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Growing more Rice with less water: the System of Rice Intensification and water productivity in Vietnam*

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We study the effects of a large-scale System of Rice Intensification (SRI) program on the water productivity of rice in Vietnam by exploiting 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 4 million tonnes more rice with the same water supply in the reasonably achievable case of 20 per cent SRI uptake across its provinces. In addition, we find that SRI also increases the output of other crops, 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 a stronger quality of provincial institutions and a weaker agricultural capital base. Numerous selectivity and randomisation tests affirm that the water productivity effect of SRI is robust to selection in SRI uptake at the province and district levels and addressing potential unobservable and omitted variable problems.

Key words: agricultural technology, impact evaluation, SRI, water productivity.

JEL classifications: O13, O33, Q18, Q25

1. Introduction

The recent resurgence of attention to agriculture stems not only from concerns over how 9 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; 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 fertiliser) for boosting cereal productivity (McArthur and McCord 2017) – is set to become a scarce

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resource, due to an increase in food demand and greater competition from other sectors. In particular, climatic shocks, including droughts occurring more frequently at the global scale, have endangered agricultural production and food security (Peck and Adams 2010; Baldos and 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. Instead, any reductions in water usage have come 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, labour intensity and seedling planting techniques (Thakur and Uphoff 2017). By 2012, SRI had reached more than 51 countries (see Appendix S1A in Table S1). From a global sustainability perspective, SRI has been reported to save significant amounts of water (25–67 per cent) in rice production in various countries, including China, Cambodia, the Philippines, Indonesia and Sri Lanka. Some early studies reported water productivity improvements of up to 100 per cent (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 generalisability of SRI's benefits. Second, cross-sectional trials provide limited information regarding the temporal effects on soil quality and nutrient preservation of such agronomic practices that (arguably) rely 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) posit that the farmers who are the first to adopt SRI are commonly also those who are most skilled, and thus, these farmers are more likely to be successful with any technology. Moreover, they tend to implement SRI on their best plots. Finally, the levels of SRI adoption are unlikely to be independent of province-level institutions that allocate funding for farmer training and the provincial infrastructure that shapes agricultural activity. Thus, the observed gains from SRI may not be attributable to the

[1] Crop production consumes 80 per cent of all freshwater resources around the world (de Fraiture and Wichelns 2010).

[2] Several studies have found limited or mixed yield benefits from SRI. Critics of SRI argue that the yield gains achieved by the system are only sporadic, not systematic. However, 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 of the yield effect of SRI).

new method directly; instead, they may reflect several observed and unobserved characteristics at the province, farmer or plot levels.

In this connection, it must be acknowledged that recent randomised controlled trials have the strong potential to provide causal evidence of some of SRI's benefits (e.g. Barrett *et al.* 2022). However, it is also crucial to understand the extent to which the SRI uptake is affected by a province's institutional and infrastructural setup, and whether aggregate policy conclusions can be derived regarding SRI's benefits. In addition, the nutrient-preservation effects of SRI over time remain in question until randomised controlled trials can be scaled up in several directions. Taken all together, it is difficult to determine either the factors behind the SRI uptake or its water productivity benefits for the agricultural sector without an analysis of large-scale implementations.

The key objective of this study is to bridge this gap by examining the effects of SRI on the 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 practised) makes a difference to water productivity. Moreover, we look beyond the contemporaneous effects, and examine the longer-term yield effects of the SRI 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 in the long term. If this is true, then SRI should have a positive effect on the rice yield and rice–water productivity in successive years along with its possible concurrent effect, relative to counterfactual observations (i.e. provinces, years and rice-cultivated areas with no SRI uptake). Furthermore, our province–year panel also enables us to explore the spillover effects of SRI uptake on the outputs of other crops. Given that other crops are produced in the same fields as rice in different seasons, we investigate whether other areas of agricultural activity experience additional gains from, or unintended (positive or negative) consequences due to, SRI practices. Finally, we shed light on the institutional and infrastructural factors that influence SRI adoption across provinces and discuss 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

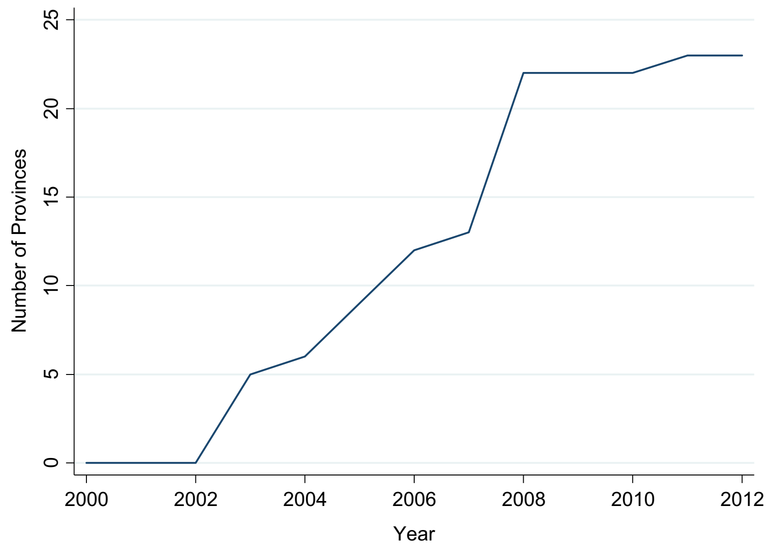

Figure 1 Number of provinces implementing SRI in Vietnam. [Colour figure can be viewed at wileyonlinelibrary.com]

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 various forms. These selection problems are generally related to the way in which the SRI roll-out occurred. First, the central government and other donors chose which provinces to allocate funds to for farmer training. Second, the selected provinces allocate the received funds to selected districts or communes. Finally, individual farmers at the district or commune level decide whether or not to adopt SRI following training. Thus, a myriad of both time-variant and time-invariant factors related to provincial rice production capacity could be important in the extent of the uptake, including the selection of districts/communes for program roll-out, the selection of districts/communes in which 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 the rice yield, rice–water productivity or SRI exposure in a province, rather than those of 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 in our province-level longitudinal data. We facilitate a reliable estimation by controlling 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] This identification approach exploits the differences in the year, province and intensity of SRI adoption 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 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 a more rapid penetration of SRI have experienced faster increases in water productivity than provinces that have not implemented 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 one-fifth of the rice-cultivated areas in a province adopt SRI (i.e. 20 per cent adoption), that province will achieve an 11 per cent higher rice yield per unit of irrigation water, compared with zero SRI adoption. This means that more than 4 million tonnes more rice could be produced in Vietnam with the same water supply. Alternatively, a 20 per cent adoption of SRI saves at least 2.6 per cent of the irrigation water, which, if applied across the country, is equivalent to 908 thousand cubic metres of water saved in Vietnam each year. Having a large rice producer such as Vietnam supplying approximately 11 per cent 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 data set also enables us to distinguish between the effects of full vs. partial practice of SRI. SRI has 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 four components are used simultaneously, while partial practice means that producers follow the first two principles but largely ignore or barely practise 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

[3] This empirical method is used widely in the health and labour economics literature (see Cesur *et al*. 2018) for studying the causal effects of policy changes on outcome variables at the province/state level with 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 farmers' decisions to take up the technology.

20 per cent full practice of SRI would increase the rice–water productivity by 30 per cent in the current year, with an additional effect of 14 per cent in the following year. Meanwhile, 20 per cent partial practice of SRI would increase the water productivity of rice by around 11 per cent 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. This suggests that the potential water saving and soil preservation effects of SRI implementation may also foster the production of these two staple crops. Turning to factors that influence the SRI uptake, we find strong evidence that provinces with a stronger provincial institutional quality tend to have a higher uptake of SRI, presumably owing to efficiencies in funding and organising farmer training programs. We also find that a lower tractor use in a province is associated with a higher SRI implementation rate. In addition, once selected for SRI roll-out, low-tractor-use provinces experience a faster rate of uptake over time. The policy implication of this finding is that returns from SRI will be higher in provinces with a 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' outputs. Third, it illuminates the institutional and infrastructural factors that affect SRI uptake across provinces and provides insights into policy formulations.

The rest of this paper is organised as follows. Section 2 discusses the process of SRI adoption in Vietnam. Section 3 presents the data and descriptive statistics and discusses the potential endogeneity of the SRI program roll-out. Section 4 describes the empirical framework. The empirical findings are discussed in Section 5, which also provides a battery of sensitivity analyses of the results. Section 6 concludes.

2. SRI practice in Vietnam

SRI is a climate-smart, agroecological technology that has been developed for the management of plants, soil, water and nutrients in rice production. Its central principles can be summarised 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 after 8–12 days, with just two leaves, to avoid damage to roots and minimise replanting shock; (iii) soil condition should be improved through enrichment with compost, with chemical fertilisers added only if needed; and (iv) rice field soils should be kept moist through intermittent rather than continuous watering, to allow for a 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, labour availability, water control and access to organic inputs are the key agroecological 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 SRI in 2003. The first outcomes of SRI were reported in 2006, with yields of 8.8 t ha^{-1} and an estimated 62 per cent reduction in water use and 85 per cent reduction in seed use (SRI-INRC 2015). In 2007, the Ministry of Agriculture and Rural Development (MARD) in Vietnam endorsed SRI as 'a technical advance' and directed government departments to spread this innovation (MARD Decree, October 15, 2007). The years 2007–2009 witnessed several efforts to disseminate 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 1 million farmers were applying SRI methods on 185,065 ha. This meant that farmers who had adopted SRI constituted ~10 per cent of all rice producers in Vietnam. In 2014, 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 on full and partial SRI practice are available at the commune level. However, 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

[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 ha in the winter–spring season and 146,943 ha in the summer season).

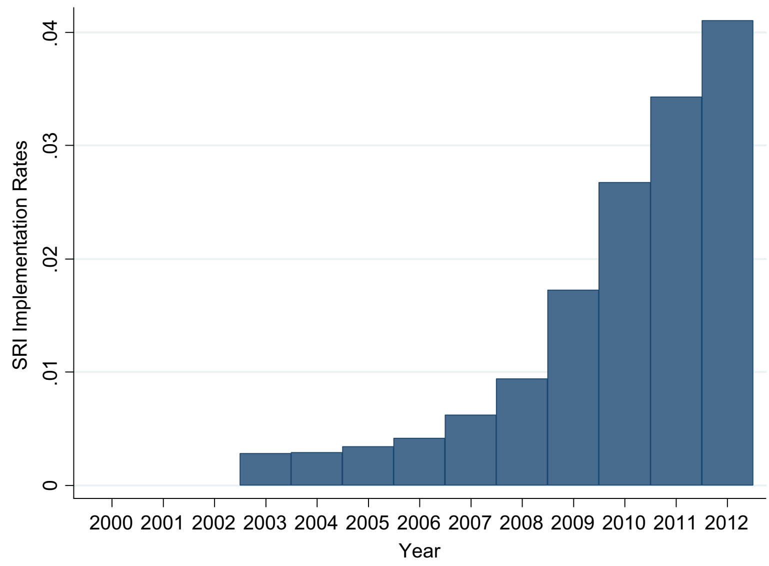

Figure 2 Proportion of SRI-implemented rice areas to total rice-cultivated areas in Vietnam. [Colour figure can be viewed at wileyonlinelibrary.com]

variations in SRI uptake with respect to the year and intensity of adoption. Table S2 in Appendix S1A lists Vietnam's 64 provinces and the total years of SRI implementation of each between 2000 and 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 method. Figure 2 shows that the proportion of SRI-implemented rice areas to total rice-cultivated areas country-wide increased rapidly over time.

Data sources for water productivity and time-varying covariates are presented in Sections 1 and 2 of Appendix S1B.

3.2 Descriptive statistics

Columns (1) and (2) of 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 descriptive statistics for the subsample of 41 provinces that never implemented SRI during our sample period (i.e. non-SRI provinces), and column (6) presents statistics for the 23 provinces that

[7] The full sample contains 796 province–year observations ($64 \times 13 = 832$, 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.

Table 1 Descriptive statistics

Sample→	(1) Mean (SD) Full Sample	(2) Observations Full Sample	(3) Mean (SD) SRI = 0 at time *t*	(4) Mean (SD) SRI = 1 at time *t*	(5) Mean (SD) SRI Ever = 0	(6) Mean (SD) SRI Ever = 1
		SRI				
SRI dummy (Yes = 1)	0.175	796	0.000	1.000	0.000	0.454
	(0.380)		(0.000)	(0.000)	(0.000)	(0.499)
SRI intensity: all 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 rate	0.001	796	0	0.005	0	0.002
	(0.007)			(0.017)		(0.012)
SRI intensity: partial implementation rate	0.013	796	0	0.075	0	0.034
	(0.052)			(0.104)		(0.08)
		Outcomes				
Rice yield (tonne/ha)	4.626	796	4.478	5.328***	4.416	4.963***
	(0.928)		(0.882)	(0.811)	(0.883)	(0.900)
Irrigation water (1,000 m^3) per hectare of rice area	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 (tonne/1,000 m^3)	0.98	796	0.95	1.13***	0.92	1.07***
	(0.3)		(0.3)	(0.29)	(0.3)	(0.29)
		Province covariates				
Irrigation water growth (per cent)	0.0049	726	0.0053	0.0031	0.0054	0.0041
	(0.069)		(0.075)	(0.036)	(0.077)	(0.054)
Rainfall (in mm)	1,849.135	720	1,885.198***	1,687.550	1,942.482***	1,707.621
	(652.493)		(685.780)	(442.807)	(742.149)	(451.799)
Fertiliser use per 1,000 hectares of rice area (tonne)	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 labourers 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 1,000 hectares of rice area	51.887	790	56.142**	32.825	70.647***	23.447

Table 1 (*Continued*)

Sample→	(1) Mean (SD) Full Sample	(2) Observations Full Sample	(3) Mean (SD) SRI = 0 at time t	(4) Mean (SD) SRI = 1 at time t	(5) Mean (SD) SRI Ever = 0	(6) Mean (SD) SRI Ever = 1
	(108.872)		(119.478)	(24.080)	(136.107)	(20.517)
Number of farms per 1,000 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)
Agricultural labour growth rate (per cent)	3.216	796	3.125	3.648***	2.993	357.418***
	(1.046)		(1.025)	(1.040)	(1.035)	(96.265)
Labour force participation rate	0.692	796	0.689	0.706**	0.683	0.707***
	(0.074)		(0.072)	(0.078)	(0.067)	(0.081)
Number of schools per 1,000 people	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 1,000 people	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 1,000 people	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)

Note: 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.

began practising SRI at some point during the sample period (i.e. SRI provinces).

Table 1 shows that 17.5 per cent of the province–year observations in Vietnam saw the implementation of SRI over the period 2000–2012. In provinces that took up SRI at some point, the mean number of years of SRI implementation is 6 years (45.4 per cent of 13 years). However, the mean adoption rate of SRI in all province–year observations – our measure of intensity – is on the low side, at 1.4 per cent. In the SRI provinces, the mean adoption rate is 3.6 per cent. These figures are 1.8 per cent and 5.2 per cent, 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, sample means mask important variations in SRI implementation. The share of SRI-full uptake saw a significant jump following the year 2007, when the Ministry of Agriculture and Rural Development endorsed SRI as a 'technological advance' (see Figure 3). Although the SRI-full implementation rate is still relatively small compared with the SRI-partial uptake, it reached 12.5 per cent of the total SRI-practised area in 2012, being adopted on 32,964 ha nationwide. The relatively faster growth rate over time of full implementation compared with partial practice implies that a wider adoption of full implementation is likely once farmers become more competent in overall SRI practice and understand more about its benefits. In general, provinces have instances of both full and partial implementation, although SRI-full is implemented less intensively than SRI-partial. This is because 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 both 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 in order to increase its water productivity (i.e. selection on the level of water productivity). Second, once SRI reaches a province, selection may occur regarding the districts/communes in which it is implemented. Third, once the program reaches a district,

[8] For example, Barrett *et al.* (2004) found that the average adoption rate of SRI among Malagasy farmers is 3 per cent. On the contrary, one province in our study implemented SRI in as many as 49.2 per cent of its plots in a certain year. Appendix S1A in Figures S1 and S2 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, a lack of government support or a lack of peer support (Mottaleb *et al.* 2015; Ogundari and Bolarinwa 2018; see also Pham *et al.* 2021, for Vietnam).

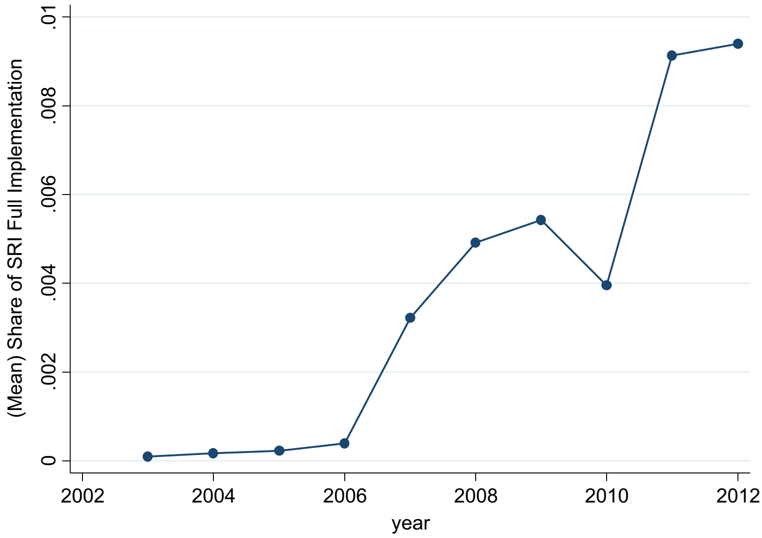

Figure 3 Evolution of SRI-full implementation over time.Notes: The share of SRI-full implementation is the rice area under SRI-full implementation divided by the total rice production area for all provinces that practise SRI. [Colour figure can be viewed at wileyonlinelibrary.com]

farmers' decisions to adopt the technique might be subject to a wide range of selection issues, such as skill, education, input (primarily labour) availability and plot choice. Thus, variations in SRI implementation across provinces are likely to be endogenous because of policymakers' selections 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. These decisions 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, Section 6.6 provides insights into this phenomenon.

4.1 Selection on time-varying province observables

Table 1 (columns (3)–(6)) shows that SRI and non-SRI provinces differ in a range of factors. First, rice yield and rice–water productivity are higher in the former than in the latter, while the opposite relationship is seen for water use per hectare of rice area. These differences are statistically significant. Second, *t* tests show that many of the 13 time-varying province covariates differ between SRI and non-SRI provinces. The most notable differences between these two sets of provinces include fertiliser and tractor use, and the number of farms. Tractor use and fertiliser use are two to three times lower in SRI provinces than in their counterparts, while the number of farms is almost five times lower. These figures suggest that SRI and non-SRI provinces differ in their agricultural production structures, 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 the 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 practise it. This points to the importance of funding from the government and donors for implementation and adoption. Such 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 them with a reasonable amount of training. In addition, SRI implementation requires a set of coexisting 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 implementation.

In general, if provinces with favourable conditions for rice production implement SRI earlier and use it more intensively, this will bias the results because they would be experiencing 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 (blue line) against non-SRI provinces (red line), and clearly shows that provinces that implemented SRI consistently had a higher rice–water productivity than non-SRI provinces.[11] Further, there are changes in trends over time in SRI- and non-SRI provinces, pointing to the need for controlling for province-specific trends in regressions.

4.3 Selection on the 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

[10] For example, 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] SRI was adopted earliest and most intensively in some Red River Delta provinces. The Delta is characterised by a stable water supply and an abundant labour force – other suitable conditions for SRI.

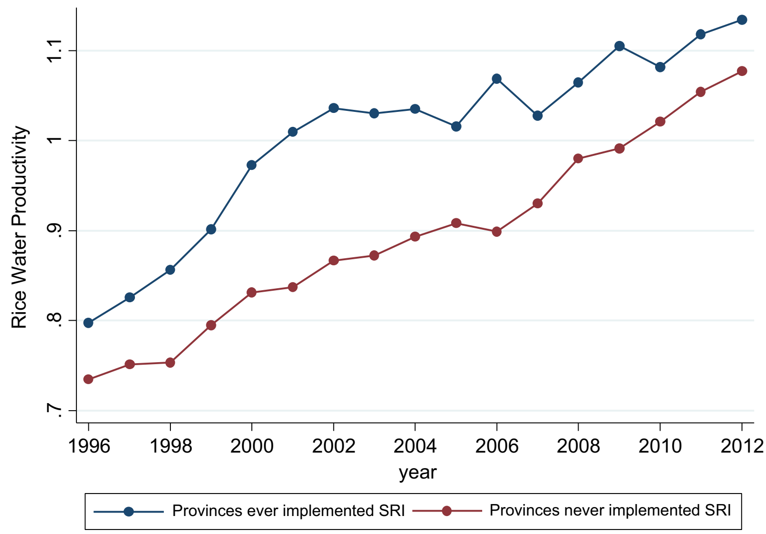

Figure 4 Evolution of rice–water productivity in 'ever' vs. 'never SRI-implemented' provinces.Notes: Data for water productivity are available from 1995. However, in 1995, data were available for only 41 provinces, whereas by 1996, data were available for 61 provinces, gradually increasing to 64. Thus, we use data from 1996 onwards, for consistency and comparability. [Colour figure can be viewed at wileyonlinelibrary.com]

other programs that are implemented in a province simultaneously with SRI. The most important economic development program over this period was the installation of special economic zones (SEZs), 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 afford to adopt SRI later than their counterparts (see Table S3 in Appendix S1A for the timing of SEZ opening and SRI adoption). Figure S1a in Appendix S1A plots the evolution of rice–water productivity growth for 10 provinces with SEZ but without SRI implementation, while Figure S1b in Appendix S1A displays the same information for 31 provinces that never practised 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 effect 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 SEZ practice.

Taken together, the 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 the 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 a value of 1 if SRI is implemented in year *t*, and 0 otherwise.[12] Consistent with our earlier argument that SRI adoption reflects selection on a full range of different aspects, the regression results show that several time-varying province covariates are associated significantly with SRI adoption. However, the link is generally broken in regressions when all of the year fixed effects, province fixed effects, region-by-year fixed effects and province-specific time trends are controlled for (see Section 3 in Appendix S1 in Table S1B for detailed results and analysis).

A similar scenario emerges in Table 2 when *SRI intensity* is used as the outcome and the full set of fixed effects are controlled for. Only two variables remain significant in explaining SRI adoption: PCI and tractor use. Specifically, a higher PCI promotes SRI uptake, with a one standard deviation (about five percentage points) increase in PCI leading to a 0.5 percentage point additional SRI uptake in that province (equivalent to 36 per cent in relative magnitude, given that the mean value of SRI uptake is 1.4 per cent). This is probably because the authorities in provinces with higher PCI are more efficient at SRI-related activities such as organising and allocating funding 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 variable (not reported) does not change this result.

Meanwhile, a higher tractor use is negatively related to the SRI adoption rate. In particular, a 10 per cent higher tractor use is associated with a 0.0023 percentage point lower SRI adoption rate, which is equivalent to a 16 per cent decrease in SRI adoption, as calculated at the mean value of the latter (1.4 per cent). This is not surprising, as SRI utilises a significant amount of labour instead of machines. Figure 5 displays the average SRI adoption rate, conditional on SRI implementation, among province–year observations with below and above the median tractor use in the previous year. Figure 5 suggests that, conditional on being selected for the SRI roll-out, provinces with a lower tractor use overtake those with a higher use in terms of SRI adoption. The slow SRI adoption rates in high-tractor-use provinces tend to support our earlier comment that the SRI adoption rate can be lower in provinces with more capital-intensive agricultural practices. In contrast, provinces with low tractor usage are associated with a consistent increase in the SRI adoption rate, even surpassing their high-use counterparts from 2011 onwards.

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

Table 2 Determinants of SRI implementation

	SRI intensity
ln rainfall	0.005
	(1.13)
First lag of ln fertiliser	−0.017
	(1.00)
First lag of ln buffalos	−0.018
	(0.97)
First lag of rice labour	−0.006
	(0.22)
First lag of ln tractors	−0.023***
	(2.78)
Irrigation water growth	−0.029
	(1.42)
ln farms	0.002
	(0.48)
Schools per population	−0.042
	(0.75)
Agriculture labour rate	−0.000
	(0.61)
Labour force participation rate	0.039
	(0.78)
University lecturers per population	−0.001
	(1.14)
College lecturers per population	0.001
	(0.24)
Provincial Competitiveness Index	0.001*
	(1.85)
Observations	383
Adjusted R^2	0.966

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

These factors are also important to identify for a different reason: controlling for these inputs in the SRI adoption equation may result in a 'bad controls' problem, in the spirit of Angrist and Pischke (2009). For example, Takahashi and Barrett (2014) showed a significant increase in labour use among SRI users, indicating that the levels of fertiliser and machinery use can potentially be adjusted to SRI practice. Thus, we allow a one-year lag of fertiliser and tractor use, the number of buffaloes and rice labour, to alleviate the bad controls problem. However, other factors such as rainfall and PCI are likely to be exogenous to SRI adoption, so we employ the current values of these covariates in the regressions.

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 the ln water productivity for rice on four leads and lags of a binary variable of the year-to-adoption

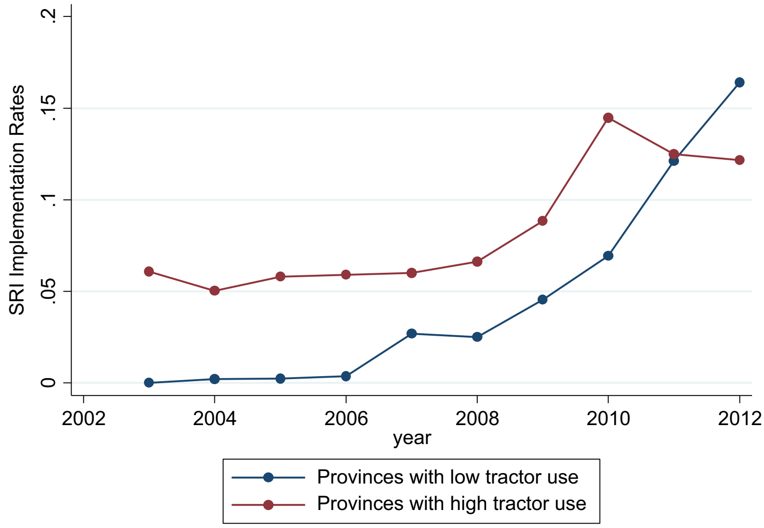

Figure 5 SRI implementation among provinces with low vs. high tractor use.Note: The two groups consist of province–year observations with below vs. above the median value of tractor use in the previous year. [Colour figure can be viewed at wileyonlinelibrary.com]

(i.e. to and from the initial year of SRI uptake). To ensure a meaningful comparison of rice–water productivity between SRI and non-SRI provinces, the two groups should normally be trending similarly in the absence of SRI introduction. We conduct three scenarios with different sets of controls alongside year-to-adoption dummies. The first scenario accounts for only year fixed effects, while the second also accounts for 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 Appendix S1A in Table S4. The parallel trend assumption is clearly 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 0.14–0.16 and significant for three and 2 years prior to SRI adoption; see column (1) of Appendix S1A in Table S4). 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 (column (2) of Appendix S1A in Table S4). Not until the third scenario (not reported graphically to save space, but the regression results are in column (3) of Appendix S1A in Table S4) 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 3 years later.[13] When time-varying province observables

[13] We use the 'missing dummy' technique to avoid the loss of observations in time-varying province covariates.

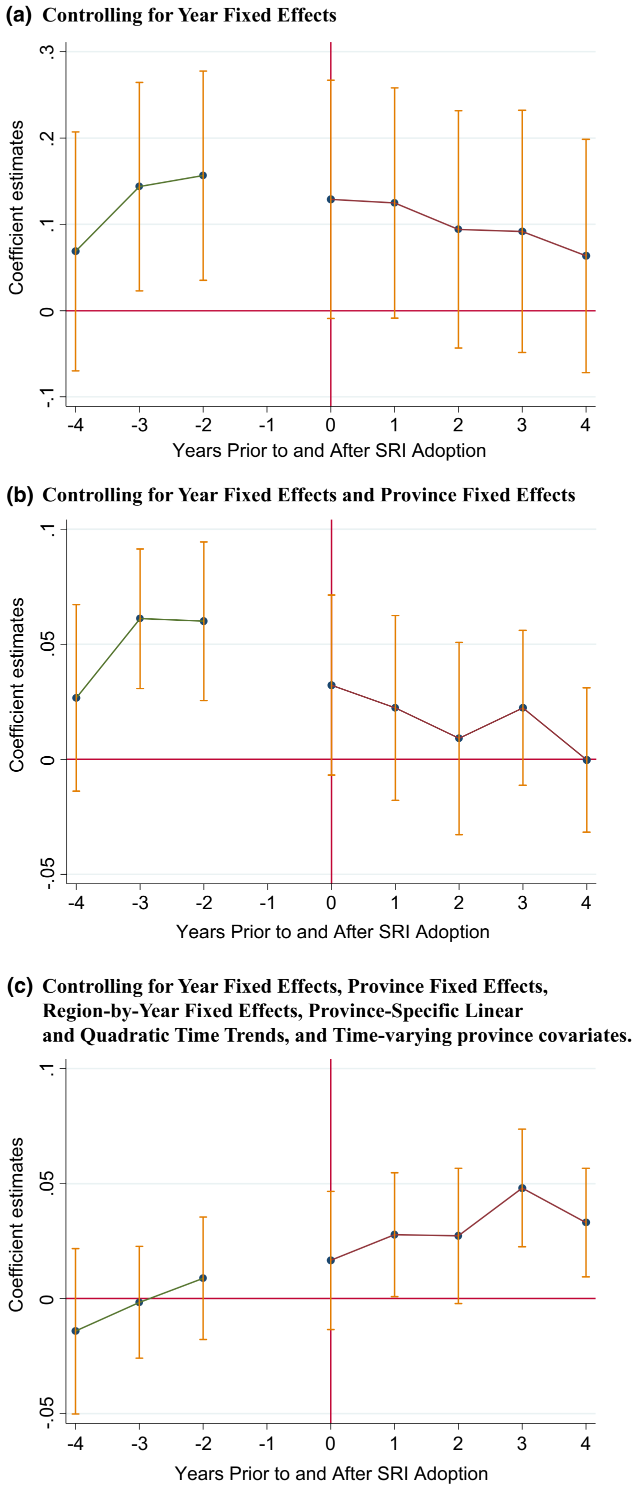

Figure 6 Event-study estimates of the effect of 'Ever Adopted SRI' on ln water productivity of rice. [Colour figure can be viewed at wileyonlinelibrary.com]

are controlled for (Figure 6c, and column (4) of Appendix S1A in Table S4), the effect shows up 1 year after SRI adoption, with the largest magnitude being seen 3 years after SRI adoption. These results indicate that our parallel trend assumption is likely to be satisfied in our richest specification. Conversely, earlier lags of year-to-adoption are significant (the trend among the SRI provinces differs significantly from that of the non-SRI provinces) in Figures 6a and 6b, suggesting that something else – such as another program – might have been occurring in those SRI provinces, or those provinces might have been selected for the SRI for another reason. In short, the event study in Figure 6c indicates that our richest specification successfully removes the pre-trend differences in the water productivity of rice between SRI provinces and their counterparts, and demonstrates an increase in rice–water productivity in the former provinces relative to the latter.

5. Empirical framework

We investigate the effects of SRI implementation on the natural logarithm (ln) of rice–water productivity as follows[14]:

$$\ln WP_{pt} = \alpha_0 + \alpha_1 SRI\ intensity_{pt} + Z_{pt} + W_{pt} + \eta_p + \kappa_{rt} + \zeta_t + \tau_{pt} + \tau^2{}_{pt} + e_{pt}, \quad (1)$$

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, dividing the rice output by the total water used 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 a vector of inputs into rice production and time-varying province characteristics as described 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 fixed effects, which account for any nationwide shock in year t; κ_{rt} is set of region-by-year fixed effects; 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 parts, SRI-full and SRI-partial, in some regressions.

[14] This equation is derived from the standard Cobb–Douglas production function for rice:

$$Y_{pt} = \propto SRIIntensity_{pt}^{\propto_1} Z_{pt} W_{pt} e^{v_{pt}}, \quad (1)$$

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 to Z_{pt}) to obtain the equation with the outcome variable of interest, water productivity. Then, we take the natural logs of both sides to obtain the estimating Equation (1).

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 implemented 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 reflects how *SRI intensity* affects the rice–water productivity.

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 fertiliser, which helps to maintain soil aeration and soil biota. We provide insights into this argument by adding the first lag of the *SRI intensity* to Equation (1):

$$lnWP_{pt} = \alpha_0 + \alpha_1 SRI\ intensity_{pt} + \alpha_2 SRI\ intensity_{p(t-1)} + \mathbf{Z}_{pt} + \mathbf{W}_{pt} + \kappa_{rtr}\eta_p + \zeta_t + \tau_{pt} + \tau^2{}_{pt} + e_{pt}. \quad (2)$$

This also allows *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 (fertiliser and tractor use, and rice labour) when the equation includes the lag of SRI intensity.

Another important question is whether the irrigation water flow saved by adopting SRI was channelled into the production of other crops. If such irrigation water was used for other crops, this would allow the benefits of adopting SRI to spill over to other agricultural activities, specifically, to other crops that share their water supply with rice. Therefore, we test the effect of SRI on the yields and outputs of maize and sweet potatoes directly, as these are often rotated with rice in the same field. Cassava is grown in hilly areas far from rice fields, so it 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.

Note that our richest specification, which controls for unobservable province permanent characteristics, province-specific trends, region-by-year fixed effects and time-varying provincial factors, has two objectives in achieving identification: to break/weaken the links between observable factors and selection into SRI, and to break/weaken the links between observable factors and the outcomes of interest, to tease out the program effect of SRI. Regarding the first objective, our results show that, of the 13 factors considered, only one factor (PCI) significantly explains the SRI dummy (column (3) Appendix S1B in Table S1), and two factors (PCI and tractor use) significantly explain SRI intensity (Table 2) after controlling for the aforementioned array of characteristics. As to the second objective, only two of the 13 factors considered as right-hand-side variables (irrigation water growth and the number of buffalos) remain significant when the outcome is rice–water productivity (see Appendix S1B in Table S2, columns (6) and (9) and Section 4 in Appendix S1B). The OLS estimate is biased if omitted variables influence both the SRI uptake and outcomes simultaneously. Our model breaks or weakens one or both of these links by capturing several dimensions of unobservable variations, thus mitigating the bias of the SRI estimate. Finally, our event study shows that our richest specification exhibits no systematic differences in water productivity between SRI and non-SRI provinces, which is the core condition for making meaningful comparisons between the two groups, analogous to the parallel trend assumption in difference-in-difference modelling.

6. Empirical results

6.1 The effects of SRI on the water productivity of rice

We present results using the richest specification with the full set of explanatory variables in Table 3; Appendix S1B in Table S2 provides the results for specifications where we include this set of controls one by one. The coefficient of SRI intensity in column (1) of Table 3 is 0.54, significant at the 5 per cent level. This estimated *SRI intensity* effect is economically meaningful and suggests that a change in *SRI intensity* of 0.2 units would increase the rice–water productivity by about 11 per cent, compared with zero SRI practice in the country. That is, a province that increases its proportion of rice-cultivated plots that implement SRI by 20 percentage points will produce 120 tonnes more rice per thousand cubic metres of water use. Equivalently, this means that Vietnam could produce over 4 million tonnes more rice with the same water supply.[15] From the year 2007, when SRI was endorsed as technological advance, SRI was practised more intensively throughout the country. Thus, we check whether the effect is stronger for the period from the year 2008 by including the interaction of period indicators (before 2008, and from 2008 onwards) with the SRI intensity. The effect (reported in Appendix S1B in Table S2, column (8)) is shown for both periods and is slightly larger for the latter period.

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

Table 3 The effects of SRI on the water productivity of rice

	(1)	(2)	(3)	(4)	(5)	(6)
	ln rice–water productivity					
SRI intensity	0.543** (2.59)					0.623*** (2.72)
SRI intensity: full implementation		1.587*** (3.92)	1.688*** (4.50)		1.260*** (2.78)	
SRI intensity: partial implementation		0.423** (2.41)		0.640*** (2.68)	0.483*** (2.83)	
First lag of SRI intensity						−0.189 (1.31)
First lag of SRI intensity: full implementation			0.999** (2.33)		0.550 (1.47)	
First lag of SRI intensity: partial implementation				−0.340 (1.40)	−0.174 (0.92)	
Observations	796	796	726	726	726	726
Adjusted R^2	0.979	0.979	0.979	0.979	0.979	0.979

Note: 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 province covariates. See Table 2 for time-varying province covariates.

Column (2) allows SRI-full and SRI-partial practice to stand in the regression separately, and reports that SRI-full practice has a huge impact on rice-water productivity relative to SRI-partial practice. The coefficient for the former is 1.59, while that for the latter is 0.42, both of which are significant.[16] In the case of SRI-full, a 20 percentage point higher practice would see an output increase of 350 tonnes per thousand cubic metres of water use, or 12 million tonnes more rice produced using the same amount of water, compared with zero SRI practice. Note that the high coefficient estimate of *SRI intensity* is within expectations, given the low uptake of SRI-full. 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 practice with the current literature.

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.[17] Thus, SRI is believed to help maintain soil nutrition better than conventional farming methods, in terms of soil aeration and soil biota. We

[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] 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. The latter indicates a more balanced soil chemistry for rice cultivation (Uphoff 2006). Also, the SRI recommends the use of compost instead of mineral fertiliser and no use of chemicals or pesticides (Stoop *et al.* 2002).

now evaluate the validity of these arguments by focusing on the dynamic effects of SRI. The results in columns (3)–(6) of Table 3 show that SRI-full is estimated to be large, with coefficients of current effects of 1.3 to 1.7, while the lag effects have coefficients of 0.55 to 1. The current effect of SRI-partial is 0.42–0.64, significant at the 1 per cent level, while its first lag is insignificant. In summary, we find that only the first lag of SRI-full is positive and significant. This result is consistent with the argument that full SRI practice helps maintain soil nutrition better.

6.3 Effects 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 provinces with tractor use below vs. above the median value.[18] We report results for the 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 values of tractor use, though the estimates generally have weaker significance and become insignificant in some cases (with *t*-statistics between 1 and 1.5). The less precise estimates are probably due to the smaller sample size. The policy implication of this finding is that more funding can be allocated to farmer training programs in provinces with a weaker agricultural capital base. However, 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). However, our water data for rice production are water pumped into the channels for agricultural production in general, meaning that the water may be used for crops other than rice, thus causing an error-in-dependent-variable problem. If the measurement error is independent of the variable of interest, *SRI intensity*, it will not cause any problem and the coefficients will be estimated consistently (Wooldridge 2002, p. 71). However, in our case, the water saved in high SRI intensity provinces is likely to be used to irrigate other crops, making the real water consumption for rice divergent from the measured water supply. This would bias the

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

Table 4 The effects of SRI on the rice–water productivity for low vs. high tractor use

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	ln rice–water productivity											
	Provinces below the median value of tractor use						Provinces above the median value of tractor use					
SRI intensity	0.781* (1.99)					0.714** (2.06)	−0.053 (0.23)					0.304 (1.05)
SRI intensity: full implementation		1.571** (2.51)	1.852*** (2.92)		1.315 (1.52)			3.113 (0.44)	3.154 (0.44)		1.614 (0.24)	
SRI intensity: partial implementation		0.576 (1.41)		0.743* (1.77)	0.500 (1.35)			−0.009 (0.04)		0.309 (1.06)	0.312 (1.06)	
First lag of SRI intensity: full implementation			0.756 (1.03)		0.337 (0.53)				−1.026 (0.28)		1.989 (0.47)	
First lag of SRI intensity: partial implementation				−0.597 (1.40)	−0.193 (0.46)					−0.615* (1.70)	−0.628 (1.65)	
First lag of SRI Intensity						−0.243 (0.92)						−0.604* (1.71)
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	0.970	0.970	0.970	0.970	0.970

Note: 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 province covariates. See Table 2 for time-varying province covariates. The median value of tractor use is measured based on the number of tractors used in the previous year.

coefficient of *SRI intensity* downward (Wooldridge 2002, p. 62). We mitigate this measurement error problem by restricting our sample to provinces with larger shares of rice production area over the total production area for all crops,[19] because the water supply for rice production in these provinces should be closer to the actual water consumption for rice production. In particular, we run the regressions in Table 5 by making use of the top 75 per cent of provinces in terms of the share of rice production area. These provinces have a mean share of rice production area of 85 per cent. The results for this sample show that the effect of *SRI intensity* on water productivity comes from both the increased rice yield (columns (1)–(4)) and the reduction in water use per rice production area (columns (5)–(8)). On average, a one percentage point increase in SRI intensity leads to 0.48 per cent increase in rice yield and a 0.13 per cent decrease in water use for rice production. An important note is that contemporaneous water saving is seen for only SRI-partial practice, but the lag effect exists only for SRI-full practice. This result suggests that SRI-full practice in the previous year enables water saving, hence preservation of the soil quality, and in the current year, only partial SRI practice is sufficient to make the water savings. One potential implication of this finding is that the water saved in the current period can be channelled to other crops (see Section 6.5).[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 the production of other crops? SRI may affect the yields and outputs of other crops in two ways. First, if SRI does indeed reduce the water used for rice, the resulting water savings could be used to grow other crops, thus boosting 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 there was not sufficient water. Second, SRI may affect other crops' yields by retaining soil quality, thus enhancing the yields of crops that are rotated into plots with rice, or are cultivated on portions of land that had previously grown rice.

One pitfall of our analysis is that any effect of SRI on water savings cannot be revealed directly through water supply information, because the water supply is fixed. However, if saved water is used for other crops that share the

[19] These crops include major crops that share the same field with rice, namely maize, sweet potato and sugar cane. Peanut and soya bean crops are not included owing to small cells of data, and cassava is not included because it is often grown in hilly areas far from rice fields.

[20] The effects of SRI intensity on the rice–water productivity shown in Table 5 (columns (9)–(12)) are similar to those for the full sample reported in Appendix S1 in Table S5, but higher in both size and significance level, as expected. We find that the effect of SRI intensity on rice yield is analogous to that of SRI intensity on the water productivity of rice, as in Table 3, columns (1)–(3) and (5), but no significant effect of SRI intensity is detected on the water use per rice production area in this full sample.

Table 5 The effects of SRI implementation on rice yield and water use and productivity in high rice production provinces

	(1) ln rice yield	(2)	(3)	(4)	(5) ln water per rice area	(6)	(7)	(8)	(9) ln water productivity of rice	(10)	(11)	(12)
SRI intensity	0.483*** (3.26)				−0.129** (2.11)				0.612*** (3.90)			
SRI intensity: full implementation		1.562*** (7.44)	1.738*** (9.37)	1.493*** (6.62)		−0.123 (1.12)	−0.166 (1.14)	−0.083 (0.44)		1.686*** (5.99)	1.905*** (7.77)	1.576*** (4.67)
SRI intensity: partial implementation		0.369*** (2.92)		0.412*** (2.75)		−0.129* (1.92)		−0.115** (2.02)		0.498*** (3.42)		0.527*** (3.66)
First lag of SRI intensity: full implementation			0.551 (1.09)	0.166 (0.35)			−0.335*** (3.05)	−0.235* (1.67)			0.886* (1.76)	0.401 (0.89)
First lag of SRI intensity: partial implementation				−0.077 (0.62)				0.035 (0.51)				−0.112 (0.71)
N	623	623	555	555	623	623	555	555	623	623	555	555
Adj. R^2	0.975	0.975	0.970	0.970	0.949	0.949	0.940	0.940	0.975	0.975	0.970	0.971

Note: 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 province covariates. See Table 2 for time-varying province covariates. The sample includes the 75% of provinces for which the rice production area has at least a 63% of share of the total production area for major crops.

Table 6 Effects of SRI implementation on other crops

	(1) ln maize output	(2) ln sweet potato output	(3) ln cassava output
SRI intensity: full implementation	1.511***	1.698**	0.130
	(3.33)	(2.18)	(0.09)
SRI intensity: partial implementation	−0.264	−0.064	0.325
	(1.28)	(0.12)	(0.63)
First lag of SRI intensity: full implementation	0.712	1.262	1.425
	(1.39)	(1.42)	(1.00)
First lag of SRI intensity: partial implementation	0.188	0.087	−0.362
	(1.15)	(0.24)	(0.46)
ln maize production area	1.035***		
	(24.47)		
ln sweet potato production area		0.876***	
		(16.05)	
ln cassava production area			1.023***
			(17.89)
Observations	719	724	678
Adjusted R^2	0.998	0.995	0.991

Note: 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 province covariates. See Table 2 for time-varying province covariates.

field with rice, as is potentially suggested in the preceding section, then any increase in the output of other crops, such as maize and sweet potatoes, may be attributable, at least in part, 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 that 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, which includes both the lagged and current effects of SRI.

Of the three other crops for which data are available, maize and sweet potatoes are often grown in the same field as rice, while cassava is grown in hilly regions far from rice fields, owing to its special biological characteristics. 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 lagged values of SRI-full and SRI-partial. The results in columns (1) and (2) show that SRI-full has large positive effects on the output of maize. The current effect for maize output (column (1)) is 1.5 (with respect to a one percentage point increase in the SRI-full implementation area), which is significant at the 1 per cent level, while the lag effect is 0.7, though this effect has a t-statistic of 1.4. The result implies that a 20 per cent adoption of SRI-full practice would result in more than a 1 million tonne increase in maize production output in Vietnam compared with zero SRI practice.[21] The effect of SRI-full practice on the output of sweet potato (column (2)) is also large and significant at the 5 per cent level. Overall, there is evidence to think that water saved from SRI could increase the yields of other crops. No significant effect of SRI intensity is seen for cassava, which is as expected, since cassava is often grown far from rice fields. Importantly, no current or lag effect of SRI-partial on the yield of any crop is found. Consistent with the results for rice–water productivity, the effects of current and lagged SRI-full are driven by provinces with low levels of tractor use (not reported).[22] The effects of SRI on the yields of these crops (not reported to save space) are similar.

6.6 Addressing other selectivity issues

Appendix S1B assesses 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) the selection of districts at the province level; (vi) selection on farmer or plot characteristics; (vii) the role of cooperatives; (viii) selection on future expectations regarding the water productivity of rice; and (ix) subjecting our results to randomisation inference, to assuage the concern of selection on unobservables. Our key findings survive all of these robustness checks.

7. Conclusion

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 was to offer a detailed evaluation of the water productivity benefits of a large-scale agronomic program – SRI – in Vietnam. We conduct our evaluation using a unique annual province-level panel data set, with data on the SRI implementation rate measuring the proportion of SRI-practised rice area to the total rice-cultivated area in each 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

[21] This is calculated by multiplying the elasticity of the responsiveness of maize output with respect to 20 per cent SRI-full implementation by the average maize output (59,910 tonnes) and the 64 provinces of Vietnam.

[22] No effect of SRI on either the yield (not reported to save space) or the output of cassava production is found for either the overall sample (columns (4)) or the sample of provinces with low levels of tractor use (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.

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 SRI across Vietnamese provinces provides a rare example of an experimental setting with strong time and geographic variation. However, it also poses its own methodological problems. The SRI roll-out in Vietnam occurred primarily through the disbursement of centrally administered funds to provinces for farmer training. These provinces, selected based on their rice production capacity, allocated the funds to districts for use in organising farmer training programs. Then, farmers made adoption decisions after receiving training. Education, skill, labour and capital endowment, and plot quality are 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 of these factors have been accounted for in the 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 per cent of its rice-cultivated area will produce 120 tonnes more rice per thousand cubic metres of irrigation water. Thus, Vietnam as a whole could produce more than 4 million tonnes of additional rice every year with the same water supply, compared with zero SRI practice in the country. 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 besides 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 the institutional and infrastructural factors that influence SRI adoption, there is strong evidence that provinces with a stronger provincial institutional quality are more likely to adopt and implement SRI more intensively, presumably owing to efficiencies in organising farmer training programs. Our results also show that a lower tractor usage in a province is associated with a higher SRI adoption intensity. This is consistent with SRI principles, which require significant labour inputs in place of machines. In addition, once selected for SRI roll-out, low-tractor-use provinces experience a faster uptake over time. The policy implication of this finding is that SRI achieves greater returns in provinces with a 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 per cent implementation of SRI in Vietnam resulting in an additional 4 million tonnes of rice production annually means that SRI could feed 15 million more persons per year with the same water supply. This suggests that SRI could have a tremendous effect on food security at both the national and global scales. Although the initial uptake of full SRI practice was small, it has been growing since, and its triple – and sustainable – effect is achieved without compromising water resources, which is important given that water scarcity is a growing concern worldwide.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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