemporaneous effects by exploiting the panel aspect of our data. SRI is said to be a sustainable farming practice, with practices such as intermittent watering and compost application helping to maintain soil nutrition better than conventional practice over the long term. If this is true, then SRI should have a positive effect on rice yield and rice–water productivity in successive year(s) relative to counterfactual observations (i.e., provinces, years, and rice-cultivated areas with no SRI uptake), along with its possible concurrent effect. Furthermore, our province-year panel enables exploring the spillover effects of SRI uptake on the output of other crops. Given that other crops are produced on the same field as rice in different seasons, this analysis shows whether there are additional gains from, or unintended (positive or negative) consequences due to, SRI practice in other areas of agricultural activity. Finally, we shed light on the institutional and infrastructural factors influencing the SRI adoption across provinces and offer possible policy implications in this regard.

SRI implementation in Vietnam started with five provinces in 2003. By the end of 2012, 23 of Vietnam's 64 provinces had implemented it (see Figure 1 for the growth in the number of provinces implementing SRI over time). Our data include the fraction of plots on which the SRI (i.e., SRI-full vs. SRI-partial practice) was implemented in each province in Vietnam, and exhibit strong variation in the timing, space, and intensity of the SRI uptake. Our data cover a total of 343,500 ha of SRI-cultivated land in 23 provinces of Vietnam in 2012. Importantly, the soil quality, climate, and geography all differ strongly across Vietnamese provinces, suggesting that any SRI effects are unlikely to be driven by a particular factor. This contrasts with many field/station experiments, which are carried out in specific situations involving different rice varieties, soil characteristics, or climate conditions. Vietnam's emergence as the world's seventh-largest consumer of rice, and, crucially, as the second-largest rice exporter worldwide, adds substantial weight to this analysis of its large-scale SRI program.

While large-scale program implementation can provide significant information about the effect of a new agricultural technology on water productivity, it also poses methodological challenges. The standard selection problems in relation to SRI adoption at the farmer level can also exist at the province level in similar or different forms. These selection problems are generally related to the way in which the SRI roll-out took place. First, the central government and other donors chose the provinces to which to allocate funds for farmer training. Second, the selected provinces allocated the received funds to some of their districts or communes. Finally, farmers at the district or commune level decide whether to adopt SRI following training. Thus, a myriad of both time-variant and time-invariant factors related to provincial rice production capacity could play important roles in the extent of the uptake, including the selection of districts/communes for program roll-out, the selection of districts/communes to encourage SRI uptake, and farmer and plot characteristics in the province. Hence, in the absence of any exogenous variation, the estimated SRI effects might only reflect selection effects that are correlated with rice yield, rice–water productivity or SRI exposure in a province, rather than those of the SRI per se.

We account for these selection problems by exploiting the variation in both the timing of SRI adoption and the intensity of SRI implementation using province-level longitudinal data. To facilitate a reliable estimation, we control for province fixed effects, year fixed effects, and linear and quadratic time trends at the province level, as well as a wide range of time-varying province characteristics and region-by-year fixed effects that might be correlated with the timing and intensity of SRI uptake and the water productivity of rice.[3] That is, by controlling for permanent province differences, year fixed effects, region-by-year fixed effects, linear and quadratic time trends, and several time-varying province covariates, we exploit the differences in the year, province, and intensity of SRI adoption, in order to estimate the effect of the SRI on water productivity. Central to this identification strategy is the assumption that, once we have controlled for province fixed effects, year fixed effects, region-by-year fixed effects, linear and quadratic provincial time trends, and time-varying provincial covariates, the remaining variation in the intensity of the SRI adoption will be reasonably free from *selection problems at the province level* and will be plausibly exogenous to rice–water productivity at that level. This identification strategy captures whether provinces with more rapid penetration of the SRI have experienced faster increases in water productivity than provinces that have not implemented the SRI.[4]

To the extent that our identification assumption is satisfied, our findings document important gains in water productivity for rice in Vietnam due to the SRI program. Our estimates suggest that, if the SRI is adopted in one-fifth of the rice-cultivated areas in a province (i.e., 20% adoption), that province will achieve an 11% higher rice yield per unit of irrigation water. Equivalently, this would mean that more than four million tons more rice could be produced in Vietnam with the same water supply. Having a large rice producer such as Vietnam supplying approximately 11% more rice to global markets due to an increase in water productivity would have significant implications for consumption, production, poverty, nutrition, the relative price of rice, and input allocation (see Bustos et al., 2016). Our unique dataset also enables us to distinguish between the effects of full vs. partial practice of SRI. SRI encompasses four components: (i) early, quick, and healthy plant establishment; (ii) reduced plant density; (iii) improved soil conditions through enrichment with organic matter; and (iv) reduced and controlled water application. Full practice of SRI means that all of these components are used simultaneously, while partial practice means that producers generally follow the first two principles but ignore or barely practice the last two (SRI in Vietnam, 2016). We find a very strong effect of full SRI practice on the water productivity of rice. The reasonably achievable case of 20% full practice of SRI would increase the rice–water productivity by 30% in the current year, with an additional effect of 14% in the following year. Meanwhile, 20% partial practice of SRI would increase the water productivity of rice by around 11% in the current year but would not affect it in the following year. In terms of the spillover effect, the full implementation of SRI exerts a strong positive effect on maize yield and output, and a positive effect on sweet potato output, suggesting that the potential water savings and soil preservation effects of SRI implementation may foster the production of these two staple crops. Turning to factors influencing the SRI uptake, we find strong evidence that provinces with stronger provincial institutional quality are more likely to uptake SRI, presumably owing to efficiencies in funding and organizing farmer training programs. We also find that lower tractor use in a province is associated with higher SRI implementation rate. In addition, once selected for SRI roll-out, low-tractor-use provinces experience a faster pace of uptake over time. The policy implication of this finding is that returns from SRI will be higher in provinces with weaker capital and infrastructure base.

Taken together, this study makes three important contributions to the extant literature. First, it documents the water productivity effects of SRI by exploiting a large-scale intervention across 64 provinces in Vietnam over a long period, offering findings robust to a wide range of selectivity problems. Second, it distinguishes between the full vs. partial practice effects of SRI, shows the soil nutrition-preserving effect of full SRI practice, and documents possible spillover effects of water savings on other crops' output. Third, it illuminates the institutional and infrastructural factors affecting SRI uptake across provinces and provides insights into policy formulations.

The rest of this paper is organized as follows. The next section discusses the process of SRI adoption in Vietnam. The third section presents the data and descriptive statistics and discusses the potential endogeneity of the SRI program roll-out. The following section describes the empirical framework. The empirical findings are discussed in the subsequent section, which also provides a battery of sensitivity analyses of the results. The final section contains the conclusion.

2. SRI Practice in Vietnam

SRI is a climate-smart, agro-ecological technology that has been developed for the management of plants, soil, water, and nutrients in rice production. Its central principles can be summarized as follows: (i) rice seedlings should be planted one seedling per hill, and spaced in a square grid of at least 20 × 20 cm to help the roots and canopy grow and to keep the leaves of the plant photosynthetically active; (ii) the replanting of seedlings should be shallow and undertaken quickly and carefully in 8–12 days' time, with just two leaves, to avoid damage to roots and minimize replanting shock; (iii) soil condition should be improved through enrichment with compost, with chemical fertilizer added only if needed; and (iv) rice field soils should be kept moist by watering intermittently, rather than continuously, to allow for better circulation of air through the soil and to help root development, thus leading to an improved diversity of aerobic soil organisms (SRI International Network and Resources Center (SRI-INRC), 2015). Weather patterns, soil conditions, labor availability, water control, and access to organic inputs are the key agro-ecological considerations for farmers when adopting the method.[5] See SRI-INRC (2015).

SRI was first implemented in Vietnam in 2002 through individual academic experiments in a few central provinces (Quang Tri, Quang Nam, Thua Thien Hue, and Thanh Hoa). Vietnam's Plant Protection Department (PPD) began training farmers on the SRI in 2003. The first outcomes of SRI were reported in 2006, with yields of 8.8 t ha^{-1} and estimated reductions in water use of 62% and in seed use of 85% (SRI-INRC, 2015). In 2007, the Ministry of Agriculture and Rural Development (MARD) in Vietnam endorsed the SRI as "a technical advance" and directed government departments to spread this innovation (MARD Decree, October 15, 2007). The years 2007, 2008, and 2009 witnessed several efforts to disseminate the SRI across Vietnam, with funding from Oxfam America and Oxfam Quebec, assisted by the Centre for Sustainable Rural Development of Vietnam.[6] In October 2011, the MARD reported that over one million farmers were applying SRI methods on 185,065 ha. This meant that farmers who had adopted the SRI constituted ~10% of all rice producers in Vietnam. In 2014, the SRI was included in the World Bank-funded Irrigated Agriculture Improvement Project to be implemented on Vietnam's central coast and in some provinces of its northern region.

3. Data and Descriptive Statistics

3.1. Data on SRI Implementation

We obtained the data on SRI adoption rates and the area of SRI implementation from the Plant Protection Department (PPD), Ministry of Agriculture and Rural Development. The PPD is the official Vietnam government department that oversees the progress of SRI implementation nationwide. The PPD obtains the information regarding SRI implementation from annual reports from provincial Plant Protection Sub-Departments. The data of SRI practice, full and partial SRI are at commune level. We aggregated the commune-level data to obtain province-level data, because data for rice output and irrigation water were available only at the province level. Despite this aggregation, the data still exhibit sizeable variations in SRI uptake with respect to the year and intensity of adoption. Online Appendix A Table 2 lists Vietnam's 64 provinces and their total years of SRI implementation during 2000–2012.

Figure 1 depicts the evolution of SRI implementation for the 23 provinces that used SRI in 2012. Only five of Vietnam's 64 provinces had implemented the SRI by 2003 but by 2012, a total of 23 provinces had implemented the system. Figure 2 shows that the proportion of SRI-implemented rice areas to total rice-cultivated areas country-wide increased rapidly over time.

Data source for water productivity and time varying covariates are presented in sections 1 and 2 in Online Appendix B.

3.2. Descriptive Statistics

Columns (1) and (2) in Table 1 report the descriptive statistics for our full regression sample.[7] Columns (3) and (4) provide descriptive statistics for province–year observations with and without SRI adoption in year *t*, respectively. Column (5) presents the descriptive statistics for the subsample of 41 provinces that never implemented SRI (i.e., non-SRI provinces) during our sample period, and Column (6) presents statistics for the 23 provinces that began practicing SRI at some point (i.e., SRI-provinces) during the sample period.

Table 1 shows that 17.5% of the province-year observations in Vietnam saw implementation of the SRI over the period 2000–2012. In provinces that took up the SRI at some point, the mean number of years of SRI implementation is six years (45.4% of 13 years). However, the mean adoption rate of the SRI in all province–year observations—our measure of intensity—is on the low side, at 1.4%. In the SRI provinces, the mean adoption rate is

3.6%. These figures are 1.8% and 5.2%, respectively, if we take the means after 2003, when SRI started in Vietnam. These rates mimic the low SRI uptake patterns in other countries.[8,9]

However, simple means mask important variations in the SRI implementation. The share of SRI-full uptake saw a significant jump following the year 2007, when SRI was endorsed as a "technological advance" by the Ministry of Agriculture and Rural Development (see Figure 3). Although the SRI-full implementation rate is still relatively small compared to the SRI-partial uptake, it reached 12.5% of the total SRI-practiced area in 2012, being adopted on 32,964 ha nationwide. The relatively faster growth rate of full implementation over time compared with partial practice implies that a wider adoption of full implementation is likely once farmers become more competent in the overall SRI practice and understand more about SRI's benefits. In general, provinces have instances of both full and partial implementation, although SRI-full is implemented less intensively than SRI-partial, given that SRI-full is more demanding both technically and procedurally while SRI-partial involves simpler principles that are easier for farmers beginning the practice to follow.

4. Selection Problems in the SRI Program Roll-Out

The roll-out of SRI across provinces is unlikely to be random and might reflect observable and unobservable province characteristics that could be correlated with the rice–water productivity. Such endogeneity could arise at several levels. First, the central government and other donors might deliberately target a specific province to increase its water productivity (i.e., selection on the level of water productivity). Second, once the SRI reaches a province, selection may occur regarding the districts/communes in which to implement the program. Third, once the program reaches a district, farmers' decisions to adopt the technique might be subject to a wide range of selection issues, such as skill, education, input (primarily labor) availability, and plot choice. Thus, variations in SRI implementation across provinces are likely to be endogenous because of policymakers' selection of provinces (or the districts within) for the program. In contrast, variations in farmers' SRI adoption across provinces are more likely to be somewhat—if not entirely—exogenous to the central government's selection of provinces for the SRI because they are determined by farmers' uptake decisions. The farmers' uptake decisions themselves may be influenced by a range of individual unobservable characteristics. While we cannot test the effects of farmer characteristics on our results directly using our province-year panel, we provide insights into this phenomenon in section 6.6.

4.1. Selection on Time-Varying Province Observables

It is shown in Table 1 (columns (3)-(6)) that SRI and non-SRI provinces are different in a range of factors. First, rice yield and rice water productivity are statistically higher in the former compared with the latter. Regarding covariates, t-tests show that 10 (columns (3)-(4)) or 9 (columns (5)-(6)) out of 13 covariates are different between SRI and non-SRI provinces. The most notable differences between these two sets of provinces include, fertilizer and tractor use, and number of farms. Tractor and fertilizer use is two to three times lower in SRI provinces compared to their counterpart, while the number of farms is almost five times lower. These figures suggest that SRI and non-SRI provinces are different in agricultural production structure, which may influence both SRI adoption and rice water productivity. We revisit this issue in section 4.4.

4.2. Selection on the Level of Water Productivity of Rice

We have shown that a wide range of time-varying rice production-related observables at province level are associated with SRI implementation and adoption. This is plausible because SRI is designed primarily for yield improvement (with soil and environment preservation as complementary targets). Note, however, that SRI is an innovative technology, and farmers need to be trained to practice it. This points to the importance of funding from the government and donors for implementation and adoption. The funds are allocated to a selected province, and a plan of proposed expenses for the farmers' training is made ex ante to ensure that sufficient funds are available to provide a reasonable amount of training for farmers. In addition, SRI implementation requires a set of co-existing factors in a province. This means that a province is considered for SRI implementation *a priori* based on its general set of requirements or its capacity for SRI practice in the long term, rather than its year-to-year yield performance or characteristics. This method of selection suggests that permanent province characteristics play an important role in explaining why a province is selected for SRI practice.

In general, if provinces with favorable conditions for rice production implement SRI earlier and use it more intensively, they would experience higher water productivity, even without SRI.[10] Thus, failing to control for attributes that are correlated positively with both SRI implementation and rice production would bias the SRI effect upwards. Figure 4 illustrates the rice–water productivity of SRI-provinces (red line) against non-SRI provinces (blue line) prior the introduction of SRI, clearly showing that, even before practicing SRI, provinces that later implemented the SRI consistently had higher rice–water productivity levels than the non-SRI provinces.[11]

4.3. Selection on Timing of SRI Adoption

It is notable that the timing of SRI implementation is not random either. The early or late implementation/adoption of SRI is likely to be influenced by other programs that are implemented simultaneously with SRI in a province. The most important economic development program over period was the installation of special economic zones (SEZ), which gradually increased from one in 2003 to 14 in 2012. These zones are granted special benefits, such as tax or investment policies, land rent, or trade policies designed to attract foreign investment and facilitate economic activity in a region. Thus, provinces with SEZ could adopt SRI later than their counterparts (see Table 3 in Online Appendix A for the timing of SEZ opening and SRI adoption). Online Appendix A Figure 1a plots the evolution of rice–water productivity growth for 10 provinces with SEZ but without SRI implementation while Online Appendix A Figure 1b displays that information for 31 provinces that never practiced either SRI or SEZ. Clearly, provinces with SEZ experience a faster evolution of rice–water productivity than most provinces in the other group, suggesting a possible positive spillover effects of SEZ on agricultural development in the region. Thus, region-by-year fixed effects can account for time-varying omitted variables at the region level such as the SEZs.

Taken together, selection on observable and unobservable province characteristics and on the timing of SRI implementation needs to be addressed when attempting to quantify the effects of SRI on rice–water productivity. Importantly, the nature of selection (i.e., one-off rather than year-to-year selection) means that provinces' long-term characteristics (i.e., their rice-production-related permanent characteristics or trends) are more likely to be the root cause of selection.

4.4. Factors Influencing SRI Implementation and Adoption

We obtain more insights into the non-randomness of the SRI roll-out by regressing the time-varying province observables mentioned in section 4.1 on *SRI Dummy,* a binary indicator of SRI implementation in a given province that takes 1 if SRI is implemented in year t, and 0 otherwise.[12] Controlling for these inputs in SRI adoption equation may result in the "bad controls" problem in the spirit of Angrist and Pischke (2009). For example, Takahashi, and Barrett (2014) showed a significant increase in labor use among SRI users. As such, the levels of fertilizer and machinery use can potentially be adjusted to SRI practise. Thus, in addition to controlling a suit of fixed effects and time trends, we allow a one-year lag of these inputs (fertilizer and tractor use, and rice labor) to alleviate the bad controls problem. Meanwhile, other factors such as rainfall and

PCI are likely to be exogenous to SRI adoption, and thus, we employ the current value of these covariates in the regressions.

Consistent with our earlier argument that SRI adoption reflects a full range of selection at different aspects, the regression results show several time-varying province covariates are significantly associated with SRI adoption, and the link is generally broken in regression when all the year fixed effects, province fixed effects, region-by-year fixed effects, and time trends are controlled for (see section 3 in Online Appendix Table B for detailed results and analysis). We thus move on with *SRI Intensity* as an outcome using regression with full set of the said fixed effects.

Results in Table 2 show that PCI promotes the SRI uptake. Specifically, a five-percentage point increase in PCI leads to 0.5% additional SRI uptake in that province (equivalent to 36% in relative magnitude given that mean value of SRI uptake is 1.4%). This is probably because authorities in provinces with higher PCI are more efficient in SRI-related activities such as organizing and allocating fund and technical support for SRI adopters. This result also suggests that PCI must be controlled for in our water productivity regressions. Using *SRI dummy* as an additional control (not reported) does not change this result.

As another factor associated with SRI uptake in a province, higher tractor use is negatively related to lower SRI implementation rate. In particular, 1% increase in tractor use leads to 2.2% decrease in SRI implementation rate. This is not surprising as SRI utilizes significant amount of labor instead of machines. Figure 5 displays the average SRI implementation rate conditional on SRI adoption among province-year observations with below and above the median of tractor use in the previous year. Figure 5 suggests that, conditional on being selected for SRI roll-out, provinces with lower tractor use overtake those with higher use in terms of SRI implementation. The slow SRI implementation rates in high-tractor-use provinces tends to support our earlier comment that once training programs for new farmers end, the implementation rate can level off, or even fall, because farmers are not retained in SRI given their capital-intensive agricultural practice. By contrast, provinces with low tractor use are associated with consistent increase in SRI implementation rate, even surpassing their high-use counterparts from 2011.

4.5. Validity of Identification Strategy

To shed more light on the validity of our identification strategy, we conduct an event-study analysis by running a regression of log water productivity for rice on four leads and lags of a binary variable of the year-to-adoption (which captures the initial year of SRI uptake). For a meaningful comparison of rice–water productivity between SRI and non-SRI provinces, the two groups should trend similarly in the absence of SRI introduction. We conduct three scenarios with different sets of controls alongside year-to-adoption dummies. The first scenario includes only year fixed effects, while the second additionally includes province fixed effects. The third scenario augments the second scenario with region-by-year fixed effects, and province-specific non-linear time trends. The regression results for these scenarios are reported in columns (1)–(3) of Online Appendix A Table 4. Clearly, the parallel trends assumption is violated in the first scenario (Figure 6a). Even prior to the implementation of SRI, the SRI provinces had higher levels of rice–water productivity (with the size of the estimate being 0.15–0.16 and significant for three and four years prior to SRI adoption, see column (1) Online Appendix A Table 4). In the second scenario (Figure 6b), the inclusion of province fixed effects halves the estimate of earlier lags of the year-to-adoption dummy, though the effects are still statistically significant (columns (2) Online Appendix Table A 4). Not until the third scenario (not reported graphically, regression results are in columns (3) Online Appendix A Table 4) are the lag effects reduced to the point where all become statistically insignificant. In addition, the positive effect of SRI implementation on the rice–water productivity starts to be revealed in three years.[13] The results where time-varying province observables are controlled for (Figure 6d, and column (4) Online Appendix A Table 4) yield the same pattern as the third scenario, with the lead effects showing clearer after three and four years. These results indicate that our parallel trends assumption is likely to be satisfied in our richest specification. Conversely, earlier lags of year-to-adoption are significant (the trend of the SRI provinces differs significantly), suggesting something else—such as another program—might have been ongoing in those provinces, or the province might have been selected for the SRI for another reason. The lead SRI effects are not revealed until three and four years after SRI adoption, which is unsurprising because the event-study analysis is based on the binary indicator of SRI participation, which does not convey the intensity of SRI uptake fully. Our empirical section addresses this shortfall by utilizing a measure of SRI intensity.

5. Empirical Framework

We investigate the effects of SRI implementation on the rice–water productivity as follows:

$$lnWP_{pt} = \alpha_0 + \alpha_1 SRI\ Intensity_{pt} + \mathbf{Z}_{pt} + \mathbf{W}_{pt} + \eta_p + \kappa_{rt} + \boldsymbol{\zeta}_t + \tau_{pt} + \tau^2_{pt} + e_{pt}\ , \qquad (1)$$ [14]

where WP_{pt} is the rice–water productivity at the province level, which is obtained by dividing the rice yield by the water used per hectare of rice production area (or, equivalently, the rice output divided by the total water use for rice production). The main variable of interest, *SRI Intensity*, denotes the proportion of SRI-adopted rice areas to total rice-cultivated areas. **Z**, and **W** are vector of inputs into rice production and time varying province characteristics as in the adoption part (see Table 2 for the list of these covariates) η_p is a set of province-specific dummies; $\boldsymbol{\zeta}_t$ is a set of year dummies, which account for any nationwide shock in year t; κ_{rt} is set of region-by-year specific dummies; τ and τ^2 are sets of province-specific linear and quadratic time trends, respectively; and

e is the error term. We also allow the SRI intensity to be decomposed into two: SRI-full and SRI-partial.

This model is based on the standard farm-level production function, aggregated to the province level, whereby inputs into the rice production in a province and the total factor productivity predict the total rice output per unit of water in that province. The model estimates the annual water productivity effects of more rapid penetration of the SRI into provinces that implement the SRI, relative to those that had not implemented the SRI. Equally importantly, our event study shows that the evolution of rice–water productivity pre-SRI adoption is similar across the two groups of provinces once province fixed effects, year fixed effects, province-specific non-linear time trends and region-by-year fixed effects are included. Thus, the coefficient α_1 would plausibly reflect how *SRI Intensity* affects the rice–water productivity (once again, PCI needs to be included in equation (1) given that it is likely to lead to selection based on provincial institutional quality).

An additional test is related to the dynamic effects of SRI on water productivity. SRI practice does not keep the soil flooded for as long as the conventional method and recommends the use of compost instead of fertilizer, helping maintain soil aeration and soil biota. To provide insights into this argument, we add the first lag of SRI intensity to Equation (1):

$$lnWP_{pt} = \alpha_0 + \alpha_1 SRI\ Intensity_{pt} + \alpha_1 SRI\ Intensity_{p(t-1)} + \mathbf{Z}_{pt} + \mathbf{W}_{pt} + \kappa_{rt\ r}\ \eta_p + \boldsymbol{\zeta}_t + \tau_{pt} + \tau^2_{pt} + e_{pt}\ . \quad (2)$$

This also allows for SRI intensity and its lag (i.e., SRI-full practice and lag of SRI-full practice, and SRI-partial practice and lag of SRI-partial practice) to be examined both in separate equations and jointly in a single equation. To be consistent with equation (1) and avoid “bad controls”, we allow two-year lags of inputs (fertilizer and tractor use, and rice labor) where the equation includes the lag of SRI intensity.

Another important question is whether the savings in irrigation water flow due to SRI were channeled to the production of other crops. If any irrigation water saved by the adoption of SRI could be used for other crops, this would mean that the benefits of adopting SRI would spill over to other agricultural activities, and specifically to other crops that share the same water supply with rice. Therefore, we test the effect of SRI on the yield and output of maize and sweet potatoes directly, as they are often rotated with rice in the same field. Cassava is grown in hilly areas far from rice fields, so cassava serves as a placebo test for the validity of our econometric specification.

Finally, we estimate the model using ordinary least squares (OLS) with robust standard errors clustered at the province level, which has been shown to take care of both heteroscedasticity (Stock and Watson, 2008) and serial correlation (Cameron and Miller, 2015) in panel data models.

6. Empirical Results

6.1 The Effects of SRI on the Water Productivity of Rice

We present results using the richest specification with full set of explanatory variables in Table 3; we provide the results for specifications where we include set of controls one by one in Online Appendix B Table 2**.** The coefficient of SRI intensity in column (1) Table 3 is 0.55 and strongly significant at 1% level. This estimated *SRI Intensity* effect is economically meaningful and suggests that, if a province were to implement SRI on its *all* rice-cultivated plots, it would experience a 55% increase in rice–water productivity. The coefficient of 0.55 for *SRI Intensity* suggests that, if a province were to implement SRI on 20% of its rice-cultivated areas, it would experience a rice output increase of almost 120 tons per thousand cubic meters of water use. Equivalently, this means that Vietnam could produce over four million tons more rice with the same water supply.[15] In the case of SRI-full, a 20% adoption would see an output increase of 350 tons per thousand cubic meters of water use, or 12 million tons more rice produced using the same amount of water.

Column (2) allows SRI-full and SRI-partial practice to stand separately, and reports that SRI-full practice exerts a huge impact on water productivity relative to SRI-partial practice. The former is 1.53, while the latter is 0.44, with both being significant.[16] Note that the high coefficient estimate of *SRI Intensity* is within expectations given the low uptake of SRI. As this is the first study to disentangle the effects of SRI-full vs. SRI-partial implementation, we are unable to compare the effects of SRI-full implementation with the current literature.

An important concern is that even though province-specific non-linear time trends are appropriate for cleaning out the selection on trend, these variables may end up being confounded with the dynamic effect of SRI intensity (Wolfers, 2006). To alleviate the concern, we employ a longer time span of data on rice–water productivity, 1995–2012, to check our results and the pattern of change in α_1. The estimation results across the specifications from columns (1)–(5) for the period 1995–2012[17], reported in Panel A of Online Appendix A Table 5, show a pattern of change that is very similar to that seen for α_1 across columns (1)–(5) of Online Appendix B Table 2. The results re-state the importance of different dimensions in the selection for SRI implementation, and provide more credibility to our econometric framework as an appropriate way of addressing the selection.

6.2. Lag Effects of SRI on Rice–Water Productivity

Under SRI, the planted soil is irrigated intermittently and kept moist, rather than being saturated or flooded for an extensive period, as in the traditional method.[18] Thus, SRI is believed to help maintain soil nutrition better than conventional farming methods, in terms of soil aeration and soil biota. We now evaluate the validity of these arguments by focusing on the dynamic effects of SRI.

Results in columns from (3)-(6) in Table 3 show that SRI-full is estimated to be large with coefficients of current effect from 1.3-1.7, while the lag effect has coefficients of 0.57-1. The current effect of SRI-partial is 0.62-0.64, and significant at the 1% level, while its first lag is insignificant. In sum, we find that only the first lag of SRI-full is positive and significant, a result that is consistent with the water-saving techniques captured in the full SRI practice.

6.3. Effect of SRI on Water Productivity among Provinces with Low vs. High Tractor Use

The adoption analysis in Table 2 shows that SRI is implemented more intensively in provinces with less modern technology. Accordingly, we should see a larger effect of SRI intensity in provinces with lower levels of tractor use. Table 4 reports results for the provinces with tractor use below vs. above the median value.[19] We report the results for specification as in Table (3). The results in columns (1)-(6) consistently show that the estimated effect seen in our overall sample is driven by provinces with lower-than-median value of tractor use though significance is weaker in some cases, probably owing to smaller sample size. The policy implication of this finding is that more funding can be allocated to farmer training programs in provinces with weaker agricultural capital base. On the contrary, no significant positive effect is observed in provinces with higher levels of tractor use (columns (7)-(12)) apart from some negative effect of lagged SRI partial implementation on rice water productivity.

6.4. The Effects of SRI on Rice Yield and Irrigation

We next investigate whether the observed increase in the water productivity of rice is due to an increase in the numerator (rice yield) or a decrease in the denominator (irrigation water per hectare). Using log rice yield as the dependent variable in equation (2), columns (1)–(4) of Table 5 provide analogous results to those in columns (1), (2), (3), and (5) in Table (3). Column (1) in Table 5 reports the *SRI Intensity* coefficient to be 0.58. In column (2), the SRI-full and SRI-partial coefficients are 1.62 and 0.46, respectively. Lag effects of SRI on the rice yield in columns (3) and (4) are found for SRI-full (though not significant in column (4)) but not for SRI-partial, results that are similar to the effect on water productivity in Table 3. Moving on to columns (5)–(8) of Table 5, SRI appears not to affect the irrigation water flow per area of rice planted. All the estimates of SRI here are small and insignificant except for lagged SRI partial implementation, which is positive and significant at 10% level. These findings suggest that the increase in water productivity observed in Table 3s due to more rice being produced per unit of water.[20]

6.5. The Effects of SRI on the Yields and Outputs of Other Crops

A crucial question is: does SRI have any effect on other crops' production? SRI may affect other crops' yield and output in two ways. First, if SRI indeed reduces the water use for rice, the resulting water savings could be used to grow other crops, and hence could boost their production. That is, as water is pumped into the irrigation channels, the water saved by SRI can be used for other crops that are grown in the same field as rice, or to grow these crops in nearby plots which would otherwise be left fallow if water was insufficient. Second, SRI can affect other crops' yields by retaining soil quality, and thus enhancing the yields of crops that are rotated into the plots with rice, or that are cultivated on portions of land that had previously grown rice.

One pitfall of our analysis is that the effect of SRI on water savings (if any) cannot be revealed directly through water supply information because the water supply is fixed. However, if water is used for other crops that share the field with rice, any increase in the output of other crops, such as maize and sweet potatoes, may be attributable, at least partly, to water savings from SRI. Further, if SRI maintains soil nutrition better than conventional methods, then it may result in higher yields of other crops which are planted in plots previously used for rice for crop rotation purposes. While the two mechanisms are difficult to disentangle, we attempt to shed light on the two effects by employing the richest specification that includes both the lagged and current effects of SRI. The lagged estimate should capture the effect of SRI through the second avenue mentioned above (i.e., sustainability of soil quality under SRI practice), while the contemporaneous estimate is more likely to reflect the first mechanism, though possibly also somewhat the second avenue, as crops can be rotated into rice plots in the same year.

Of three other crops for which data are available, maize and sweet potatoes are often grown in the same field as rice, while cassava, owing to its special biological characteristics, is grown in hilly regions far from rice fields. If our econometric framework captures the spillover effects rightly, we should not see any effect of SRI on cassava production.

Table 6 reports the estimation results for maize, sweet potatoes, and cassava for our full specification with both current and lag of SRI full and partial. The results in column (1) & (2) show that SRI-full has large positive effects on both the yield and the output of maize. The current effect for maize yield and output (columns (1)–(2)) is 1.2–1.4% (with respect to a 1% increase in the SRI-full implementation area), which is significant at the 5% and 10% level, while the lag effect is 0.8-0.9, though significant for maize yield only. The result implies that an SRI-full implementation rate of 1% would increase the maize production output nationwide by more than 50 thousand tons, calculated at the mean value of the maize output.[21] The effect of SRI-full implementation on the output of sweet potato (column (3)) is also large and significant at 5% level.[22] Importantly, no current or lag effect of SRI-partial on the yield of any crop is found. This confirms that water savings and soil quality improvements are more likely to be associated with full SRI. Consistent with results for rice water productivity, the effect of current and lag of SRI full is driven by provinces with low level of tractor use (not reported).[23]

6.6. Addressing Other Selectivity Issues

In an Online Appendix B, we subject the sensitivity of our key finding to a number of selection tests, including (i) whether targeting a province for program participation matters; (ii) the intensity effect once program participation of the province is controlled; (iii) selection bias on the initial level and growth of water productivity of rice; (iv) selection on the timing of implementation (i.e., does an early vs. late start matter?); (v) selection of districts at the province level; (vi) selection on farmer or plot characteristics; (vii) the role of cooperatives; (viii) selection on future expectations in regard to the water productivity of rice; (ix) subjecting our results to randomization inference to assuage the concern of selection on unobservables. Our key findings survive all of these robustness checks.

7. Conclusions

Water scarcity and food security are major problems globally, which has rendered advances in the efficient use of water for agricultural production even more critical. The primary objective of this paper is to offer a detailed evaluation of the water productivity benefits of a large-scale agronomic program—the SRI—in Vietnam. We conduct our evaluation using a unique annual province-level panel dataset with unique data on SRI implementation rate measuring the proportion of SRI-implemented rice area to the total rice-cultivated area in a province over the period 2000–2012. Our evidence is predicated on a total of 343,500 ha of program-implemented rice cultivation in 23 SRI-implementing provinces. This scale of analysis is in sharp contrast to the existing literature, which has almost exclusively employed small plot-level samples in the range of 1 to 70 ha.

The gradual implementation of the SRI across Vietnamese provinces provides a rare example of strong time and geographic variation for an experimental setting. However, it also poses its own methodological problems. The SRI rollout in Vietnam occurred primarily through the disbursement of centrally-administered funds to provinces for farmer training. Provinces, selected based on their rice-production capacity, allocated the funds to districts for use in organizing farmer-training programs. Then, farmers made adoption decisions after receiving training. Education, skill, labor and capital endowment, and plot quality were all relevant farmer characteristics in the adoption decision.

Our identification isolates a range of time-invariant province characteristics, year fixed effects, province-specific linear and quadratic time trends, region-by-year fixed effects, and various other time-varying province covariates that may be relevant to rice production. Central to our identification strategy is the assumption that, once all these factors have been accounted for in program evaluation, the remaining variation in the intensity of SRI adoption is plausibly exogenous to the determinants of rice yield at the province level.

We find that SRI has led to significant water productivity gains in rice production. Our estimate suggests that a province that implements SRI on 20% of its rice-cultivated area will produce 120 tons more rice per thousand cubic meters of irrigation water. Thus, Vietnam could produce more than four million tons of additional rice every year with the same water supply. There is also strong evidence that the effect is much larger if all SRI procedures are followed. In addition, SRI results in higher levels of water productivity and rice yield in the following year, supporting the credibility of this method as a sustainable and environmentally-friendly farming practice. The evidence also suggests that SRI uptake leads to significantly higher yields and production of other crops, including maize and sweet potatoes, the two major staple crops of Vietnam along with rice. This effect may be attributable, at least in part, to the water saved because of SRI, as well as to the soil preservation effect of SRI practice. Turning to institutional and infrastructural factors influencing the SRI adoption, there is strong evidence that provinces with stronger provincial institutional quality are more likely to adopt and implement SRI more intensively, presumably owing to efficiencies in organizing farmer training programs. Our results also show that lower tractor use in a province is associated with higher SRI adoption intensity. This is consistent with SRI principles that require significant labor inputs in place of machines. In addition, once selected for SRI roll-out, low-tractor-use provinces experience a faster pace of uptake over time. The policy implication of this finding is that returns will be higher from SRI in provinces with weaker capital and infrastructure base.

The results of this paper have very important policy implications for water usage in rice production. The sheer prospect of a reasonably achievable 20% implementation of SRI resulting in an additional four million tons of rice production annually means that SRI could feed 15 million more persons per year with the same water supply. This suggests that SRI can have a tremendous effect on food security at both the national and global scales. Although the initial uptake of the full SRI practice was small, it has been growing since, and its triple, and sustainable, effect will come without compromising water resources, which is important given that water scarcity is a growing concern worldwide.

References

Angrist, J. and Pischke, J.S. 2009, *Mostly Harmless Econometrics: An Empiricist's Companion,* Princeton University Press.

Baldos, U. L. C., & Hertel, T. W. (2014). Global food security in 2050: The role of agricultural productivity and climate change. *Australian Journal of Agricultural and Resource Economics*, *58*(4), 554–570.

Barrett, B., C. M. Moser, O. McHugh, and J. Barison. 2004. "Better Technology, Better Plots, or Better Farmers? Identifying Changes in Productivity and Risk among Malagasy Rice Farmers." *American Journal of Agricultural Economics, 86*: 869–888.

Barrett, B. C., A. Islam, M. A. Malek, D. Pakrashi, and U. Ruthbah. 2021. "Experimental Evidence on Adoption and Impact of the System of Rice Intensification**."** *American Journal of Agricultural Economics, forthcoming.*

Bustos, P., B. Caprettini, and J. Ponticelli. 2016. "Agricultural Productivity and Structural Transformation: Evidence from Brazil." *American Economic Review, 106*(6): 1320-1365.

Cameron, A. C., and Miller, D. L. 2015. "A Practitioner's Guide to Cluster-robust Inference." *Journal of Human Resources, 50*(2): 317-372.

Carrijo, D. R., M. K. Lundy, and B. A. Linquist. 2016. "Rice Yields and Water Use under Alternate Wetting and Drying Irrigation: A Meta-Analysis." *Field Crops Research, 203*(1): 173-180.

Cesur, R., E. Tekin, and A. Ulker. 2018. "Can Natural Gas Save Lives? Evidence from the Deployment of a Fuel Delivery System in a Developing Country." *Journal of Health Economics, 59*: 91-108.

de Fraiture, C., and D. Wichelns. 2010. "Satisfying Future Water Demands for Agriculture." *Agricultural Water Management, 97*: 502–511.

Kahimba, F. C., E. E. Kombe, and H. F. Mahoo. 2014. "The Potential of System of Rice Intensification (SRI) to Increase Rice Water Productivity: a Case of Mkindo Irrigation Scheme in Morogoro Region, Tanzania." *Tanzania Journal of Agricultural Sciences, 12*(2): 10-19.

McArthur, J. W., and G. C. McCord. 2017. "Fertilizing Growth: Agricultural Inputs and Their Effects in Economic Development." *Journal of Development Economics, 127*: 133-152.

Mottaleb, K. A., Mohanty, S., & Nelson, A. (2015). Factors influencing hybrid rice adoption: A

Bangladesh case. *Australian Journal of Agricultural and Resource Economics*, *59*(2), 258–274.

Noltze et al. 2013. "Impacts of Natural Resource Management Technologies on Agricultural Yield and Household Income: The System of Rice Intensification in Timor Leste." *Ecological Economics, 85*:59–68.

Ogundari, K., & Bolarinwa, O. D. (2018). Impact of agricultural innovation adoption: a meta-analysis. *Australian Journal of Agricultural and Resource Economics*, *62*(2), 217–236.

Peck, D. E., & Adams, R. M. (2010). Farm-level impacts of prolonged drought: Is a multiyear event more than the sum of its parts. *Australian Journal of Agricultural and Resource Economics*, *54*(1), 43–60.

Pham, G., S.H. Chua, and S. Feeny (2021). Factors affecting the adoption of sustainable agricultural practices: Findings from panel data for Vietnam", *Ecological Economics*, 184: 1-13.

Satyanarayana, A., Thiyagarajan, T. M., & N. Uphoff. 2007. "Opportunities for Water Saving with Higher Yield from the System of Rice Intensification." *Irrigation Science, 25*(2): 99-115.

Schlenker, W., and M. J. Roberts. 2009. "Nonlinear Temperature Effects Indicate Severe Damages to US Crop Yields Under Climate Change." *Proceedings of the National Academy of Sciences, 106*(37): 15594-15598.

SRI International Network and Resources Center (SRI-INRC). 2015. http://sri.cals.cornell.edu/index.html, retrieved 25 February 2015. Cornell University.

SRI in Vietnam. 2016. https://vietnamsri.wordpress.com/2017/04/25/the-10-years-journey-of-sri-in-vietnam/, retrieved 25 March 2017.

Stock, J. H., and Watson, M. W. 2008. "Heteroskedasticity-robust Standard Errors for Fixed Effects Panel Data Regression." *Econometrica, 76*(1): 155-174.

Stoop, W., N. Uphoff, and A. Kassam. 2002. "A Review of Agricultural Research Issues Raised by the System of Rice Intensification from Madagascar: Opportunities for Improving Farming Systems for Resource-poor Farmers." *Agricultural Systems, 71*: 249–274.

Suryavanshi, P., Y. V. Singh, R. Prasanna, A. Bhatia, and Y. S. Shivay. 2013. "Pattern of Methane Emission and Water Productivity under Different Methods of Rice Crop Establishment." *Paddy Water Environment, 11*(1-4): 321-329.

Thakur, A. K., S., Rath, D. U. Patil, and A. Kumar. 2011. "Effects on Rice Plant Morphology and Physiology of Water and Associated Management Practices of the System of Rice Intensification and Their Implications for Crop Performance." *Paddy Water Environment, 9*(1): 13-24.

Thakur, A. K., & Uphoff, N. T. (2017). How the system of rice intensification can contribute to climate-smart agriculture. *Agronomy Journal*, *109*(4), 1163–1182.

Uphoff, N. 2006. "The System of Rice Intensification (SRI) As a Methodology for Reducing Water Requirements In Irrigated Rice Production**."** Paper presented at the *International Dialogue on Rice and Water: Exploring Options for Food Security and Sustainable Environments*, IRRI, Los Baños, Philippines, March 7–8, 2006.

Wolfers, J. 2006. "Did Unilateral Divorce Laws Raise Divorce Rates? A Reconciliation and New Results." *American Economic Review 96*(5): 1802-1820.

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[1] Crop production consumes 80% of all freshwater resources around the world (de Fraiture & Wichelns, 2010).
[2] Several studies have found limited or mixed yield benefits from the SRI. Critics of the SRI argue that the yield gains achieved by the system are not systematic but are only sporadic. Nonetheless, significant yield gains due to SRI have been reported in many countries, such as Bangladesh, Cambodia, Cuba, Gambia, Indonesia, the Philippines, and Sierra Leone (see Noltze et al. (2013) for a detailed review on yield effect of SRI).

[3] This empirical method is used widely in the health and labor economics literature (see Cesur et al., 2018 for recent applications) for studying the causal effects of policy changes on outcome variables at the province/state level longitudinal data.

[4] In this paper, "implementation" refers to the central government's decision to select a province to participate in the SRI program roll-out, and "adoption" refers to the farmers' decision to take up the technology.

[5] These principles can also be applied to other crops (such as wheat, sugarcane, teff, and pulses), in which case the method is referred to as the System of Crop Intensification.

[6] The National Workshop on SRI in 2010 reported that, in 2009, 440,833 farmers in 21 provinces used SRI methods on 232,365 ha (85,422 in the winter–spring season and 146,943 in the summer season).

[7] The full sample contains 796 province–year observations (64 × 13 = 832, minus 14 missing observations on SRI-adopted area and a further 22 missing observations on total rice-cultivated area). Note that unavailable data on the SRI adoption rate do not seem to drive our findings. Using a "missing dummy" approach for these observations does not change the key results.

[8] For example, Barrett et al. (2004) found that the average adoption rate of the SRI among Malagasy farmers is 3%. One province in our study implemented the SRI in as many as 49.2% of its plots in a certain year. Online Appendix A Figures 1 and 2 show that there no such outliers in our sample.

[9] The adoption rate of other sustainable agricultural technologies is also low. Several important factors can explain the low adoption rate, such as the quality of the local infrastructure, lack of government support, or the lack of peer support (Mottaleb et al., 2015; Ogundari & Bolarinwa, 2018; see also Pham et al. 2021 for Vietnam).

[10] For example, some provinces that have higher water productivity levels due to the availability of a more stable and efficient water supply are more likely to implement SRI first, as water control and water management are core requirements of SRI practice.

[11] The SRI was adopted earliest and most intensively in some Red River Delta provinces. The Delta is characterized by a stable water supply and an abundant labor force—other suitable conditions for the SRI.

[12] A probit/logit estimation yields analogous findings to those obtained using OLS.

[13] Including the set of time-varying controls reduces the number of observations to less than half of overall sample. Though the results from reduced sample are largely the same (not reported), we use missing dummy techniques to avoid the loss in number of observations.

[14] This equation is derived from the standard Cobb-Douglas production function for rice $Y_{pt} = \propto SRIIntensity_{pt}^{\propto_1} Z_{pt} W_{pt} e^{v_{pt}} (1')$, where Y_{pt} is the rice yield of province p in year t (rice output/rice production area). We divide Equation (1') by the irrigation water per rice production area (which is one of the inputs in Z_{pt}) to obtain the equation with the outcome variable of interest, water productivity. Then, we take the logs of both sides to obtain the estimating equation (1).

[15] The total increase in rice output is calculated by multiplying 120 by the mean value of water use in the whole country, which is roughly 34.7 million tons per year.

[16] The SRI estimate in Column (1), 0.55, is the weighted average of the SRI-full and SRI-partial estimates in Column (2).

[17] We do not have data for the control variables for the period 1995–2012 required to run the regression in column (6).

[18] If soil is kept flooded continuously, the nitrogen available is almost entirely in ammonium (NH_{4+}) form, whereas under intermittent watering, as in SRI, nitrogen is available in both the ammonium and nitrate (NO_{3-}) forms, which indicates a more balanced soil chemistry for rice cultivation (Uphoff, 2006). Also, the SRI recommends the use of compost instead of mineral fertilizer and no use of chemicals and pesticides (Stoop et al., 2002).

[19] To be consistent with the adoption part we divide the subsamples based on level of tractor use in the last year to minimize the potential reverse causality of SRI intensity on tractor use in current year.

[20] We also use the equivalent outcome as the log of rice output and the log of irrigation water. With these two outcomes, we use the total inputs for the production function instead of scaled inputs (inputs per hectare of rice production area). These regressions use the log rice production area as an additional control. The results with the outcomes being the log of rice output and the log of water supply are similar and therefore are not reported to save space.

[21] This is calculated by multiplying the elasticity of the responsiveness of maize output with respect to SRI full implementation (1.4%) by the average maize output (57,600 tons) and the 64 provinces of Vietnam.

[22] The effect on the yield of sweet potatoes is positive but insignificant (not reported).

[23] No effect of SRI on either the yield (not reported to save space) or the output of cassava production is found for both overall sample (columns (4) and sample of provinces with low level of tractor (not reported). This crop serves to ensure that our econometric framework is not falsely capturing something other than the spillover effect of SRI on other crop production.

Figure 1: Number of Provinces Implementing SRI in Vietnam

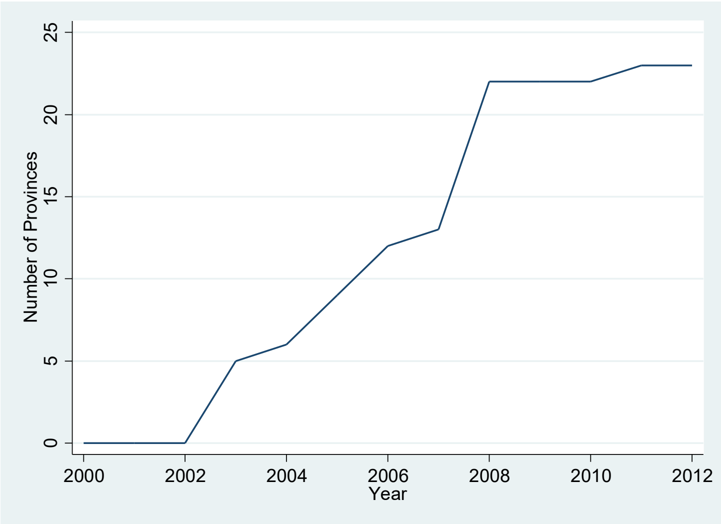


Figure 2: Share of SRI-Implemented Rice Area in Vietnam

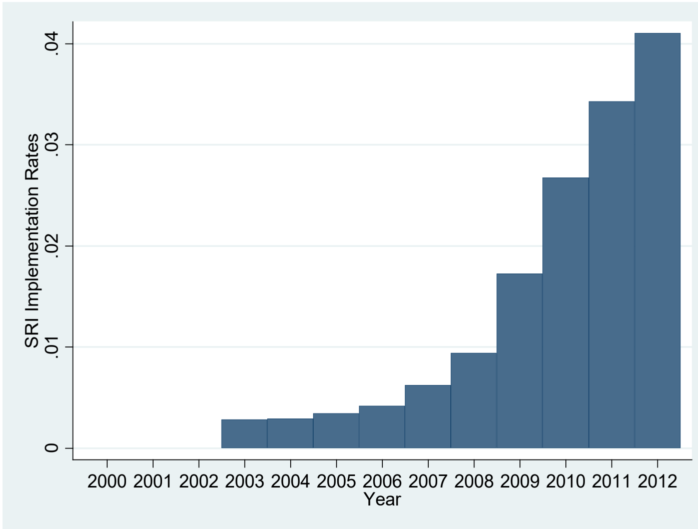


Figure 3: Evolution of SRI Full Implementation over Time

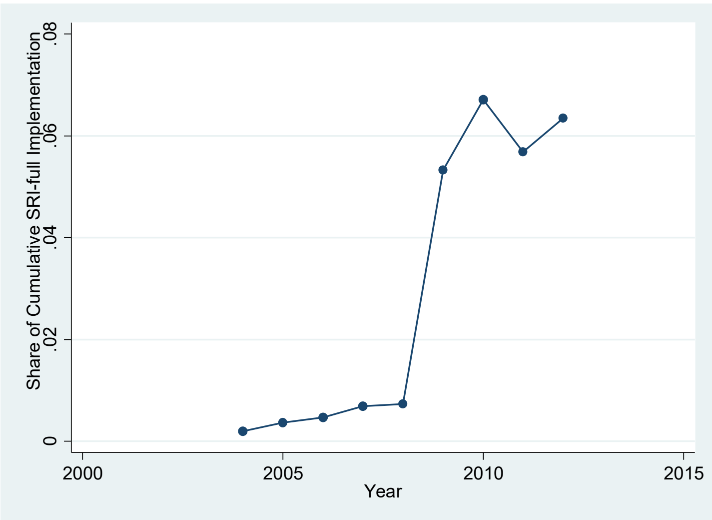
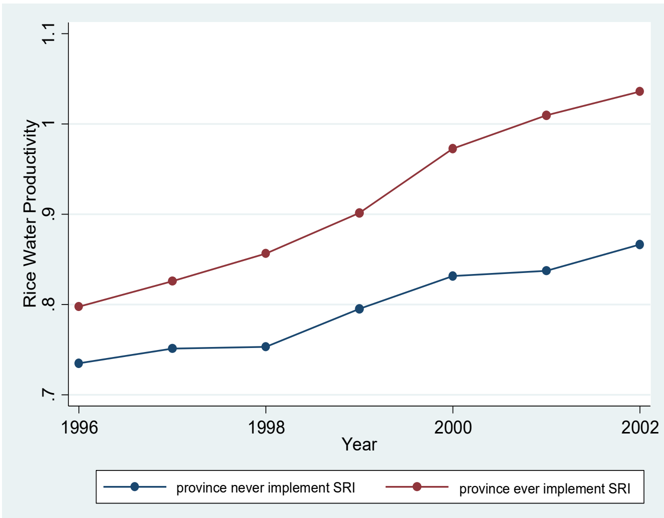
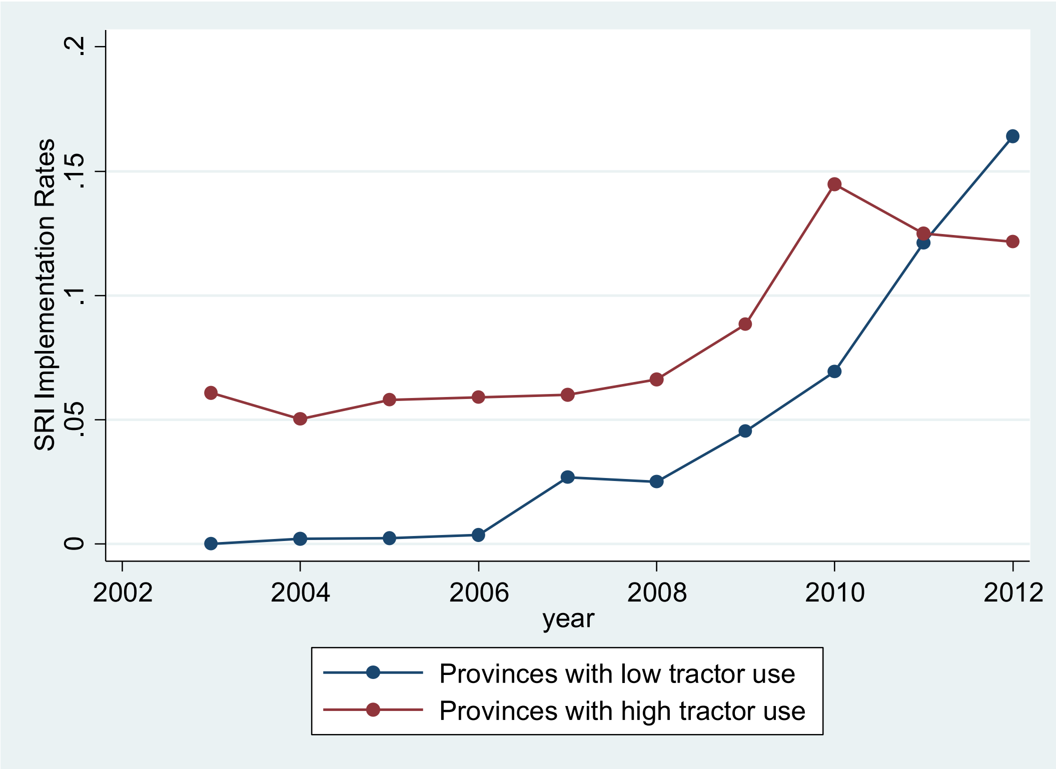


Figure 4: Rice–Water Productivity Before Any SRI Implementation



Notes: Data for water productivity are available from 1995. However, the 1995 data are available for only 41 provinces, while those from 1996 are available for 61 provinces, gradually increasing to 64 provinces. Thus, we use the data from 1996 for consistency and comparability.

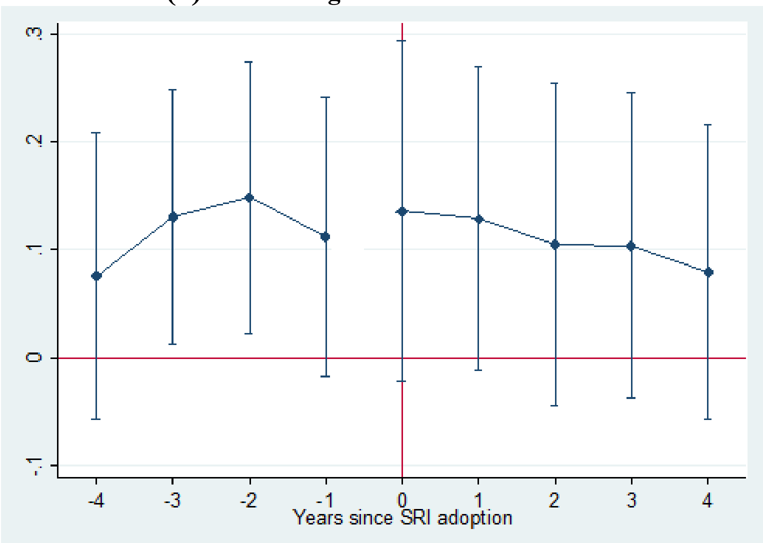
Figure 5: SRI Implementation among Provinces with Low vs. High Tractor Use



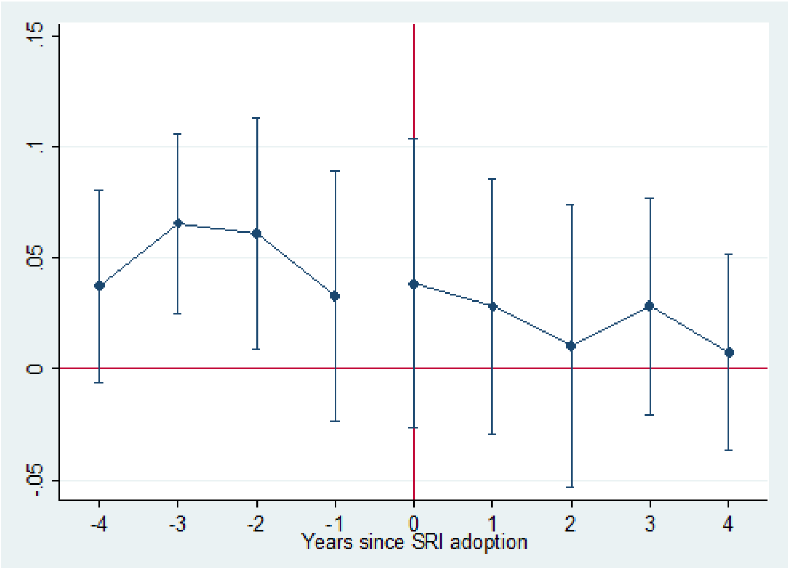
Notes: The two groups include province-year observations with below vs. above median value of tractor use in the last year.

Figure 6: Event Study

(a) Controlling for Year Fixed Effects



(b) Controlling for Year Fixed Effects and Province Fixed Effects



c) Controlling for Year Fixed Effects, Province Fixed Effects, Region-by-Year Fixed Effects, Province-Specific Linear, Quadratic Time Trends, and Control Variables

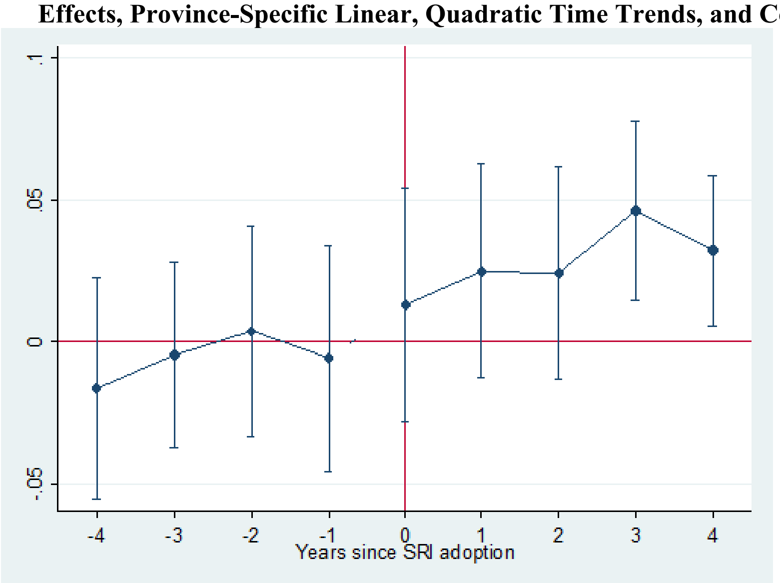


Table 1: Descriptive Statistics

	(1) Mean (SD)	(2) Observations	(3) Mean (SD)	(4) Mean (SD)	(5) Mean (SD)	(6) Mean (SD)
Sample→	**Full Sample**	**Full Sample**	**SRI = 0 at time *t***	**SRI = 1 at time *t***	**SRI Ever = 0**	**SRI Ever = 1**
SRI Dummy	0.175	796	0.000	1.000	0.000	0.454
	(0.380)		(0.000)	(0.000)	(0.000)	(0.499)
SRI Intensity (Implementation Rate)	0.014	796	0.000	0.080	0.000	0.036
	(0.056)		(0.000)	(0.112)	(0.000)	(0.085)
SRI Intensity: Full Implementation	0.001	796	0	0.005	0	0.002
	(0.007)			(0.017)		(0.012)
SRI Intensity: Partial Implementation	0.013	796	0	0.075	0	0.034
	(0.052)			(0.104)		(0.08)
Rice Yield (ton/ha)	4.626	796	4.478	5.328***	4.416	4.963***
	(0.928)		(0.882)	(0.811)	(0.883)	(0.900)
Irrigation Water (thousand m^3) per Hectare of Rice	5.106	796	5.15***	4.903	5.304***	4.79
	(1.762)		(1.9)	(0.866)	(2.141)	(0.76)
Water Productivity of Rice (ton/thousand m^3)	0.98	796	0.95	1.13***	0.92	1.07***
	(0.3)		(0.3)	(0.29)	(0.3)	(0.29)
Irrigation Water Growth (percent)	0.0049	726	0.0053	0.0031	0.0054	0.0041
	(0.069)		(0.075)	(0.036)	(0.077)	(0.054)
Rainfall (in mm)	1849.135	720	1885.198*	1687.550	1942.482***	1707.621
	(652.493)		(685.780)	(442.807)	(742.149)	(451.799)
Fertilizer Use per Thousand Hectares of Rice Area	1.456	796	1.527**	1.139	1.832***	0.887
	(2.244)		(2.469)	(0.424)	(2.806)	(0.452)
Number of Buffalos per Hectare of Rice Area	0.875	796	0.837	1.049***	0.724	1.105***
	(1.222)		(1.209)	(1.270)	(1.153)	(1.289)
Number of Laborers per Hectare of Rice Area	4.776	796	4.857	4.959	4.834	4.952
	(3.026)		(3.414)	(1.549)	(3.776)	(1.467)
Number of Tractors per Thousand Hectares of Rice	51.887	790	56.142**	32.825	70.647***	23.447
	(108.872)		(119.478)	(24.080)	(136.107)	(20.517)
Number of Farms per Thousand Hectares of Rice Area	22.250	782	25.384***	8.318	30.689***	6.728
	(52.562)		(57.621)	(7.171)	(63.585)	(6.397)
Agriculture Labor Rate	321.623	796	312.494	364.770**	299.269	357.418*
	(104.588)		(102.484)	(104.007)	(103.447)	(96.265)
Labor Force Participation Rate	0.692	796	0.689	0.706**	0.683	0.707***
	(0.074)		(0.072)	(0.078)	(0.067)	(0.081)
Population (in 1000s)	1321.177	796	1305.327	1396.096	1316.458	1328.734
	(1002.179)		(960.389)	(1180.956)	(1033.261)	(951.907)
Schools per Population	0.343	652	0.338	0.356	0.322	0.372
	(0.170)		(0.166)	(0.198)	(0.161)	(0.186)
Number of University Lecturers per Population	1.927	596	1.618	2.981	1.799	2.174
	(8.488)		(7.826)	(10.403)	(8.451)	(8.575)
Number of College Lecturers per Population	0.185	543	0.195*	0.152	0.193	0.170
	(0.217)		(0.213)	(0.229)	(0.212)	(0.226)
Provincial Competitiveness Index	56.817	519	57.165**	55.785	57.763***	54.973
	(6.563)		(6.975)	(5.038)	(6.611)	(6.075)

Notes: The sample includes all 64 provinces in Vietnam over the period 2000–2012. SRI stands for System of Rice Intensification. Standard deviations (SD) are given in parentheses. *, **, and *** indicate that the means of the samples in columns (3) and (4) or columns (5) and (6) are statistically different at the 10%, 5%, and 1% levels, respectively.

Table 2: SRI Adoption and Implementation

	SRI Intensity
Ln Rainfall	0.006
	(1.27)
First Lag of Ln Fertilizer	-0.015
	(0.90)
Ln Buffalos	-0.013
	(1.51)
First Lag of Rice Labor	-0.019
	(0.59)
First Lag of Ln Tractors	-0.022**
	(2.63)
Irrigation Water Growth (percent)	-0.025
	(1.35)
Ln Farms	0.002
	(0.41)
Schools per Population	-0.043
	(0.74)
Agriculture Labor Rate	-0.000
	(0.62)
Labor Force Participation Rate	0.050
	(0.96)
University Lecturers per Population	-0.001
	(1.10)
College Lecturers per Population	0.001
	(0.21)
Provincial Competitiveness Index	0.001**
	(2.08)
SRI dummies	
Observations	383
Adjusted R^2	0.967

Note: all regressions control for year fixed effects, province fixed effects, region-by-year fixed effects, province specific linear and quadratic time trends.

Table 3: Effects of SRI Implementation on ln Water Productivity of Rice

	(1)	(2)	(3)	(4)	(5)	(6)
SRI Intensity	0.554***					0.620***
	(2.73)					(2.77)
SRI Intensity: Full Implementation		1.528***	1.683***		1.247***	
		(3.78)	(4.51)		(2.73)	
SRI Intensity: Partial Implementation		0.443**		0.638***	0.482***	
		(2.50)		(2.73)	(2.88)	
First Lag of SRI Intensity						-0.196
						(1.38)
First Lag of SRI Intensity: Full Implementation			1.004**		0.567	
			(2.38)		(1.55)	
First Lag of SRI Intensity: Partial Implementation				-0.349	-0.187	
				(1.46)	(0.99)	
Observations	796	796	726	726	726	726
Adjusted R^2	0.978	0.978	0.979	0.979	0.979	0.979

Notes: all regressions control for year fixed effects, province fixed effects, region-by-year fixed effects, province specific linear and quadratic time trends, and time-varying covariates. See Table 2 for time-varying covariates.

Table 4: Effect of SRI Implementation on Rice Water Productivity for Low vs. High Tractor Use Use

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Provinces below Median Value of Tractor Use in the Last Year						**Provinces above Median Value of Tractor Use in the Last Year**					
SRI Intensity	0.688*					0.690*	-0.028					0.273
	(1.80)					(1.93)	(0.11)					(0.89)
SRI Intensity: Full Implementation		1.486**	1.795***		1.373			1.697	1.714		0.136	
		(2.54)	(2.85)		(1.58)			(0.25)	(0.25)		(0.02)	
SRI Intensity: Partial Implementation		0.484		0.714	0.462			-0.047		0.280	0.293	
		(1.19)		(1.68)	(1.23)			(0.20)		(0.91)	(0.94)	
First Lag of SRI Intensity: Full Implementation			0.727		0.309				-0.862		2.441	
			(0.97)		(0.47)				(0.23)		(0.56)	
First Lag of SRI Intensity: Partial Implementation				-0.537	-0.108					-0.627*	-0.650*	
				(1.26)	(0.24)					(1.85)	(1.80)	
First Lag of SRI Intensity						-0.211						-0.615*
						(0.82)						(1.86)
Observations	362	362	362	362	362	362	359	359	359	359	359	359
Adjusted R^2	0.984	0.984	0.983	0.983	0.983	0.983	0.969	0.969	0.969	0.970	0.969	0.970

Notes: all regressions control for year fixed effects, province fixed effects, region-by-year fixed effects, province specific linear and quadratic time trends, and time-varying covariates. See Table 2 for time-varying covariates.

Table 5: The Effects of SRI Implementation on Rice Yield and Water Use per Rice Production Area

	(1) ln Rice Yield	(2) ln Rice Yield	(3) ln Rice Yield	(4) ln Rice Yield	(5) ln Water per Rice Area	(6) ln Water per Rice Area	(7) ln Water per Rice Area	(8) ln Water per Rice Area
SRI Intensity	0.579***				0.026			
	(3.39)				(0.27)			
SRI Intensity: Full Implementation		1.624***	1.869***	1.610***		0.097	0.189	0.366
		(6.73)	(9.58)	(6.95)		(0.42)	(0.61)	(1.10)
SRI Intensity: Partial Implementation		0.461***		0.421**		0.018		-0.057
		(3.08)		(2.55)		(0.19)		(0.73)
First Lag of SRI Intensity: Full Implementation			0.919*	0.442			-0.070	-0.115
			(1.95)	(1.02)			(0.30)	(0.66)
First Lag of SRI Intensity: Partial Implementation				-0.026				0.163*
				(0.18)				(1.69)
Observations	796	796	726	726	796	796	726	726
Adjusted R^2	0.967	0.967	0.966	0.966	0.975	0.975	0.975	0.975

Notes: all regressions control for year fixed effects, province fixed effects, region-by-year fixed effects, province specific linear and quadratic time trends, and time-varying covariates. See Table 2 for time-varying covariates.

Table 6: The Effects of SRI Implementation on the Production of Maize and Sweet Potato

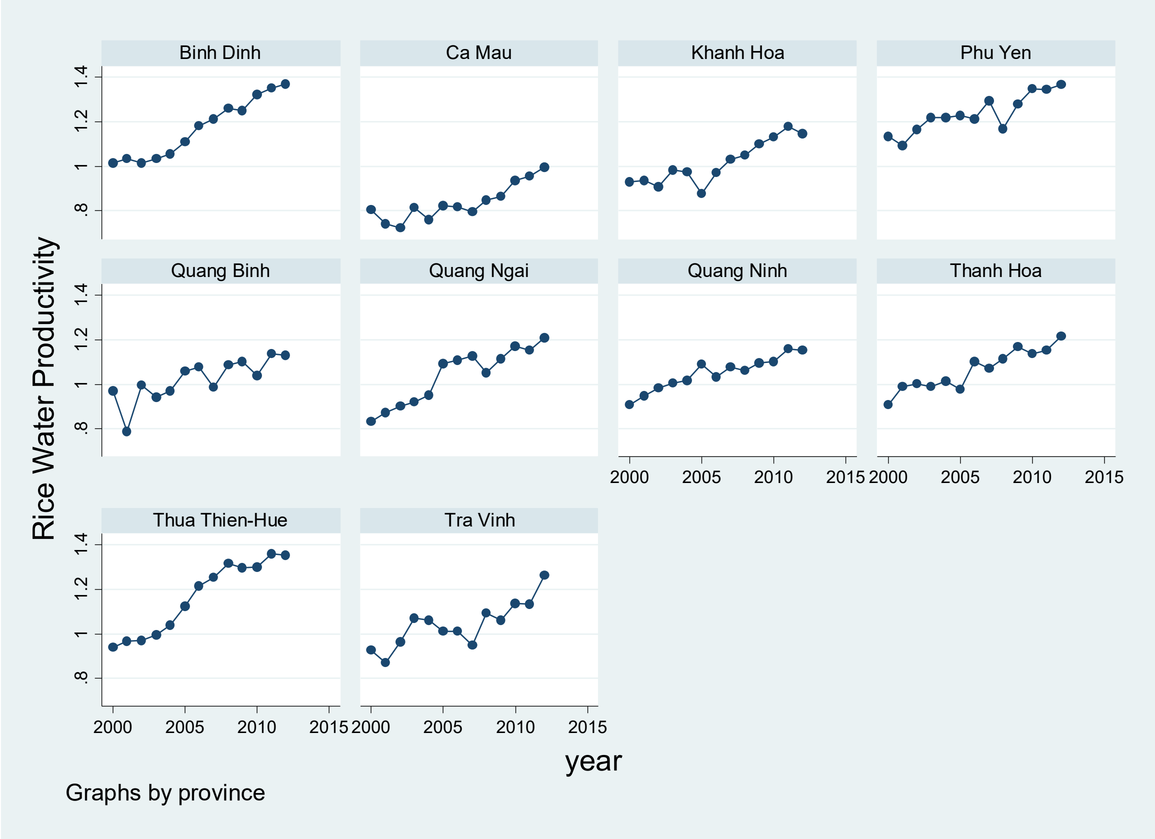
	(1) ln Maize Yield	(2) Ln Maize Output	(3) ln Sweet Potatoes Output	(4) ln Cassava Output
SRI Intensity: Full Implementation	1.361**	1.185*	1.671**	0.099
	(2.23)	(1.89)	(2.11)	(0.07)
SRI Intensity: Partial Implementation	-0.346	-0.335	-0.070	0.284
	(1.27)	(1.30)	(0.14)	(0.51)
First Lag of SRI Intensity: Full Implementation	0.942*	0.829	1.276	1.307
	(1.69)	(1.46)	(1.43)	(0.92)
First Lag of SRI Intensity: Partial Implementation	0.135	0.161	0.060	-0.208
	(0.66)	(0.84)	(0.17)	(0.26)
ln Maize Production Area		1.030***		
		(25.00)		
ln Sweet Potatoes Production Area			0.878***	
			(15.98)	
ln Cassava Production Area				1.022***
				(18.51)
Observations	719	719	724	678
Adjusted R^2	0.955	0.998	0.995	0.991

Notes: all regressions control for year fixed effects, province fixed effects, region-by-year fixed effects, province specific linear and quadratic time trends, and time-varying covariates. See Table 2 for time-varying covariates.

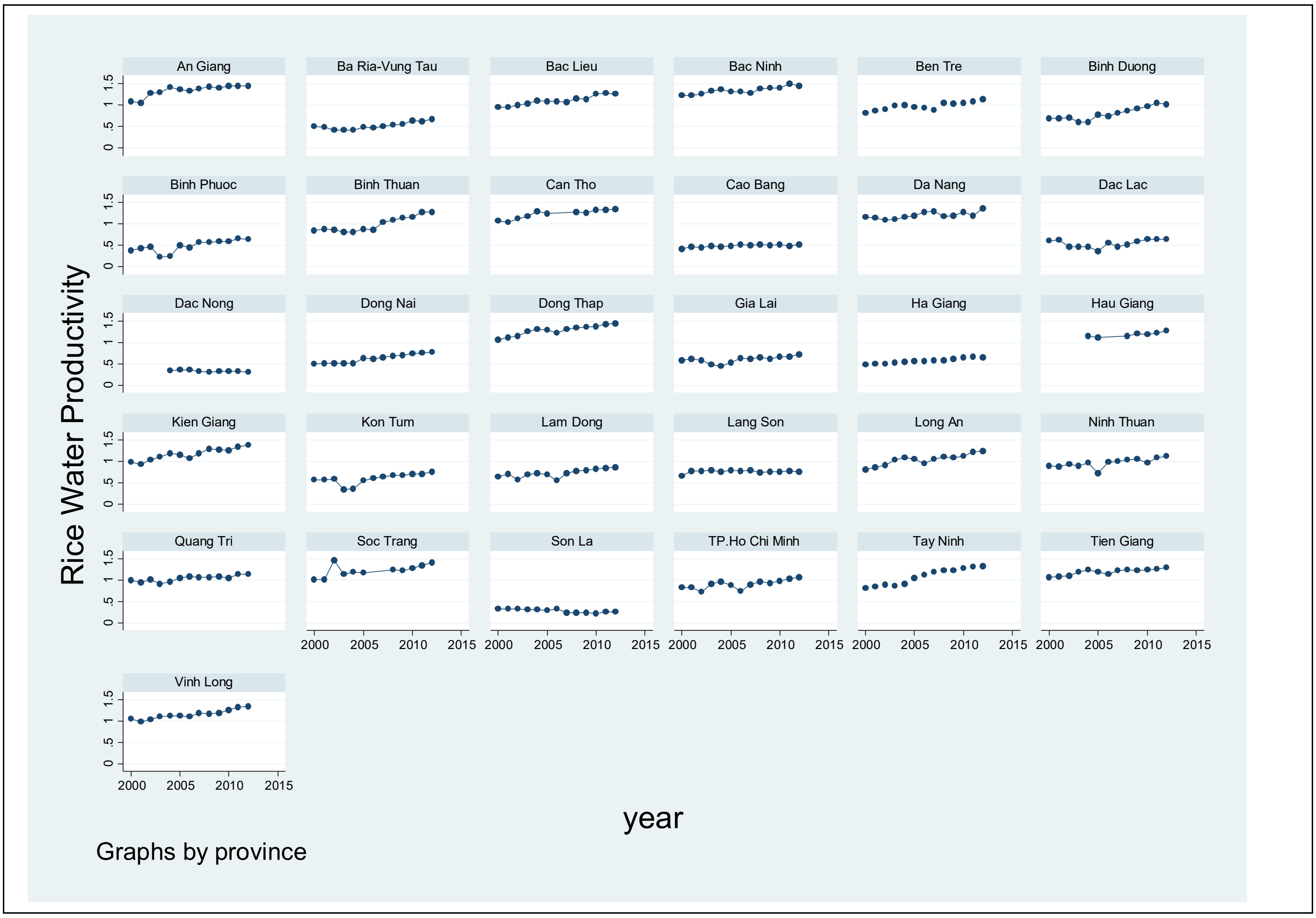
ONLINE APPENDIX A

Online Appendix A Figure 1

a) Provinces that never implemented SRI and had special economic zones at some point



b) Provinces that never implemented SRI and do not have special economic zones



Online Appendix A Table 1: Spread of SRI around the World By 2012

Time Period	Country Adopting SRI for the First Time
<1999	Madagascar
1999	China, Indonesia
2000-01	Bangladesh, Cuba, Laos, Cambodia, Gambia, India, Nepal, Myanmar, Philippines, Sierra Leone, Sri Lanka, Thailand
2002-03	Benin, Guinea, Mozambique, Peru
2004-05	Senegal, Pakistan, Vietnam
2006	Burkina Faso, Bhutan, Iran, Iraq, Zambia
2007	Afghanistan, Brazil, Mali
2008	Rwanda, Costa Rica, Ecuador, Egypt, Ghana, Japan
2009	Malaysia, Timor Leste
2010	Kenya, DPRK, Panama, Haiti
2011	Colombia, Korea, Taiwan, Tanzania
2012	Burundi, Dominican Republic, Niger, Nigeria, Togo

Source: Cornell University, SRI website.

Online Appendix A Table 2:

Number of Years of SRI Implementation for Each Province During the Sample Period (2000–2012)

Province	SRI Adoption Years	Province	SRI Adoption Years	Province	SRI Adoption Years	Province	SRI Adoption Years
An Giang	0	Dac Nong	0	Kien Giang	0	Quang Ninh	0
Ba Ria-Vung Tau	0	Dien Bien	5	Kon Tum	0	Quang Tri	0
Bac Can	5	Dong Nai	0	Lai Chau	5	Soc Trang	0
Bac Giang	7	Dong Thap	0	Lam Dong	0	Son La	0
Bac Lieu	0	Gia Lai	0	Lang Son	0	TP.Ho Chi Minh	0
Bac Ninh	0	Ha Giang	0	Lao Cai	5	Tay Ninh	0
Ben Tre	0	Ha Nam	9	Long An	0	Thai Binh	10
Binh Dinh	0	Ha Noi	5	Nam Dinh	9	Thai Nguyen	5
Binh Duong	0	Ha Tay	8	Nghe An	8	Thanh Hoa	0
Binh Phuoc	0	Ha Tinh	5	Ninh Binh	10	Thua Thien-Hue	0
Binh Thuan	0	Hai Duong	2	Ninh Thuan	0	Tien Giang	0
Ca Mau	0	Hai Phong	7	Phu Tho	5	Tra Vinh	0
Can Tho	0	Hau Giang	0	Phu Yen	0	Tuyen Quang	7
Cao Bang	0	Hoa Binh	10	Quang Binh	0	Vinh Long	0
Da Nang	0	Hung Yen	10	Quang Nam	9	Vinh Phuc	6
Dac Lac	0	Khanh Hoa	0	Quang Ngai	0	Yen Bai	5

Online Appendix A Table 3: Provinces that Implemented SRI and Provinces with SEZ

Province with SRI implementation	Year Starting SRI	Province with special economic zone (SEZ)	Year Opening SEZ
Hoa Binh	2003	Quang Nam	2003
Hung Yen	2003	Quang Ngai	2005
Ninh Binh	2003	Binh Dinh	2005
Quang Nam	2003	Quang Ninh	2006
Thai Binh	2003	Thanh Hoa	2006
Ha Nam	2004	Ha Tinh	2006
Nam Dinh	2004	Thua Thien-Hue	2006
Ha Tay	2005	Khanh Hoa	2006
Nghe An	2005	Nghe An	2007
Bac Giang	2006	Hai Phong	2008
Hai Phong	2006	Quang Binh	2008
Tuyen Quang	2006	Phu Yen	2008
Vinh Phuc	2007	Tra Vinh	2009
Bac Can	2008	Ca Mau	2010
Dien Bien	2008		
Ha Noi	2008		
Ha Tinh	2008		
Lai Chau	2008		
Lao Cai	2008		
Phu Tho	2008		
Thai Nguyen	2008		
Yen Bai	2008		
Hai Duong	2011		

Online Appendix A Table 4: Estimation Results for Event Study

	(1)	(2)	(3)	(4)
Outcome: ln Rice–Water Productivity				
Four Years Prior to SRI Adoption	0.073	0.034	-0.027	-0.016
	(0.87)	(1.32)	(1.17)	(0.69)
Three Years Prior to SRI Adoption	0.147**	0.068***	0.005	-0.005
	(2.01)	(3.50)	(0.19)	(0.23)
Two Years Prior to SRI Adoption	0.160**	0.067***	0.010	0.004
	(2.17)	(3.05)	(0.33)	(0.17)
One Year Prior to SRI Adoption	0.126	0.031	-0.001	-0.006
	(1.63)	(1.26)	(0.03)	(0.24)
Year of SRI Adoption	0.132	0.039	0.020	0.013
	(1.57)	(1.59)	(0.66)	(0.52)
One Year Since SRI Adoption	0.128	0.029	0.017	0.025
	(1.58)	(1.16)	(0.63)	(1.10)
Two Years Since SRI Adoption	0.098	0.016	0.031	0.024
	(1.17)	(0.61)	(1.16)	(1.08)
Three Years Since SRI Adoption	0.095	0.029	0.037*	0.046**
	(1.11)	(1.36)	(1.75)	(2.42)
Four Years Since SRI Adoption	0.069	0.007	0.024	0.032**
	(0.83)	(0.33)	(1.58)	(2.01)
Observations	796	796	796	796
Adjusted R^2	0.021	0.937	0.969	0.978
Year Fixed Effects	Yes	Yes	Yes	Yes
Province Fixed Effects	No	Yes	Yes	Yes
Province-Specific Linear and Quadratic Time Trends	No	No	Yes	Yes
Region-by-Year Fixed Effects	No	No	Yes	Yes
Time-Varying Covariates	No	No	No	Yes

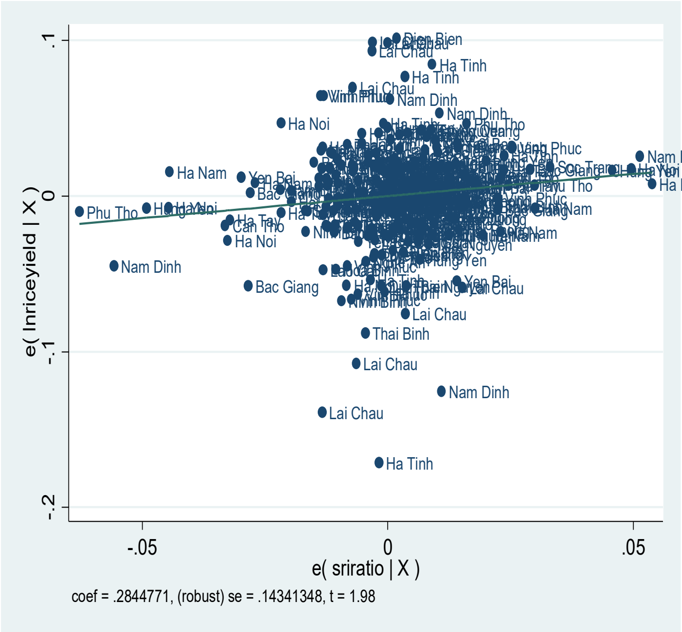
Notes: Each column displays the result of a simple OLS regression model, where up to four years of lead and lag of initial year of SRI adoption being explanatory variables. Robust standard errors are clustered at the province level. *t*-statistics are given in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Online Appendix A Table 5:
Effect of SRI Implementation on Rice–Water Productivity Using Different Samples and Outcome Measures

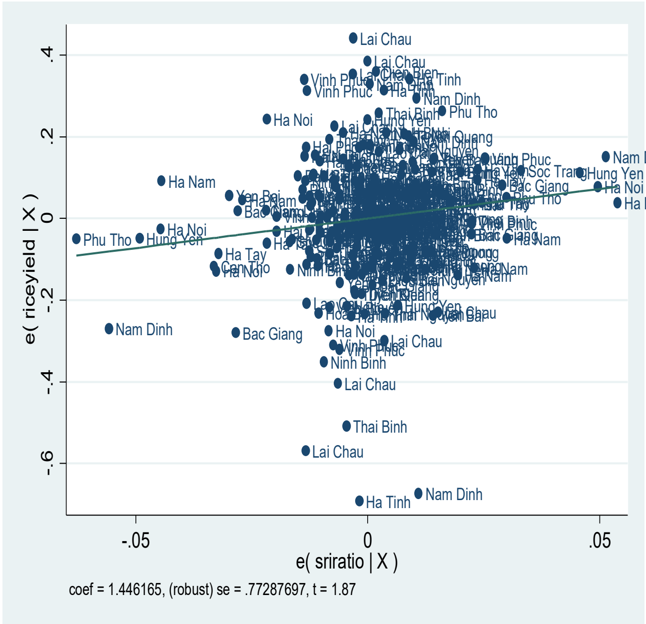
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: The Effects of SRI Implementation on Water Productivity for the Period 1995–2012, All 64 Provinces							
SRI Intensity	1.232***	–0.041	0.168	0.521**	0.468***		
	(4.00)	(0.15)	(0.57)	(2.52)	(2.73)		
Observations	1086	1086	1086	1086	1086		
Adjusted R^2	0.091	0.896	0.906	0.948	0.956		
Panel B: Effect of SRI Implementation on Water Productivity among the 23 Provinces that Implemented SRI							
SRI Intensity	1.086***	0.253	0.341	0.394*	0.557***	0.592***	
	(2.89)	(0.92)	(1.20)	(2.01)	(2.85)	(3.01)	
SRI Intensity: Full Implementation							1.586***
							(3.40)
SRI Intensity: Partial Implementation							0.525**
							(2.52)
Observations	306	306	306	306	306	306	306
Adjusted R^2	0.054	0.922	0.920	0.949	0.960	0.968	0.968
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province Fixed Effects	No	Yes	Yes	Yes	Yes	Yes	Yes
Region-by-year Fixed Effects	No	No	Yes	Yes	Yes	Yes	Yes
Province-Specific Linear Time Trends	No	No	No	Yes	Yes	Yes	Yes
Province-Specific Quadratic Time Trends	No	No	No	No	Yes	Yes	Yes
Time-Varying Covariates	No	No	No	No	No	Yes	Yes

Notes: Ha Tay merged with Ha Noi in 2008, so there were 23 provinces implementing SRI in 2012. However, the panel data used in Panel B include Ha Tay and Ha Noi as separate provinces prior to 2008. Thus, we have 23 × 13 + 8 = 307 observations in total. One missing value of SRI intensity results in 306 observations in Panel B.

Online Appendix A Figure 1:
Avplot for ln Water Productivity of Rice
(Table 3, Column (8))



Online Appendix A Figure 2: Avplot for Water Productivity of Ric
in Levels (Appendix Table 4, Column (8))



ONLINE APPENDIX B

Other Data and Selectivity Issues

1. Data on Water Supply and Rice Production

We obtained our province-level data on the irrigation water supply for rice production from the General Statistics Office (GSO) of Vietnam. GSO estimates the water supply for rice by multiplying the total water pumped to the channels by the proportion of rice area over total crop area for a given year at the province level. Thus, the data on rice water irrigation represent the water supply rather than the water consumption for rice. However, it is reasonably a good approximation of the rice water consumption because rice is the main crop in Vietnam, with its production area accounting for around 70–80% of all crop area. The data on rice output, rice production area, and the production outputs and areas of other crops, are also collected from GSO.

2. Data on Province-Level Indicators

Our time-varying control variables at the province level include standard input variables for production function (i.e., the numbers of tractors, buffaloes, pumps, rice laborers and farms, and fertilizer use), as well as other indicators (namely the number of schools, people in the labor force, total population, number of university and college lecturers), all of which are obtained from GSO. The *Provincial Competitiveness Index (PCI)*[1] is collected from www.pcivietnam.vn. We collected the data on rainfall prior to 2006 from the World Bank,[2] while rainfall data for the later period are obtained from the Ministry of Agriculture and Rural Development.[3,4]

The data on irrigation water, and rice, maize, sweet potato, and cassava production outcomes are available for the period 1995–2012. Data on university and college lecturers are available from 2003 while PCI data are available from 2004. Meanwhile the data for almost all other control variables are available from 2000 onwards.[5] Thus, we restrict the sample considered in our analysis to the period 2004-2012 and 2000–2012. However, we also utilize a longer time frame for the irrigation-water productivity (i.e., 1995–2012) when checking the robustness of our results regarding pre-existing trends, a la Wolfers (2006).

3. Factors Influencing SRI Implementation and Adoption

Column (1) in Online Appendix B Table 1 reports the results when only year fixed effects are controlled for while column (2) cumulatively adds province fixed effects, and column (3) includes region-by-year fixed effects, province-specific linear and quadratic trends, addressing potentially endogenous trends across provinces. Column (1) shows several factors that are associated with SRI adoption including fertilizer use, labor inputs, agricultural labor rate, and labor force participation rate. Adding province fixed effects (column (2)) mutes the effect of these factors, though agricultural production scale (number of farms) and strong presence of higher education mark their important role in SRI selection. Importantly, trend related dummies (region-by-year fixed effects, province specific linear and quadratic time trends) successfully mute the statistical significance of almost all covariates (column (3)), except for that of PCI, which is significant at 10% in influencing the SRI adoption. These results point out that the link between province characteristics and SRI implementation is generally broken in columns (3). That is, once all the year fixed effects, province fixed effects, region-by-year fixed effects, and time trends have been controlled for, the remaining variation in SRI uptake is plausibly exogenous to the determinants of rice–water productivity at the province level.

4. Effect of SRI Implementation on Rice Water Productivity

Online Appendix B Table 2 presents the estimation results from Equation (1). Column (1) includes only *SRI Intensity* as the key independent variable, along with year dummies, while Column (2) adds province fixed effects. Columns (3) and (4) control for region-by-year effects and linear province-specific time trends, respectively. Column (5) adds quadratic province-specific time trends, while Column (6) adds time-varying control variables. Column (7) utilizes SRI-full and SRI-partial separately using our richest specification in Column (6).

The model reported in Column (1) finds the coefficient of *SRI Intensity* to be positive (1.232) and significant at the 1% level. Column (2) adds province fixed effects, and *SRI Intensity* becomes insignificant. This is unsurprising given the importance of permanent province characteristics in the selection process.[6] Column (2) of Table 3 concords with the result in column (2) of Table 2 in showing that non-SRI provinces are not comparable to SRI provinces, as they trend differently prior to SRI introduction. Unsurprisingly, the inclusion of region-by-year fixed effects in Column (3) begins to reveal the effect of SRI penetration, with the magnitude of the effect being 0.31, though with a *t*-statistic of 1.2. Noting that region-by-year fixed effects level off some trend differences, the trend divergence at the province level remains unresolved. We therefore enhance the model by including province-specific time trends, and the effect of SRI intensity increases to 0.38 (Column (4)) becoming significant at the 5% level. Allowing a quadratic trend in Column (5), the estimate of SRI increases further to 0.5, significant at 1% level.

In our richest specification, only water growth has significant direct effects on the rice–water productivity. The coefficient is –0.51, significant at the 1% level in the last two specifications (Columns (6) and (7)), suggesting the law of diminishing returns to water use. That is, when water application increases by 1%, the rice output return per unit of water use decreases by 0.51%. No other covariate at the province level has a significant impact on water productivity at conventional levels, probably because our fixed effects dummies largely explain the differences in time-varying covariates at the province level.[7]

5. Selection Based on Observables

Our main finding is that, controlling for all permanent province differences, year fixed effects, province-specific linear and quadratic time trends, region-by-year fixed effects, and an array of time-varying rice production inputs and province-level covariates, more rapid SRI penetration into a province increases the water productivity of rice in that province. Our key identification assumption is that, once the above factors are isolated, SRI intensity (rate of adoption by farmers) is free from selection bias and exogenous to rice–water productivity at the province level. We now subject the sensitivity of this finding to a number of selection tests. Recall that the implementation of full and partial SRI is simultaneous in a province once SRI is adopted. Similarly, lag effect of SRI is a relevant consideration conditional on SRI implementation of SRI. Thus, this section carries out the selection exercise using specification with *SRI intensity* without separating into different components of SRI and current and lag of SRI.

Excluding Provinces that Never Implemented SRI. There might be something fundamentally different about Vietnam's 38 provinces that have never implemented the SRI (e.g., some provinces may comprise only metropolitan areas). In addition, this group of provinces might be driving some of the selectivity problems facing our regressions. These provinces are likely to have a poorer base of rice production in one way or another; thus, we are likely to face $Cov(SRI_{pt}, e_{pt}) > 0$ in our estimates using Equation (1). Thus, we estimate our models by excluding these provinces. This exercise exploits the variation only in the timing of SRI implementation (in addition to the intensity differences) in the provinces that have ever seen the SRI.[8] Online Appendix Table 3 Panel A reports the results. The patterns in this table are quite comparable to those in Online Appendix Table 2 and the estimate in the richest specification (Column (6)) even increases to 0.592, compared with 0.543 for overall sample. These findings fundamentally rule out the possibility that the effects of the SRI are driven by provinces that never implemented the SRI.

Does Program Participation (of the Province) Matter? We take a binary treatment approach and pool all the treatment provinces into one group. This binary treatment variable is named

SRI Dummy, instead of *SRI Intensity*, and the results are reported in Panel B of Online Appendix Table 3. Focusing on the preferred specification in Column (6) in Panel B, the coefficient of *SRI Dummy* is estimated to be negligible and statistically insignificant. This finding suggests that, even if a particular province is targeted by the central government, province-specific linear time trends used in the model seem to account for such selection (see Column [3], where *SRI Dummy* becomes insignificant). This exercise also suggests that failing to recognize the continuous nature of the treatment in our case may cause a misleading conclusion about the influence of the SRI on rice–water productivity.

SRI Program Participation vs SRI Intensity. To assess whether the intensity effect prevails once the participation status of the province is accounted for, we include both *SRI Dummy* and *SRI Intensity* in the same regression. Panel C in Online Appendix Table 3 shows that our intensity effect prevails, with a coefficient of 0.56, while the program participation effect is insignificant in the preferred specification (Column [6]). This finding suggests that, even if a particular province is targeted for some reason, the variation in SRI penetration, after controlling for an array of covariates, seems to explain the observed rice water productivity significantly.

Selection on the Initial Level and Growth of Water Productivity of Rice. A province may be selected for the SRI by decision makers on the assumption that provinces with a more substantial record of rice water productivity in the initial years of the sample can deliver better outcomes. To check whether, after controlling for a wide range of controls, this selection afflicts our main finding, we interact *SRI Intensity* with the level of rice–water productivity in 2003. In an alternative regression, we use the interaction between *SRI Intensity* and growth of rice water productivity, where growth is measured by the four-year average of rice water productivity growth in a province during 2000 to 2003. Interaction terms between *SRI Intensity* and initial rice water productivity is large and strongly significant pointing to the presence of selection. The estimate becomes smaller in magnitude and statistically insignificant in the last two columns attesting to our econometric framework in addressing the selection issue. The effect of *SRI intensity* on rice water productivity in our preferred specification (column (6)) in Panel D, and E is similar to that in Table 3.

Selection on Timing of Implementation: Does Early/Late Start Matter? Provinces that start the SRI earlier may have advantages over provinces that take up the technology later. This may lead to a learning-by-doing effect. Evidence for this effect is mixed at the farmer level (see Barrett et al. (2004)). Should it exist at the province level, the observed effects of SRI may not be attributable to the technology *per se*, and may suffer from selection bias. A different way of stating this problem is determining whether an early start provides a benefit to a province, compared with provinces that start later. Both learning-by-doing and the timing of the implementation indicate the possibility of building "SRI human capital" in the province, with the consequence of $Cov(SRI_{pt}, e_{pt}) > 0$. We test the implications of these issues by including a variable measuring cumulative SRI implementation in Equation (1) in linear and quadratic forms. Controlling for several factors, Panel F in Online Appendix Table 3 indicates no evidence of such a selection, with our estimated coefficient slightly higher at 0.634.[9]

Selection of Districts at the Province Level. Once the central government's decision to implement the SRI reaches a province, the provincial administration identifies on which districts it will focus efforts. The decision-making process at this layer may be subject to selection bias for reasons similar to the province-level selection above. We do not have data on rice output and irrigation water at the district level to examine $Cov(SRI_{ptd}, e_{ptd})$, where d is the subscript for districts. However, we can surmise that, for a given number of districts within a province, if SRI is implemented, on average, in better (or worse) performing districts, then we would have $Cov(SRI_{pt}, e_{pt}) > 0$ (< 0). To check whether our main finding is driven by potential selectivity at the district level, we use a Herfindahl-type concentration index of

SRI intensity across districts within a province.[10] In other words, for a given level of SRI implementation in a province, if only few selected districts implement the SRI (high concentration), then it is likely that provincial authorities purposefully selected these districts. If there is an equal spread of SRI intensity across the districts of a province (low concentration), then it is likely that such selection is lower. The results in Panel G in Online Appendix Table 3 show that controlling for such concentration does not affect our main finding. The Herfindahl-based control is not statistically different from zero, and the coefficient on *SRI Intensity* remains unchanged at 0.56. The unchanged SRI coefficient suggests that the water productivity contribution of the SRI is independent of the concentration of districts within a province implementing the SRI.

Selection on Farmer or Plot Characteristics. An important concern is whether the SRI captures something else, such as farmer skills or better plot quality. In this vein, it is indicated that typically the best farmers adopt the SRI first, use the system on their best plots, and are good at practicing almost any technology (Barrett et al., 2004). If SRI-adopting farmers are, on average, better farmers and/or the SRI is adopted on overall better plots, then we would have $Cov(SRI_{pt}, e_{pt}) > 0$. That is, farmer- or plot-level selections might explain our results if they dominate the SRI practice in Vietnam.

Noting that we use a province-level variation, it is difficult to see $Cov(SRI_{ptdf}, e_{ptdf})$, where *d* and *f* are subscripts for districts and farmers, respectively. We use two approaches to address this concern. First, controlling for water productivity of other crops (including maize, cassava, sweet potato, peanut, and sugar cane) should deal with the selection at farmer and plot level because better plots or better farmers would be associated with higher water productivity of other crops. In specification with water productivity of other crops are additional controls the effect of *SRI intensity* on rice water productivity increase to 0.64 (not reported to save space). In another approach, we check for non-linearity, where we split the distribution of *SRI Intensity* into three groups—low , medium , and high intensity—based on 0–33, 34–66, and 67–100th percentile (in provinces that ever adopted the SRI). These intensities correspond to 0–1%, 1–5%, and 5–49% of rice-cultivated areas with SRI adoption. We assume that the larger the SRI area in a province, the more likely it is adopted on different types of soils. We also assume that, if only better plots are selected for the SRI within a province, then the low- and (to some extent) medium-intensity SRI uptakes are more likely to convey information on such selection. If the suspected selection exists, those groups of observations should produce stronger results.[11] Panel H of Online Appendix Table 3 shows that the high-intensity practice is 5% significant, with an estimated coefficient of 0.442, while the low- and medium-intensity practice are estimated to be insignificant, ruling out farmer or plot selectivity as the driver of our main findings.[12]

Controlling for the Role of Cooperatives. Another potential selectivity concern is that membership in farmer associations could assist farmers with access to new information and in dealing with new technologies. This suggests that the availability of farmer cooperatives could lead to selection into SRI adoption (Moser & Barrett, 2003). Controlling for the number of cooperatives at the province level leaves the coefficient of SRI essentially unchanged—see Panel I. Thus, the number of cooperatives (a time-varying variable) is insignificant.

Selection on Future Expectations. Whether or not a province receives ongoing funding from the central government or a national or international organization for SRI training largely depends on its performance. This means that water productivity expectations for the near future might provide feedback for SRI implementation and intensity. We test for this "feedback effect" by including the lead values of *SRI Intensity* in the model (Wooldridge, 2002 p. 285). The "strict exogeneity" condition is satisfied if the lead values of *SRI Intensity* are not related to current outcomes. In Columns (3) to (6) in Panel J in Online Appendix Table 3 demonstrate that the coefficients of lead *SRI Intensity* become insignificant while the effect of *SRI Intensity* is 0.393.[13]

6. Randomization Inference Tests

Numerous tests carried out in the previous section strongly support our econometric specification in successfully purging selection on observables. Nonetheless, one may be concerned with selection on unobservables, caused by any omitted variables that have not explicitly been accounted for in our selectivity tests. To assuage this concern, we utilize the randomization inference test, which is based on the principle of randomized control trial in experimental research to test for the validity of causality inferred by observational studies. Randomization inference was introduced by Fisher (1935), further developed by Rosenbaum (2002), and has recently been employed by high impact studies in economics and political science literature (see for example, Fujiwara and Wantchekon 2013, Ichino and Schundeln 2012, Cohen and Dupas 2010).

Online Appendix B Table 4 and Online Appendix B Table 5 displays randomization inference tests with 2000 replications for rice outcomes and other crops outcomes, respectively. In particular, the former reports the tests for each of estimates for our preferred specification from Table 3 and Table 5. Likewise, the latter reports the tests for estimates in Table 6. In each Appendix Table, the test results are reported in cells that have the same order as the main results. Three indicators of randomization inference reported include c, the number of times that randomization exercise yields the estimate that larger than the observed estimate; p-value, the probability that the randomization exercise exceeds the observed estimate, and the standard error of p-value. In total, we have 31 estimates for our explanatory variables of interest for rice, whose randomization tests are reported in Online Appendix B Table 4. Meanwhile, the 36 randomization tests associated with 36 estimates for other crops outcomes are displayed in Online Appendix B Table 5.

Overall, the randomization inference tests provide strong indication that our treatment effect found in the main results is not captured by chance. In particular, for all 16 estimates that we find significant effect in the main results for rice water productivity and related outcomes (in rows 1-6, 8-10, 12, and 14-20 in Online Appendix B Table 4), the likelihood that randomization assignment of treatment effect under null hypothesis of no treatment effect exceeding the observed effect largely centers around zero. The maximum value of p-value is 0.12 which is slightly higher than the conventional statistically significant at 10% level (in row 9 in Online Appendix B Table 4 which estimates the effect of first lag of SRI full implementation on water productivity). Furthermore, all the 10 significant effect of SRI on yield and output of other crops found in the main analysis yields p-value in randomization inference that is mostly close to zero (rows 1-2, 4, and 6 for outcome being ln Maize Yield and ln Maize Output, rows 4 and 6 for outcome being ln Sweet Potato Output). Equally important, randomization test for estimates that are not statistically significant in our main results reflects a different pattern validating the randomization inference exercise. In particular, out of 41 insignificant estimates from our main results, 21 of them have p-value from randomization test that is larger than conventional level while the remaining (half of them) have p-value smaller than conventional levels. This pattern indicates that the randomization inference distributes evenly around the observed estimates when the estimates fail to reject the null hypothesis of no treatment. These together validate the observed sample as a random draw from a population, or more precisely, our econometric model succeeds in purging selectivity bias. The standard error of p-value for randomization test is small in all cases indicating accurate estimates of randomization inference. The results hardly change when we increase the number of replications to more than 2000. Furthermore, the randomization inference is largely the same when we use estimated t-statistics instead of the treatment effect (not report to save space). In short, the randomization inference strongly advocates our estimates as treatment effect rather than those captured by chance.

Online Appendix B Table 1: Factors Influencing SRI Implementation and Adoption

	(1) SRI Dummy	(2) SRI Dummy	(3) SRI Dummy
Ln Rainfall	-0.141	0.037	0.039
	(1.57)	(0.91)	(0.78)
First Lag of Ln Fertilizer	-0.348***	-0.198	-0.048
	(3.20)	(1.19)	(0.57)
Ln Buffalos	0.015	-0.029	0.033
	(0.46)	(0.38)	(0.34)
First Lag of Rice Labor	0.330***	-0.247	0.045
	(3.26)	(0.93)	(0.18)
First Lag of Ln Tractors	-0.001	0.119	0.016
	(0.02)	(1.48)	(0.17)
Irrigation Water Growth (percent)	-0.143	-0.144	-0.046
	(0.74)	(1.07)	(0.54)
Ln Farms	0.042	0.052*	-0.013
	(1.22)	(1.68)	(0.36)
Schools per Population	0.070	-0.461	-0.239
	(0.16)	(1.23)	(0.53)
Agriculture Labor Rate	0.001**	0.002	-0.001
	(2.55)	(0.85)	(0.19)
Labor Force Participation Rate	2.180***	-0.182	-0.203
	(2.69)	(0.23)	(0.41)
University Lecturers per Population	0.001	0.003*	-0.002
	(0.55)	(1.80)	(0.82)
College Lecturers per Population	-0.057	0.206**	0.010
	(0.53)	(2.47)	(0.21)
Provincial Competitiveness Index	-0.003	-0.002	0.006*
	(0.80)	(0.46)	(1.92)
SRI dummies			
Observations	383	383	383
Adjusted R^2	0.352	0.786	0.916

Note: all regressions control for year fixed effects, province fixed effects, region-by-year fixed effects, province specific linear and quadratic time trends.

Online Appendix B Table 2: The Effects of SRI Implementation on ln Water Productivity of Rice

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
SRI Intensity (Implementation Rate)	1.232***	-0.012	0.305	0.375**	0.499***	0.554***	
	(4.00)	(0.05)	(1.20)	(2.23)	(2.67)	(2.73)	
SRI Intensity - Full Implementation							1.528***
							(3.78)
SRI Intensity - Partial Implementation							0.443**
							(2.50)
Ln Rainfall						0.005	0.004
						(0.47)	(0.38)
First Lag of Ln Fertilizer						-0.008	-0.008
						(0.56)	(0.62)
Ln Buffalos						-0.017	-0.015
						(0.64)	(0.58)
First Lag of Rice Labor						0.035	0.033
						(1.22)	(1.15)
First Lag of Ln Tractors						-0.007	-0.007
						(0.50)	(0.52)
Irrigation Water Growth (percent)						-0.507***	-0.506***
						(16.87)	(16.92)
Ln Farms						0.012	0.013
						(1.51)	(1.55)
Schools per Population						0.117	0.118
						(1.03)	(1.05)
Agriculture Labor Rate						-0.000	-0.000
						(0.32)	(0.28)
Labor Force Participation Rate						-0.006	-0.006
						(0.04)	(0.04)
University Lecturers per Population						0.000	-0.000
						(0.05)	(0.10)
College Lecturers per Population						-0.042	-0.042
						(1.07)	(1.07)
Provincial Competitiveness Index						-0.000	-0.000
						(0.11)	(0.10)
Observations	796	796	796	796	796	796	796
Adjusted R^2	0.045	0.937	0.948	0.966	0.969	0.978	0.978
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province Fixed Effects	No	Yes	Yes	Yes	Yes	Yes	Yes
Region-by-year Fixed Effects	No	No	Yes	Yes	Yes	Yes	Yes
Province-Specific Linear Time Trends	No	No	No	Yes	Yes	Yes	Yes
Province-Specific Quadratic Time Trends	No	No	No	No	Yes	Yes	Yes
Time-Varying Covariates	No	No	No	No	No	Yes	Yes

Notes: OLS regressions. Robust standard errors are clustered at the province level. *t*-statistics are given in parentheses. *, **, and *** indicates significance at the 10%, 5%, and 1% levels, respectively. The rice irrigation water growth is the annual percentage increase in the amount of irrigation water used for rice production; the water productivity of rice is the rice output divided by the amount of irrigation water used for rice production. Fertilizer is in 1000 tons; buffalos are counted in 1000s; rice labor is counted in 1000s. Schools, number of university and college lecturers per population is the total number of these indicators divided by the population; the agriculture labor rate is calculated as Agriculture Labor/Population; the labor force participation rate is the number of people in the labor force divided by the population. ln Fertilizer, ln Buffalos, ln Rice Labor, ln Tractors, ln Farms are all calculated per 1000 hectares of rice production area.

Online Appendix B Table 3: Addressing Potential Selection Issues and Omitted Variables

	(1)	(2)	(3)	(4)	(5)	(6)
	Outcome Variable: ln Rice Water Productivity					
Panel A: Excluding Provinces Which Never Implemented SRI						
SRI Intensity	1.086***	0.253	0.341	0.394*	0.557***	0.592***
	(2.89)	(0.92)	(1.20)	(2.01)	(2.85)	(3.01)
Observations	306	306	306	306	306	306
Adjusted R^2	0.054	0.922	0.920	0.949	0.960	0.968
Panel B: Does Program Participation Matter?						
SRI Dummy	0.164*	-0.045	0.019	0.007	0.019	0.013
	(1.88)	(1.66)	(0.57)	(0.31)	(0.89)	(0.75)
Observations	796	796	796	796	796	796
Adjusted R^2	0.039	0.938	0.947	0.965	0.968	0.969
Panel C: SRI Effects Controlling for Program Participation						
SRI Intensity	0.910***	0.104	0.294	0.380**	0.490***	0.560***
	(2.71)	(0.39)	(1.18)	(2.31)	(2.77)	(3.18)
SRI Dummy	0.094	-0.051**	0.008	0.003	0.015	0.013
	(0.99)	(2.20)	(0.26)	(0.18)	(0.97)	(0.93)
Observations	796	796	796	796	796	796
Adjusted R^2	0.050	0.938	0.948	0.966	0.969	0.978
Panel D: SRI Effects Controlling for SRI Interaction with Initial Water Productivity						
SRI Intensity	0.810***	0.102	0.384***	0.425***	0.500**	0.573***
	(3.09)	(0.54)	(2.79)	(3.31)	(2.58)	(3.19)
SRI Intensity*ln Water Productivity of Rice in 2003	2.695***	-1.437**	-1.504***	-0.782*	-0.073	-0.140
	(4.59)	(2.12)	(3.42)	(1.79)	(0.19)	(0.33)
Observations	796	796	796	796	796	796
Adjusted R^2	0.115	0.938	0.950	0.966	0.969	0.978
Panel E: SRI Effects Controlling for SRI Interaction with Initial Water Growth Rate						
SRI Intensity	1.135***	-0.015	0.300	0.411**	0.440*	0.469**
	(3.93)	(0.06)	(1.20)	(2.56)	(1.91)	(2.54)
SRI Intensity*Water Productivity of Rice Growth 2000-03	1.041	-1.151	-0.340	-1.383**	1.311	1.332
	(0.42)	(0.54)	(0.19)	(2.24)	(1.24)	(1.13)
Observations	771	771	771	771	771	771
Adjusted R^2	0.057	0.931	0.945	0.964	0.965	0.976
Panel F: Potential Selection on Timing of Program Participation: Does Early/Late Start Matter?						
SRI Intensity	0.934**	0.405*	0.428*	0.386*	0.544***	0.634***
	(2.32)	(1.95)	(1.94)	(1.89)	(3.09)	(3.51)
Cumulative SRI Years	0.036	-0.020**	0.003	-0.001	-0.004	0.006
	(0.86)	(2.22)	(0.27)	(0.05)	(0.17)	(0.31)
Cumulative SRI Years-squared	-0.003	-0.001	-0.003**	0.000	-0.003	-0.002
	(0.65)	(0.77)	(2.12)	(0.01)	(1.24)	(0.91)
Observations	796	796	796	796	796	796
Adjusted R^2	0.046	0.940	0.949	0.966	0.969	0.978
Panel G: Potential Selection of Districts by Provincial Officials: Controlling for Herfindahl Index						
SRI Intensity	1.166***	-0.004	0.311	0.373**	0.500**	0.560***
	(4.01)	(0.02)	(1.20)	(2.09)	(2.63)	(3.02)
Herfindahl Index	0.093	-0.073**	-0.002	-0.005	0.006	-0.004
	(0.56)	(2.01)	(0.04)	(0.25)	(0.33)	(0.24)
Observations	796	796	796	796	796	796
Adjusted R^2	0.048	0.938	0.948	0.966	0.969	0.978
Panel H: Non-Linearity in SRI Intensity (Excluding Non-Adopting Provinces)						
SRI Intensity*Low Intensity	-25.380	-3.684	1.933	-0.686	2.575	0.807
	(0.96)	(0.66)	(0.25)	(0.14)	(0.59)	(0.14)
SRI Intensity*Medium Intensity	0.464	0.229	0.239	0.811	0.294	0.567
	(0.15)	(0.25)	(0.21)	(1.11)	(0.54)	(1.07)
SRI Intensity *High Intensity	1.271**	0.277	0.340	0.402*	0.557***	0.442**
	(2.64)	(0.90)	(1.15)	(2.05)	(2.93)	(2.53)
Observations	277	277	277	277	277	277
Adjusted R^2	0.073	0.923	0.921	0.951	0.962	0.969
Panel I: SRI Effects Controlling for Number of Cooperatives						
SRI Intensity	1.144***	-0.008	0.304	0.380**	0.493**	0.564***
	(3.80)	(0.03)	(1.20)	(2.24)	(2.60)	(3.15)
ln Number of Cooperatives	0.000**	-0.000	-0.000	-0.000	0.000	0.000
	(2.07)	(1.22)	(0.60)	(0.40)	(0.09)	(0.22)
Observations	796	796	796	796	796	796

Adjusted R^2	0.053	0.937	0.948	0.966	0.969	0.978
Panel J: Controlling for Lead Effects						
SRI Intensity	-0.013	0.471*	0.442*	0.461***	0.395**	0.393**
	(0.03)	(1.91)	(1.79)	(4.04)	(2.50)	(2.50)
SRI Intensity at t+1	1.251**	-0.390*	-0.092	-0.004	0.202	0.262
	(2.17)	(1.82)	(0.44)	(0.02)	(0.90)	(1.36)
Observations	726	726	726	726	726	726
Adjusted R^2	0.041	0.935	0.946	0.964	0.967	0.977
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Province Fixed Effects	No	Yes	Yes	Yes	Yes	Yes
Region-by-year Fixed Effects	No	No	Yes	Yes	Yes	Yes
Province-Specific Linear Time Trends	No	No	No	Yes	Yes	Yes
Province-Specific Quadratic Time Trends	No	No	No	No	Yes	Yes
Time-Varying Covariates	No	No	No	No	No	Yes

Online Appendix B Table 4: Randomization Inference for Rice Related Outcomes

Row number	Test for results in	Explanatory Variables of Interest	Outcome Variables	(1) c	(2) p	(3) Se(p)
1	Column (1) Table 3	SRI Intensity	Ln Water Productivity	0	0	0
2	Column (2) Table 3	SRI Intensity: Full Implementation	Ln Water Productivity	0	0	0
3	Column (2) Table 3	SRI Intensity: Partial Implementation	Ln Water Productivity	0	0	0
4	Column (3) Table 3	SRI Intensity: Full Implementation	Ln Water Productivity	3	0.0015	0.0009
5	Column (3) Table 3	First Lag of SRI Intensity: Full Implementation	Ln Water Productivity	123	0.0615	0.0054
6	Column (4) Table 3	SRI Intensity: Partial Implementation	Ln Water Productivity	0	0	0
7	Column (4) Table 3	First Lag of SRI Intensity: Partial Implementation	Ln Water Productivity	0	0	0
8	Column (5) Table 3	SRI Intensity: Full Implementation	Ln Water Productivity	4	0.002	0.001
9	Column (5) Table 3	First Lag of SRI Intensity: Full Implementation	Ln Water Productivity	248	0.124	0.0074
10	Column (5) Table 3	SRI Intensity: Partial Implementation	Ln Water Productivity	0	0	0
11	Column (5) Table 3	First Lag of SRI Intensity: Partial Implementation	Ln Water Productivity	12	0.006	0.0017
12	Column (6) Table 3	SRI Intensity	Ln Water Productivity	0	0	0
13	Column (6) Table 3	First Lag of SRI Intensity	Ln Water Productivity	4	0.002	0.001
14	Column (1) Table 5	SRI Intensity	Ln Rice Yield	0	0	0
15	Column (2) Table 5	SRI Intensity: Full Implementation	Ln Rice Yield	0	0	0
16	Column (2) Table 5	SRI Intensity: Partial Implementation	Ln Rice Yield	0	0	0
17	Column (3) Table 5	SRI Intensity: Full Implementation	Ln Rice Yield	0	0	0
18	Column (3) Table 5	First Lag of SRI Intensity: Full Implementation	Ln Rice Yield	119	0.0595	0.0053
19	Column (4) Table 5	SRI Intensity: Full Implementation	Ln Rice Yield	0	0	0
20	Column (4) Table 5	SRI Intensity: Partial Implementation	Ln Rice Yield	0	0	0
21	Column (4) Table 5	First Lag of SRI Intensity: Full Implementation	Ln Rice Yield	392	0.196	0.0089
22	Column (4) Table 5	First Lag of SRI Intensity: Partial Implementation	Ln Rice Yield	0	0	0
23	Column (5) Table 5	SRI Intensity	Ln Water per Rice	874	0.437	0.0111
24	Column (6) Table 5	SRI Intensity: Full Implementation	Ln Water per Rice	1923	0.9615	0.0043
25	Column (6) Table 5	SRI Intensity: Partial Implementation	Ln Water per Rice	889	0.4445	0.0111
26	Column (7) Table 5	SRI Intensity: Full Implementation	Ln Water per Rice	1802	0.901	0.0067
27	Column (7) Table 5	First Lag of SRI Intensity: Full Implementation	Ln Water per Rice	535	0.2675	0.0099
28	Column (8) Table 5	SRI Intensity: Full Implementation	Ln Water per Rice	810	0.405	0.011
29	Column (8) Table 5	SRI Intensity: Partial Implementation	Ln Water per Rice	336	0.168	0.0084
30	Column (8) Table 5	First Lag of SRI Intensity: Full Implementation	Ln Water per Rice	869	0.4345	0.0111
31	Column (8) Table 5	First Lag of SRI Intensity: Partial Implementation	Ln Water per Rice	0	0	0

Notes: all regressions control for year fixed effects, province fixed effects, region-by-year fixed effects, province specific linear and quadratic time trends, and time-varying covariates. See Table 2 for time-varying covariates.

Online Appendix B Table 5: Randomization Inference for other Crop Outcomes

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Outcome Variables→	Ln Maize Yield			ln Maize Output			ln Sweet Potato Output			ln Cassava Output		
Explanatory Variables of Interest	c	p	Se(p)	c	p	Se(p)	c	p	Se(p)	c	p	Se(p)
SRI Intensity: Full Implementation	0	0	0	0	0	0	16	0.008	0.002	84	0.042	0.0045
SRI Intensity: Full Implementation	0	0	0	0	0	0	27	0.0135	0.0026	98	0.049	0.0048
SRI Intensity: Partial Implementation	0	0	0	0	0	0	33	0.0165	0.0028	1	0.0005	0.0005
SRI Intensity: Full Implementation	13	0.0065	0.0018	13	0.0065	0.0018	79	0.0395	0.0044	301	0.1505	0.008
First Lag of SRI Intensity: Full Implementation	343	0.1715	0.0084	343	0.1715	0.0084	704	0.352	0.0107	359	0.1795	0.0086
SRI Intensity: Full Implementation	7	0.0035	0.0013	7	0.0035	0.0013	75	0.0375	0.0042	826	0.413	0.011
SRI Intensity: Partial Implementation	0	0	0	0	0	0	455	0.2275	0.0094	0	0	0
First Lag of SRI Intensity: Full Implementation	483	0.2415	0.0096	483	0.2415	0.0096	375	0.1875	0.0087	465	0.2325	0.0094
First Lag of SRI Intensity: Partial Implementation	0	0	0	0	0	0	1877	0.9385	0.0054	117	0.0585	0.0052

Notes: all regressions control for year fixed effects, province fixed effects, region-by-year fixed effects, province specific linear and quadratic time trends,, and time-varying covariates. See Table 2 for time-varying covariates.

References

Fisher, R. A. 1935. *The Design of Experiments*. Edinburgh: Oliver & Boyd.

Rosenbaum, P. R. 2002. *Observational Studies*. 2nd ed. New York: Springer.

Fujiwara, T., and L. Wantchekon. 2013. Can informed public deliberation overcome clientelism? Experimental evidence from Benin. *American Economic Journal: Applied Economics* 5: 241–255.

Ichino, N., and M. Sch¨undeln. 2012. Deterring or displacing electoral irregularities? Spillover effects of observers in a randomized field experiment in Ghana. *Journal of Politics* 74: 292–307.

Cohen, J., and P. Dupas. 2010. Free distribution or cost-sharing? Evidence from a randomized Malaria prevention experiment. *Quarterly Journal of Economics* 125: 1–45.

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[1] Provincial competitiveness index ranks provincial government quality (the higher the index the higher quality of the government is) in providing a good business environment for the private sector. The index is constructed based on a range of criteria including entry cost for new firms, land access, transparency, time costs of regulatory compliance, informal charges, proactivity of provincial leadership, policy bias, business support services, labor training and legal institutions.

[2] https://datacatalog.worldbank.org/dataset/wps5491-rainfall-data-172-weather-stations-vietnam.

[3] http://fsiu.mard.gov.vn/CoSoDuLieu.htm.

[4] We average the rainfalls of all stations belonging to a province (there are 172 stations across all provinces) to impute the province-level rainfall.

[5] While the data for control variables prior to 1999 could be gathered from other sources, this would pose problems for data consistency and accuracy.

[6] The adjusted R^2 becomes 0.9 once province fixed effects are included. This figure is comparable to those found in previous studies (e.g., Schlenker & Roberts, 2009; Zhang et al., 2017) that have estimated fixed-effects models.

[7] The result that no observable covariates are significant in explaining the outcome in the richest specification is common in studies using this framework (see for example Cesur et al., 2017). The pattern of change in α_1 across specifications (1) to (6) in Table 4 attests to our aforementioned analysis of the selection of SRI implementation and reflects the relative importance of the selection of different dimensions (i.e., based on observable province characteristics, permanent characteristics, and the evolution of the rice–water productivity over time). It is shown that province permanent characteristics play the most crucial role in SRI implementation (as the coefficient immediately drops from 1.232 to –0.012 when province fixed effects are controlled for). Beside permanent provincial differences, selection on the timing of SRI is also substantial. Observable province characteristics, though important for selection into the SRI program (as was shown in the descriptive statistics analysis), are largely washed away when selection on permanent characteristics and the timing of SRI implementation/adoption are taken into account.

[8] The downside of this approach is to eliminate the provinces with "random zeroes"— the provinces that did not implement the SRI randomly and would have constituted valid members of the control group.

[9] A related question is whether the first year of the SRI implementation in a province is determined by the preceding year's level and growth of rice–water productivity. In an unreported regression, we run a regression of the first year of SRI implementation on lagged ln rice yield, using the SRI-implementing provinces in a cross-sectional set-up. The coefficients of lagged ln rice yield turn out to be insignificant.

[10] This Herfindahl index is the sum of the squared shares of each district implementing the SRI in the total SRI-implemented area within a province. This exercise uses only the 17 provinces that provide SRI data at the district level. The remaining six provinces with SRI data at province level are considered missing.

[11] Our data do not inform whether the same or different plots are used for the SRI over time. This does not appear to be a weakness because, if the SRI is adopted on different plots over time, our findings would only be strengthened, given the applicability of the method in diverse areas.

[12] This finding suggests that our estimated SRI effects are driven by high-intensity practice. We check whether the high adopters are only a few provinces, and this is not the case. High adopters include 15 provinces that are scattered across Vietnam and exhibit extensive adoption in different periods. In an unreported regression, we exclude from the sample the highest adopter, Hanoi, with an *SRI Intensity* as high as 45%. Our results change only little.

[13] In an unreported regression, we add more province covariates to the right-hand side—including ln freight; the ratio of people aged 15–25 to the total population; the unemployment rate; the number of primary schools per population; the number of high school graduates per population; the number of cows, pigs, and poultry per population; and the urbanization rate—to capture various dimensions of connectivity, labor market conditions, education level, and type of agriculture. Our main finding remains unchanged.