Agricultural Systems 143 (2016) 159–168

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

System of Rice Intensification provides environmental and economic gains but at the expense of social sustainability — A multidisciplinary analysis in India

Alfred Gathorne-Hardy [a,*], D. Narasimha Reddy [b], M. Venkatanarayana [b], Barbara Harriss-White [a]

[a] Oxford University, Somerville College, Oxford OX2 6HD, UK
[b] National Institute for Rural Development, NIRD Rd, Rajendranagar mandal, Hyderabad, Telangana 500030, India

ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form 11 December 2015
Accepted 19 December 2015
Available online 11 January 2016

Keywords:
System of Rice Intensification
SRI
Interdisciplinary analysis
Livelihoods
India
Life Cycle Assessment

ABSTRACT

The System of Rice Intensification (SRI) is claimed to make rice more sustainable by increasing yields while reducing water demand. However, there remains a shortage of high quality data to test these assertions, and a major research gap exists concerning the wider social and economic implications of SRI techniques.

Using primary data we developed a model to simultaneously analyse social, economic and environmental sustainability (greenhouse gas (GHG) emissions, ground water abstracted, energy use, costs, profit, gender, employment quality and employment quantity) to compare SRI to conventional flooded-rice production systems (control). Data was based on farmer-recall questionnaires in Andhra Pradesh, India. Analysis was per hectare and per kg of paddy.

SRI offered substantial environmental and economic benefits: >60% yield gain; GHG emissions, ground-water, fossil energy down by 40%, 60%, and 74% kg^{-1} respectively. SRI costs reduced significantly ha^{-1}, and returns after costs increased by over 400% ha^{-1}.

However, the socio-economic benefits accrued to the farmer at the expense of landless labourers. Employed labour demand ($h\ ha^{-1}$) reduced to 45% of control, with the greatest decline in female employment — rural India's most vulnerable sector. SRI reduced casual labour remuneration per hectare by 50%. Doubling rates of pay maintain total casual-labour remuneration, and only reduces SRI farm returns by 10%. Yet with no policy support it is unlikely that the private economic benefits of SRI will be shared to landless labourers.

Internalising environmental externalities (electricity and GHG) impacted control farms more than SRI farms, including producing negative economic returns when electricity was charged at INR4.7 $unit^{-1}$ for control farms. Increasing the farm gate price for paddy by 10% increased control farm returns by 38%, yet even with this substantial increase control farm returns were only a third of SRI returns *without* a price increase.

Identifying and understanding the trade-offs associated with SRI is essential for policy management — while it is not possible to eliminate all trade-offs, identifying them allows for the mitigation of losers.

1. Introduction

Rice is the most important crop worldwide. It is the staple food for 50–60% of the global population and its demand continues to grow (Carriger and Vallee, 2007; Mohanty, 2013; Stoop et al., 2009). Within India rice provides 31% of total calorie intake, and from 1961 to 2007, annual rice production increased by 3 times to over 140million (FAOSTAT, 2008; IRRI, 2011). Rice production also provides employment; for 1 bn people globally (Dawe, 2000), while in India agriculture employs 57% of India's workforce and accounts for around a fifth of GDP[1] (Lerche, 2011).

Rice likewise has a large physical and environmental footprint. Globally 157m hectares are used for growing rice, over 44million hectares of these in India (FAO, 2011). The environmental implications of widespread production, heavy agrochemical use and flooded production conditions are substantial water use and pollution (Bouman et al., 2007a; Wang et al., 2014), a high dependence on energy (Nelson et al., 2009), and substantial GHG emissions (Li et al., 2006).

The System of Rice Intensification (SRI) is a production system that has been widely promoted for its ability to offer substantial yield gains, reduce water use and GHG emissions and increase profitability. SRI is distinguished from conventional irrigated-rice production systems by a suite of 5 processes: (a) earlier transplanting (at the 2–3 leaf stage, typically less than 15 days old, compared to up to 30–45 days old); (b) only one plant per hill (in contrast to 3–5 plants); (c) hills laid out in a grid pattern with wide spacing; (d) emphasis on manure and other organic fertilisers; and (e) intermittent flooding and draining of

* Corresponding author.
E-mail address: alfred.gathorne-hardy@some.ox.ac.uk (A. Gathorne-Hardy).

[1] Agriculture declined from over 50% GDP at Independence (Planning Commission, 2008).

http://dx.doi.org/10.1016/j.agsy.2015.12.012
0308-521X/

the rice paddies rather than continuously flooded soils (Reddy and Venkatanarayana, 2013; Stoop et al., 2002; Uphoff, 2008). The reduction in flooded conditions changes both the composition and the quantity of weeds, and the grid planting allows weeds to be controlled using a mechanical weeder.

However, SRI remains a controversial technology, with questions remaining about the reliability of some yield and cost claims (Berkhout et al., 2015; Sumberg et al., 2013). Furthermore, the range of impacts investigated by individual studies tends to be narrow, with focus on either yield, profitability or water, and little attention given to either the wider social implications or the interactions between different kinds of impact. This paper explores key environmental, social wellbeing and economic sustainability issues associated with rice production: water and energy use, GHG emissions, economic return, labour demand the quality of employment. The list is not exhaustive, for example the social sustainability metrics focus on aspects of social equity more than societal stability and the environmental metrics. Through modelling primary data we then look at both the impact of SRI on these sustainability indicators, and manipulate the model to understand how the system could be changed to enhance synergies and reduce trade-offs between sustainability indicators.

1.1. The sustainability of rice: environmental aspects

1.1.1. Water

Rice is unique amongst major crops in that it can grow in flooded conditions. Irrigated (flooded) rice is responsible for most rice production worldwide, the 79million ha of irrigated lowland rice produces 75% of annual global output (IRRI, 2013). This rice has been estimated to use 34–43% of global irrigated water, or 24–30% of the total freshwater withdrawals (Bouman et al., 2007b). Water footprints of rice can vary from 1.5–7 t water kg rice^{-1} (Aldaya et al., 2010; Mekonnen and Hoekstra, 2014).

In India, rice irrigation is a key driver of India's chronic water shortage and falling water tables, and has been widely discussed in the literature (Nelson et al., 2009; Prasad and Nagarajan, 2004; Rodell et al., 2009; Shah, 2009; Toung and Bouman, 2003). The intermittent flooding of SRI has the potential to reduce water demand compared to conventionally irrigated rice (Gathorne-Hardy et al., 2013; Geethalakshmi et al., 2011; Suryavanshi et al., 2013).

1.1.2. Energy use

Agriculture has traditionally involved using stored solar energy to harvest further solar energy. This use of the sun as the sole source of energy made generating a positive energy return on investment (EROI) essential. Yet in the last hundred years fossil fuels have reduced the need for a positive EROI to the extent that some estimates suggest the United States food system requires 1.6 units of farm energy to produce 1 unit of food calories, and when the wider food system is included this ratio increases considerably, potentially up to 7:1 (Heller and Keoleian, 2000; Markussen and Østergård, 2013). Energy use is a broad indicator for wider sustainability (Schramski et al., 2013), and globally farm energy use is dominated by synthetic fertiliser production (especially nitrogen) and pesticides. In irrigated rice cultivation, however, the pumping of ground water often dominates energy use (Nelson et al., 2009). So far little research has specifically looked at the potential of SRI to reduce energy use, although the reduced reliance on water, synthetic fertilisers and pesticides would suggest an increased EROI.

1.1.3. Greenhouse gas emissions

Due to the dominance of fossil fuels in the energy mix, the energy demand for most industries is closely correlated with GHG emissions. Energy for irrigation alone represents 4–6% of India's total GHG emissions (Shah, 2009). Similarly, pesticides and fertilisers are both energy and thus GHG intensive in their production (Elsayed et al., 2003; Wood and Cowie, 2004).

However, in contrast to most industries, agricultural GHG emissions are dominated by soil based emissions, largely nitrous oxide (N_2O) in dryland agriculture and methane (CH_4) for rice. The flooded nature of irrigated rice produces an anaerobic soil environment, restricting the full oxidation of organic matter and resulting in the release of CH_4 rather than CO_2 (although up to 90% of methane may be oxidised before reaching the atmosphere) (Kögel-Knabner et al., 2010). While relatively short-lived compared to CO_2 (11 yrs) methane is a powerful GHG, so methane emissions typically dominate irrigated rice GHG production (Gathorne-Hardy, 2013; Li et al., 2006; Wang et al., 2010).

The anaerobic environment driving CH_4 emissions decreases N_2O emissions (N_2O is reduced to N_2), yet the GHG savings associated with reduced N_2O is more than compensated for by the high CH_4 emissions, so the GHG footprint of rice is typically about four times higher than that of wheat (Linquist et al., 2012).

1.2. The sustainability of rice: socio-economic aspects

1.2.1. Economic returns to farmers

Agricultural systems that consistently fail to provide positive economic returns for land managers cannot be deemed sustainable. In India farmers (cultivators) constitute approximately 10% of the entire population (Chandramouli, 2013) and poor economic returns — especially for the 85% who farm holdings smaller than 2 ha (GOI, 2014) — are resulting in alarming levels of poverty. A recent survey of over 8000 farmers found 10% of families had endured days with no food over the previous year (CIDS, 2014), and high levels of farm poverty is closely linked to agricultural debt, including debt-related farmer suicides (Mishra, 2006; Sainath, 2014).[2]

1.2.2. Drudgery or employment?

When social criteria are incorporated into Indian agricultural sustainability research they are commonly limited to the welfare of farmers (for example Noltze et al. (2013) and Senthilkumar et al. (2008)). Yet rural poverty is especially prevalent amongst landless labour — two thirds of whom are below the poverty line and who, for the first time in India, outnumber landed labour (Chandramouli, 2013; Harriss-White and Gooptu, 2009). Nonetheless, while sustainability analysis of any agricultural system should not ignore landless labour, the role of agriculture in providing employment is unclear; should displacement of agricultural labour be seen positively for reducing drudgery, or negatively for reducing employment? The role of agriculture in providing employment to reduce poverty is a complex and polarised debate (Biggs et al., 2011).

Poor people derive most of their income from work (Hull, 2009). While agriculture is reducing its dominance in India's rural employment (due to the MGNREGA[3] and growing off-farm sources of income (Carswell and De Neve, 2014; GoI, 2013)) it remains the prevailing employer in rural India (Harriss-White et al., 2004). Yet in order to evaluate the merits of agricultural employment, meaningful baselines or counterfactuals are necessary. But what is the counterfactual to an agricultural labourer's job — a better job, or no job?

One argument suggests that, with the exception of sanitary work, in much of India agricultural jobs are some of the 'worst' jobs in terms of physical conditions of work, employer–employee relationships and pay; in which case fewer agricultural jobs represent progress. But it can be counter-argued that there is a section of society who, for reasons of caste, religion, gender, and site (and the inter-section of these

[2] Recent research suggests that agricultural suicides are no higher than the wider rural population (Patel et al., 2012).

[3] The Mahatma Gandhi National Rural Employment Guarantee Act was designed as a social security measure and provides every rural household with the right to 100 day work a year and growing off-farm sources of income

identities), cannot escape rural labour markets or rural work. For these individuals, the counterfactual is no job, and any job is better than none.

For decades, both before and after formal liberalisation in 1991, the Indian government promoted labour-displacing technologies (for instance subsidies on tractors and milling equipment (Binswanger, 1985; Harriss, 1977a, 1977b)) — a practise carrying the assumption that the rural labour surplus will be absorbed by industry and services. Yet at present India's economic growth is characterised as jobless. For example 60% of growth between 1990–2005 was in services, a relatively small-employing sector compared with the manufacturing industry that has dominated China's growth (Corbridge et al., 2014). So the displacement of agricultural labour, well attested by the spreading negative labour elasticities of agriculture and the growing literature on migration (Sen, 2002) results instead in increased un- or under-employment in the informal economy.

Behind this paper therefore lies an assumption that must be made explicit: people stay in agricultural labour due to lack of alternative options, and more jobs are better than no jobs.

2. Methods

As yet no models have been developed to provide a multi-disciplinary understanding of rice production sustainability. To fill this gap we combined methodological approaches from different disciplines into a single model allowing the social, economic and environmental metrics to be measured at the same time. This permits the identification of trade-offs and synergies between different sustainability indicators. The model is based on a streamlined Life Cycle Assessment (LCA), following ISO standard 14040/14044 (ISO, 2006) and the International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010). To this we fused Value Chain Analysis (VCA) and social measures of employment quality and quantity.

2.1. Goal and scope definition

The goal of this study is to understand the sustainability of SRI production compared to the conventional, irrigated, intensive, 'green revolution' production methods (hereafter referred to as 'control'). We deploy an unusually broad understanding of sustainability, not confined to environmental but also including social and ecological measures, see Fig. 1 below. To this end we identified two functional units:

1 kg of (un-milled) rice at the farm gate.
1 ha of (un-milled) rice production over 1 season.

The second functional unit is needed for the land-based part of this research, where reducing some of social parameters, such as the provision of labour, to a dimensionless unit is inappropriate.

2.2. SRI

SRI has been described as an adaptable suite of principles rather than a set of prescribed fixed practises (Uphoff et al., 2011). Farmers self-identify as using SRI when applying subsets of the overall suite of SRI options, for example simply planting at a wider spacing — while continuously flooding and still transplanting multiple seedlings to a paddy-hill at later stages in development. During data collection, we ensured that all SRI farms followed key SRI principles (early transplanting of single plants/hill, aerobic soils and wide spacing between hills) and that the control farmers did not, see Table 1.

To achieve the goal defined above all relevant aspects of paddy production were included, alongside a set of social, economic and environmental metrics as shown in Fig. 1. Due to the modelled set up, it is possible to include imputed values — labelled 'derived metrics' in Fig. 1. The costs of carbon, electricity and the inclusion of opportunity costs for family labour (based on the local casual labour rate) were all included in later stages of analysis.

2.3. Allocation

When necessary, we used economic allocation to allocate between different co-products (European Commission, 2010). Details are given in Table 2.

2.4. Inventory analysis and data sources

Data collection took place in the Janagaon region of Warangal District, Andhra Pradesh, SE India, as part of a wider project, see: http://www.southasia.ox.ac.uk/resources-greenhouse-gases-technology-and-jobs-indias-informal-economy-case-rice. This is a semi-arid area with

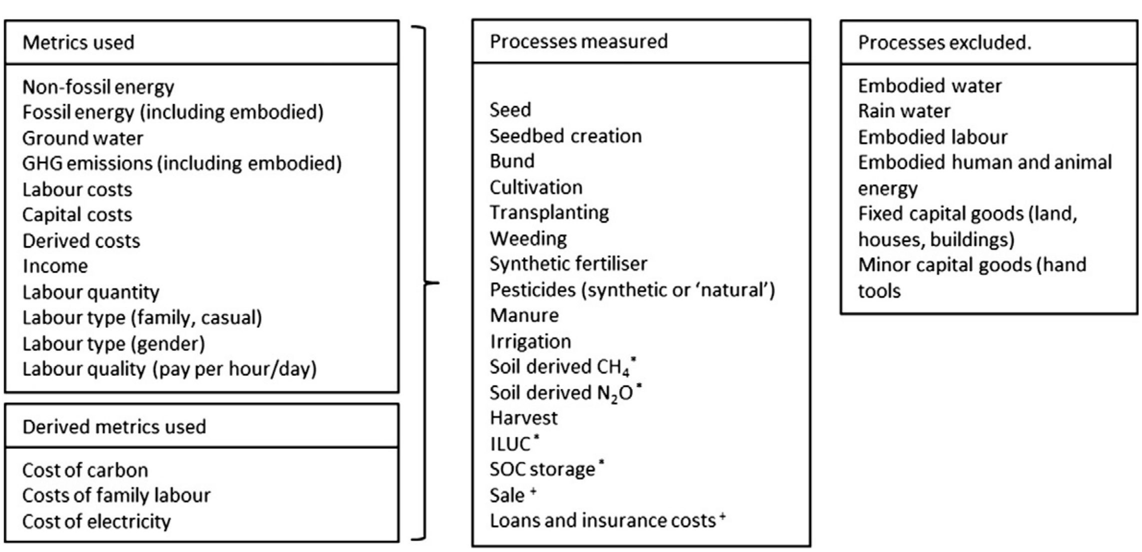

Fig. 1. System boundaries, and metrics used in analysis. Processes marked with an * have no labour and optionally no economic metrics associated with them. Those marked with an + have no social or environmental metrics associated with them.

Table 1
Agronomic practises of SRI and control farmers (S.E. in parentheses).

Agronomic practises	SRI	Control (conventional Green Revolution techniques)
Planting date (age of seedling, in days)	18 (1.1)	32.5 (1.7)*
Number of plants per hill	1.8 (0.2)	5 (0)**
Distance between hills (cm)	25 (0)	12 (0)**
Number of days irrigation (days/season)	71.8 (6.2)	118.8 (12.8)**
Quantity of manure (t ha^{-1})	18.7 (4)	17.0 (2)

* Asterisks indicate degree of significant difference between the farming systems; no asterisk = no significant difference * = $p < 0.05$, ** = $p < 0.01$ (S.E. shown in parentheses). Taken from Gathorne-Hardy et al. (2013).

average annual rainfall of 865 mm, concentrated in the SW monsoon season, with 624 mm falling from June to September (Anon. 2013). The altitude is approximately 380 m above sea level. Data was collected from 20 SRI and 10 'control' farmers using a recall survey for a single season, based on a 31 page questionnaire as described in Gathorne-Hardy et al. (2013). The control farms were ones using standard, intensive, flooded paddy production with 'Green Revolution' production methods. In both control and SRI surveys, individual farms were chosen using a semi-random snowballing technique, the semi-random aspect including the selection of farms ensured that the distribution of farm-sizes was representative of those in the Agricultural Census for the district. There proved to be no statistical differences between control and SRI farms in key socio-economic and environmental attributes (see Section 3.2). All farms were owner-occupied (reflecting tenure suggested by data in the Agricultural Census), and 53% of farmers rented in extra land. Climate variables were not considered due to the close and overlapping locations of the control and SRI farms. Soil types were consistent between SRI and non-SRI plots.

2.5. Water table

The water table is assumed to be 10 m in both cases. This marks a difference between this and a previous analysis (Gathorne-Hardy et al., 2013), which used the water table as described by the farmers. The advantage of using a constant figure is it reduces the difference between the farm systems; it allows easy manipulation to test the sensitivity of water table to the final result; and it allows easy comparisons between this and other areas. Energy and GHG emissions associated with irrigation have been fixed for a 10 m water table.

While agricultural research is ideally based around experimental techniques (Berkhout et al., 2015; Cassman, 2007) such an approach was not practical for this research due to the range of socio-economic indicators that have to be included. Socio-ecological systems of this complexity cannot be effectively controlled. Instead the 'control' farms are all from the same area, so that the socio-economic environment (i.e. gender roles, the labour pool) and biophysical environment are held constant.

A full list of assumptions and data sources is found in Table 2.

2.6. Ground water use

Ground water use was calculated using the size of motor(s), the length of time they were working, the depth of the water table and an assumption of motor efficiency (Nelson et al., 2009). All farms used only ground water for irrigation.

2.7. Fossil energy return on investment

We use a generalised EROI methodology in line with other energy food studies ((Pimentel and Pimentel, 1983; Schramski et al., 2013; Schramski et al., 2011), however we are restricting energy inputs analytically to fossil energy. We include both direct and indirect (embodied) and energy, and ignore insolation (solar energy) on the basis that all food will be eaten and/or otherwise decay into thermal energy. Our EROI calculations therefore ignore any sequestered soil carbon and instead assume that all soil carbon is eventually oxidised, releasing energy as long wave radiation.

2.8. Analysis

Analysis was carried out using a LCA model built in Excel, and statistics were tested with SPSS software.

A macro was written in Excel to test the elasticity and sensitivity of input values of the model. The elasticity of a result with respect to an input parameter is defined as the ratio of the percentage change of the result to the percentage change in the parameter (Slade, 2009).

2.9. Costs and labour requirements

Each task in the rice production chain (see Fig. 1) was discussed individually with the farmer. The total costs, the total number of hours, and hours per day, were recorded, including the gender and the labour status of the workers: casual or family labour. No surveyed farms had attached labour. The rate of pay (per day or piece rate depending on payment method) was also recorded. All data could then be converted into labour hours per hectare, and minutes per kg of rice.

2.10. The quality of work

The terms and conditions of work — its 'qualities' — are long established as measurable in many ways. However, intensive research by the International Labour Organisation (ILO, 1999), and the EU (Lorano, 2005), suggest such an extremely large set of criteria — 125 variables in the case of the ILO's Decent Work — such that their conceptual refinements are un-implementable and thus irrelevant for most practical research. A reductionist alternative, confined to income and the economic value of benefits in kind, while missing the holistic aspiration of Decent Work as an analytical tool, has the benefit of collectability and can be scaled so that it can be compared and contrasted across different occupations. Here, we are forced to use income as a proxy for the quality of work. Rates of pay per hour were determined for each task, and for both male and female employment for each job.[4]

3. Discussion and results

3.1. Environmental metrics

Perhaps the most important difference between SRI rice production systems and the intensive 'control' is the substantial increase in SRI yield (from 4.8 to 7.6 t ha^{-1}) (Gathorne-Hardy et al., 2013). Higher yields result in lower area based impacts when yield scaled, reduces pressure on land elsewhere and helps increase food security (Dumortier et al., 2011). Previous papers have noted significant yield gains associated with SRI ((Geethalakshmi et al., 2011; Roy and Bisht, 2012; Sinha and Talati, 2007), but Berkhout et al. (2015) suggest that a number of these fail to take account of differences in plot-level soil fertility or unobserved farmer and farm characteristics. Within this study a split-plot design was not appropriate, but there is no reason to suspect differences in background soil fertility between SRI and control sites. It is possible to calculate the human labour input to the different production processes (see below), but the quality of effort and other unobserved farmer characteristics is impractical to measure. However, if a portion of SRI yield gain should be ascribed to an inherent attention-

[4] A fuller picture of work quality in the Indian food system using a small subset of the 125 ILO variables selected on grounds of their relevance to worker mobilisation is being produced concurrently (Mody et al., 2013).

Table 2
The assumptions, data, methods and data sources used in this study.

Description	Figure	Source/comment
Diesel use (l/km)	Dependent upon lorry type, age.	Survey data
GHG and energy emissions of diesel use ($kg\ CO_2$ eq/l MJ/l)	3.0168	Renewable energy directive Directive 2009/28/EC (2009)
Energy emissions of diesel use (MJ/l)	43.71	Renewable energy directive Directive 2009/28/EC (2009)
Embodied energy of steel (MJ/kg)	36	Gumaste (2006)
Lorry maximum age (yrs)	20	Assumed. In reality we never found a lorry owner who had sold a vehicle for scrap so this is likely to be an underestimate. However, as the embodied energy and GHG emissions if <0.1% of transport emissions this will have an inconsequential impact
Embodied GHG of steel ($kg\ CO_2$-eq/kg steel)	2.7	CSE (2012)
Tractor composition	Assumed to be 100% steel	
Tractor weight (kg)	1952.5	John Deere (2012), Mahindra (2012)
Emissions ($kg\ CO_2$-eq/kg steel)	2.4	CSE (2012)
Tractor diesel use (l/h)	4	Response from interviews (interviews rather than tractor specifications for actual rather than factory engine efficiency)
GHG intensity diesel ($kg\ CO_2$ eq/l)	3.0168	EU (2009)
Emission factor for indigenous working bullock ($kg\ CO_2$ eq/animal/yr)	823.5	Singh et al. (2002)
Emissions factor for indigenous cows milking ($kg\ CO_2$ eq/animal/yr)	899.25	Singh et al. (2002)
Manure emission factor	50	IPCC (2006)
Life expectancy of bullock	18 yrs	Farmer response
Allocation of the adults' emissions to manure (compared to milk and carcass value).	6%	Economic allocation was used. Manure was ascribed the percentage of value associated with macro-nutrients compared to other major value streams (Milk and meat). Milk and meat values were gathered from respondents. NPK value of manure was taken from Tennakoon and Hemamala Bandara (2003) manure nutrient values, multiplied by market values for NPK from respondents.
Speed of livestock pulling manure (km/h)	3.4	From respondents
Bullock cart load of FYM (kg)	223	From respondents
Nutrient content of manure (kg t dry matter)	N – 12 P – 5 K – 14.5	Tennakoon and Hemamala Bandara (2003)
GHG density of pesticides ($kg\ CO_2$ eq/kg ai)	4.921	Elsayed et al. (2003)
Energy density of pesticides (MJ/kg ai)	102	Elsayed et al. (2003)
DAP production emissions ($kg\ CO_2$ eq/kg active product (N and P))	1.38	Wood and Cowie (2004)
Urea production emissions ($kg\ CO_2$ eq/kg Urea-N)	0.7	Centre for Science and Environment (2009)
Transport GHG emissions (assumed 4000 km) ($kg\ CO_2$ eq/kg Urea-N)	0.23	From main project transport data analysis
Storage of soil organic carbon on paddy field from manure		Calculated using tier II methods from the IPCC (2006)
Assumed water table	10 m	
Manure economic emissions allocation		
Energy for 1 h of male labour	0.27 MJ ha^{-1}	Canakci et al. (2005)
Energy for 1 h female labour	0.216 MJ ha^{-1}	Canakci et al. (2005)
Energy for 1 h pair of bullocks	2.7 MJ ha^{-1}	Canakci et al. (2005)
Nitrogen use efficiency	n/a	This study defined NUE as the recovery efficiency of applied N in harvested above ground biomass. For this we assumed the nitrogen content of paddy to be 1.39%, and of rice straw 0.65% Dobermann and Fairhurst (2002)
Carbon price (Rs/kg CO_2)	0.736	Taken from Certified Emission Certificate prices in June 2010, before the big crash (€12.87) and exchange rate June 2010 (€1 = Rs 57.16).
Simulated price for irrigation electricity (INR $unit^{-1}$)	4.7	Mean price paid by large scale electricity users in the wider study (mill users in TN)
Family labour (INR)	n/a	Family labour is costed at gender specific casual labour rates

demanding nature of SRI (of which we have no evidence), there is no reason why this should not be legitimately ascribed to SRI.

Most green revolution cereal yield gains are associated with increases in the harvest index (the proportion of grain to total above ground biomass) and reductions in nutrient or disease stress (Islam et al., 2010; Khush, 2001). By contrast the macro nutrient (NPK) input is significantly lower for SRI production, see Table 3, demonstrating an apparent increase in nutrient use efficiency (NUE) from 16 to 33% ($p < 0.01$). Yet it is possible that the aerobic nature of SRI soils could be releasing nutrients through oxidising the organic matter sequestered during previous flooded paddy regimes. If this is the case, SRI would not be as nutrient efficient as Table 3 suggests. In addition to synthetic fertilisers, pesticide use also fell with SRI, although the difference was not significant.

The SRI practise of intermittently rather than continuously flooding reduces ground water demand by 1.5 and 2.5 times per hectare and per kg respectively ($p < 0.01$ for both) (Gathorne-Hardy et al., 2013). This is in line with other SRI water research (Adusumilli and Bhagya Laxmi, 2011). Associated with this reduction in water demand, SRI requires substantially lower fossil energy input (the major component of fossil energy from this study is in electricity used in irrigation) and has a corresponding higher fossil EROI, >3 times that of the control ($p < 0.01$), see Table 4.

The standardisation of water tables to 10 m has reduced the difference between SRI and control GHG emissions so that the difference is not significant per hectare, in contrast to Gathorne-Hardy et al. (2013). However, the higher yield of SRI reduces GHG emissions to 60% of control per kg of paddy ($p < 0.01$) see Table 4. Due to the

Table 3
Nutrient inputs and water table for SRI and control farms.

Farming system	Synthetic N (kg N ha^{-1})	Quantity of manure (t ha^{-1})	Total N (kg N)	N used by crop (kg ha^{-1})	NUE (kg N utilised kg^{-1} N applied)	Total synthetic K (kg ha^{-1})	Total synthetic P (kg ha^{-1})	Quantity of pesticide (kg ai ha^{-1})
SRI	157**	18.2	377	129	33%**	80*	166**	2.9
	(36)	(2)	(34)	(5)	(0.0%)	(18)	(38)	(0.9)
Control	226	16.7	427	80	16%	111	250	3.0
	(17)	(2)	(37)	(4)	(1.4%)	(18)	(25)	(1.3)

* Asterisks indicate degree of significant difference between the farming systems; no asterisk = no significant difference, * = $p < 0.05$, ** = $p < 0.01$. (S.E. shown in parentheses). Including data presented in Gathorne-Hardy et al. (2013).

importance of irrigation in GHG emissions and energy use, the GHG benefits of SRI are positively correlated with the depth of the water table — as the water table shifts from 10 m to 20 m for example, the GHG emissions increase by 15% and 26% for SRI and control kg rice^{-1}, and 15% and 25% for SRI and control ha^{-1} respectively. This linking of the water-table to energy and GHG emissions shows a potential virtuous relationship; if more farmers switch to SRI more rice will be produced with lower GHG emissions, and the lower H_2O demand will raise the water table, further reducing GHG emissions and energy use.

However, with the exception of yield and agrochemical inputs these gains are positive externalities and as such largely irrelevant to the farmer. Electricity for irrigation is free, no charges exist for water and there is no market for GHG emissions. Internalising externalities is a commonly proposed solution for environmental problems. The implications of doing this are explored below.

3.2. Social metrics

3.2.1. Costs and returns

Total costs ha^{-1} are significantly lower for SRI compared to control farms ($p < 0.01$), see Table 5. The three largest and significant cost differences, in decreasing order, are: weeding, transplanting and synthetic fertilisers. Each of these is associated with a difference in practise between SRI and conventional production — SRI production uses a mechanical weeder, SRI transplanting is done in a marked grid using younger seedlings and SRI emphasises manure rather than synthetic fertilisers. The reduction in weeding costs is in contrast to some SRI studies, where costs increase due to the increased use of more expensive male labour (Moser and Barrett, 2006; Senthilkumar et al., 2008). An increase in male labour for SRI was also found in this project, yet the impact on costs was traded-off against a reduction in female employment, as discussed under 'Employment Quantity' below. SRI transplanting is more commonly recognised as a labour-saving change in technique (Reddy and Venkatanarayana, 2013), and the SRI transplanting cost savings are entirely due to the reduction in labour requirements. Interestingly the cost savings associated with reduced fertiliser use by SRI are not mirrored by an increase in SRI manure costs — there is no difference between manure application rates between the SRI sample and the controls. There are no operations where the SRI methods prove significantly more expensive than those of the control.

The difference in costs is amplified on a per kg basis due to the higher SRI yields. By way of contrast, there is no difference in income between SRI and the control cultivation method on a per kg basis as both samples sold to the same market. The combination of lower costs and an identical market results in dramatically higher net returns for SRI farms — greater than four times higher per hectare ($p < 0.01$).

However this increase in net returns does not include family labour, which when included in other SRI studies reduces the difference in net income to being non-significant (Takahashi and Barrett, 2014). If family labour is costed in this study (at casual labour rates) then costs significantly change, but the pattern of advantage between SRI and control samples remains constant. The costs for both systems increase by approximately 45%, making control production a loss-making enterprise on both a hectare and per kg basis. In contrast, even including family labour the net returns after costs for SRI remain highly positive and above those of the control sample when family labour is not included, see Table 9.

The data presented here demonstrates that SRI provides substantial gains to the farmer, largely through increasing yields compared to costs. However, there is a risk that SRI becomes another "technology treadmill". Assuming a relatively inelastic demand and widespread adoption of SRI the higher yield could reduce the price of rice. If this occurs the higher profits associated with increased production would only be available to early SRI adopters, with long term gains captured as a consumer rather than producer surplus (Barrett et al., 2010).

3.2.2. Employment quantity

The increase in labour intensity associated with SRI has been reported to limit SRI uptake (Berkhout et al., 2015; Stoop et al., 2002). Yet the empirical data from our research shows SRI reduces overall labour demand per hectare ($p < 0.01$), see Table 6. Accordingly when examining labour as a measure of efficiency, SRI has substantially superior efficiency — increasing labour-productivity by a factor of 2.4 compared to control ($p < 0.01$) to 9 kg paddy h^{-1}.

The social benefit of labour results from its provision of poverty-reducing employment for those who would otherwise remain unemployed. Consequently the total quantity of labour is less important than the quantity of employed labour.

The reduction in overall labour requirements is largely driven by a reduction in employed labour (down to 45% of control); there is no difference in family labour demand between the SRI and control systems. This shift is entirely due to a reduction in female employment — down from 702 h ha^{-1} to 257 h ha^{-1} ($p < 0.001$). There is no significant shift in male employed labour. So while SRI increases returns to the farmer by over three times per hectare, SRI reduces employment to the most marginal members of society (female landless labourers). Sixteen percent of farmers recorded agricultural work when asked about economic activity other than farming, so some farmers could be acting as labour on neighbouring farms.

Table 4
Farm details, GHG emissions, yield, and water use from SRI and control farms.

Farming system	Yield (kg ha^{-1})	Number of farms	Farm size (ha)	GHG emissions (CO_2-eq ha^{-1})	GHG emissions (kg CO_2-eq kg paddy^{-1})	Water use (t ha^{-1})	Water use (t kg paddy^{-1})	Fossil energy use per hectare	Fossil EROI
SRI	7609*** (304)	20	1.23 (0.62)	9461 (613)	1.3** (0.10)	16,049* (3682)	2.05** (0.47)	16,713** (538)	6.8** (0.34)
Control	4834 (197)	10	1.11 (0.33)	9765 (595)	2.8 (0.17)	24,980 (3274)	4.90 (0.46)	38,752 (3545)	1.9 (0.15)

* Asterisks indicate degree of significant difference between the farming systems; no asterisk = no significant difference, * = $p < 0.05$, ** = $p < 0.01$ (S.E. shown in parentheses).

Table 5
Costs, income and return after costs for SRI and control farms over a hectare and per kg paddy. Figures in parentheses represent 1SE.

	Costs (INR ha^{-1})	Income (INR ha^{-1})	Return after costs (INR ha^{-1})	Costs (INR kg^{-1})	Income (INR kg^{-1})	Return after costs (INR kg^{-1})
SRI	38,265**	110,386**	71,991**	5.1**	14.1	9.0***
	(1791)	(4456)	(5512)	(0.4)	(0.1)	(0.4)
Control	48,996	66,266	17,270	10.6	13.7	3.1
	(4064)	(3458)	(6440)	(1.3)	(0.2)	(1.3)

*Asterisks indicate degree of significant difference between the farming systems; no asterisk = no significant difference, * = p 0. 0.05, ** = p 0.01.

Within the production process, the reduction in labour demand for SRI is dominated by weeding and transplanting, the two most labour-intensive operations in most rice systems (except when harvest occurs by hand — not relevant here). For weeding and transplanting, SRI requires only 63% and 55% of the labour required by the control methods respectively per hectare ($p < 0.01$ for both), see Table 7 and Table 8. Other studies have shown a cost penalty associated with increased male labour demand for weeding (Moser and Barrett, 2006; Senthilkumar et al., 2008). While there is indeed a large increase in male labour demand for SRI weeding (more than nine times more h ha^{-1}($p < 0.01$)), this increase is dominated by family labour, and the cost increase from male wage labour is more than compensated for by a decrease in overall female labour, (including an *increase* in family female labour ($p < 0.01$)) with female wage-labour declining from almost 400 h ha^{-1} to less than 100 ($p < 0.01$). Our data does not explain whether this increase in family labour for weeding is due to the unwillingness of the traditional labour-pool to weed in a new manner (so potentially forcing a reallocation of family labour from off- to on-farm), or alternatively whether the different weeding methods associated with SRI make it more attractive to family labour.

This pattern of increased family labour within an overall decrease in labour (dominated by the reduction in employed casual labour) was not repeated for transplanting, where the only significant change was a reduction in female casual labour ($p < 0.01$), see Table 7.

While we have measured the total labour requirements, this work does not detail the intensity or timeliness of labour requirements. SRI requires more precise and management-intensive labour. For example there is considerably less flexibility on transplanting dates, and more management effort may be required to maintain aerobic but moist, rather than fully flooded, soils.

3.2.3. Employment quality

Using the rate of pay as a proxy measure, there was no difference in employment quality between the two production methods. For both systems men were always paid INR200 day^{-1} and women INR150 day^{-1}. There was a small difference in the day length between genders with men working on average a 30 min longer day, but the difference was not significant ($p > 0.05$).

The control sample provided an average of INR15,161 of remuneration to labour per hectare, compared to INR7503 ha^{-1} for the average SRI farm — a reduction of over 50%. This is particularly affected by a reduction in female labour, and so in turn could have a disproportionate impact on household sustainability, as, compared to men, women are reported to use more of their income for the benefit of the household (María et al., 2013).

3.3. Interactive elements

3.3.1. Social factors

SRI provides substantially higher economic returns compared to the control production methods. SRI also provides wider societal benefits (reduced electricity and water use, as well as reduced agro-chemical use and GHG emissions). But these gains are at the expense of local employment, SRI reduces the quantity of pay to the local landless labour market. The adoption of improved agricultural technologies is essential for rural development (Barrett et al., 2010), and unless they generate unambiguous damage it is impractical to legislate against the uptake of novel and profitable practises; especially those that result in substantial positive externalities. A theoretical alternative would be for farmers to increase the rate of casual labour pay.

Modelling the impact of increasing rates of pay shows that this option has surprisingly little impact on farmer returns. Increasing the pay rates by 50% increases total costs by only 10%, reduces net returns by only 5%, and still provides significantly higher returns than the control sample without a pay increase, see Table 8 ($p < 0.01$). Pay to labour has to increase by over 100% before parity in remuneration to casual labour is achieved. Interestingly, even with this large increase in pay, the net return for SRI declines by just 10%, and remains 3.7 times that of the control farms *without pay increase*.

The relatively small effect is due to the high proportion of costs covered by cultivation, fertilisers and harvest, where in all cases labour represents a small fraction of total costs.

While this simulates a theoretical mechanism for redistributing some of the socio-economic gains of SRI at present captured by the farmer, there is unfortunately little reason to think that this would occur on the ground. In contrast the opposite may occur due to the positive relationship between labour supply and wages. As labour demand falls the rates of pay that farmers have to offer also decreases (Dasgupta and Goldar, 2006). If this occurred the negative social trade-off could be substantially higher then what is portrayed here.

3.3.2. Internalising environmental externalities

Some farmers comment that they would prefer to pay for reliable electricity than suffer the existing subsidised yet low quality electricity supply. With this in mind, we modelled how charges for electricity would affect farm costs, at INR4.7 $unit^{-1}$. Charging for electricity at this rate dramatically affects farm profitability — especially for control farmers where electricity use is higher — to the extent that control farm returns become negative, assuming all other costs remain constant, see Table 9.

Table 6
Labour demand from control and SRI farms (figures in parentheses represent 1SE).

	Total Labour demand (hrs ha^{-1})	Total employed labour (hrs ha^{-1})	% female labour	% female labour employed	% male labour employed	Daily wage (M) (100Rs)	Daily wage (F) (100Rs)	Labour (min/kg)	Labour productivity (kg paddy per labour hour)
Control	1355**	788**	72.8**	71.9**	24.1	200	150	17.5**	3.8**
	(84)	(38)	(1.3)	(2.1)	(2.9)	(0)	(0)	(1.6)	(0.4)
SRI	954	353	54.8	48.9	23.4	200	150	7.5	8.9
	(65)	(28)	(1.3)	(3.0)	(3.1)	(0)	(0)	(0.7)	(0.6)

* Asterisks indicate degree of significant difference between the farming systems; no asterisk = no significant difference * = $p < 0.05$, ** = $p < 0.01$.

Table 7
Hours of labour per hectare for weeding and transplanting according to gender and family.

		Family M	Family F	Employed M	Employed F	Total
Weeding	SRI	89**	89**	18	96*	292*
	Control	28	38	3	399	468
Transplanting	SRI	33	32	5	104*	173*
	Control	27	35	2	251	314

*Asterisks indicate degree of significant difference between the farming systems; no asterisk = no significant difference, * = $p < 0.05$, ** = $p < 0.01$.

Table 8
Impact of changing casual labour rate of pay on total remuneration and returns after profit, per hectare.

	Local remuneration (INR ha^{-1})	Return after costs (INR ha^{-1})
Control pay ha^{-1}	15,161	17,270
	(1200)	(6440)
SRI pay	7503	72,122
	(792)	(5477)
	11,254	68,370
SRI pay increase of 50%	(1188)	(5550)
SRI pay increase of 100%	15,005	64,619
	(1583)	(5649)

Farmers are receiving a massive subsidy (effectively a INR22,486 ha^{-1} paddy $season^{-1}$ subsidy for electricity alone assuming INR4.7 $unit^{-1}$). While Table 9 shows this as an economic cost, the limited supply of electricity in much of rural India means that electricity use is a zero sum game — excessive use by farmers is directly reducing access by others to potentially critical factors for sustainable development including lighting, computing and refrigeration. Yet while there is a clear need to reduce the overuse of electricity – and SRI could provide one such pathway – the charging for electricity is unlikely to be immediately possible. At politically acceptable rates it may cost more to collect than to deliver (although any reduction in use would still be environmentally beneficial). Alternative routes to reducing electricity use are showing success in Gujarat including providing separate agricultural to non-agricultural electricity combined with strict control of when electricity would be available, see Shah et al. (2008).

Including a very modest carbon price (INR0.736 kg CO_2-eq) reduces the returns to farmers by 9% and 59% for SRI and control farmers respectively ($p < 0.001$) (see Table 9). If such a charging system were put in place, this would further drive a shift towards SRI, but due to the lack of obvious local beneficiaries from reducing GHG emissions – in contrast to reduced electricity use – it is arguable that local policies to price carbon are unlikely, and alternative local methods such as described by Shah et al. (2008) for water are equally unlikely.

However, the corollary is that the very global nature of GHG impacts which makes their costs hard to internalise locally can provide access to new global carbon offsetting markets, for example the payments for non-flooded rice production suggested by the Environmental Defence Fund (Environmental Defence Fund, 2015).

3.3.3. The impact of increasing the farm gate price

Farmer poverty is often blamed on low farm gate prices. The minimum support price (MSP) has been in place for almost half a century, and is designed to provide assistance to farmers through putting a floor to the agricultural market price post-harvest. The MSP is responsible for a range of unintended consequences including creating an imbalance in supply and demand of several important products, for example a shift from oils and pulses to wheat and rice (Chand, 2003) and for decades its continuation has been debated (Ali et al., 2012). However, at present it remains an important mechanism for controlling the farm gate price in many states. Table 9 shows that increasing the farm-gate price for rice (through the MSP or alternative methods) by 10% increases the returns by 38% and 15% for control and SRI respectively. This is a dramatic increase for control farmers, but from a lower base, so a price increase of over 180% is required before the control return matches that of un-manipulated SRI returns. So interestingly, while the farm gate price is critical, its importance is marginal compared to the choice of rice cultivation methods.

3.4. A paradox — why is SRI not more widespread?

SRI offers benefits to the local and global environment and to food security, as well as to farm returns. Yet if the local economic benefits are as great as this research suggests, why has SRI not spread further and faster throughout India already? This could be due the different sets of skills that workers may be unfamiliar with/dislike (for example the use of mechanical weeders, the 'fiddly' nature of transplanting individual plants) (Reddy and Venkatanarayana, 2013). Alternatively there could be a risk aversion concerned with the less flexibly aspects of SRI, especially the need to transplant within a smaller time-window that combined with increasingly erratic monsoons can potentially devastate an entire crop. Interestingly Andhra Pradesh is having less success in SRI coverage compared with Tamil Nadu where a financial subsidy for SRI is offered (INR4000 ha^{-1}). It is possible that the guaranteed income associated with a subsidy is more heavily weighted in decision-making than is the potential income from gains in yield.

The provision of carbon offsets for SRI production systems has also been suggested (Environmental Defence Fund, 2015), which could mimic the Tamil Nadu subsidy. Assuming a payment of INR4000 ha^{-1} this would equate to 0.6 t CO_2-eq 1000 INR^{-1} (calculated as the area based emissions saved due to yield gain). However, the validity of such offsetting schemes is difficult to guarantee as the high returns

Table 9
Costs, income and return after costs under different scenarios. All figures are in Indian Rupees.

	Basecase		Including family labour		Charging for electricity (INR4.7 $unit^{-1}$)		Including a carbon price		Increased farm gate price for paddy by 10%	
	SRI	Control	SRI	Control	SRI	Control	SRI	Control	SRI	Control
Costs (ha^{-1})	38,265	48,996	60,626	91,013	44,116	71,482	44,639	59,156	38,265	48,996
	(1791)	(4064)	(2694)	(3804)	(1775)	(3605)	(1857)	(4043)	(1791)	(4064)
Income (ha^{-1})	110,386	66,266	110,386	66,266	110,386	66,266	110,386	66,266	121,425	72,892
	(4456)	(3458)	(4456)	(3458)	(4456)	(3458)	(4456)	(3458)	(4902)	(3804)
Return after costs (ha^{-1})	72,122	17,270	49,760	−24,747	66,270	−5217	65,747	7,110	83,160	23,896
	(5,477)	(6440)	(5,753)	(6,473)	(5,344)	(5,349)	(5,491)	(6,367)	(5,904)	(6,730)
Costs (kg^{-1})	5.1	10.6	8.0	19.5	5.9	15.2	5.9	12.8	5.1	10.6
	(0.4)	(1.3)	(0.5)	(1.8)	(0.4)	(1.4)	(0.4)	(1.4)	(0.4)	(1.3)
Income (kg^{-1})	14.1	13.7	14.1	13.7	14.1	13.7	14.1	13.7	15.5	15.1
	(0.1)	(0.2)	(0.1)	(0.2)	(0.1)	(0.2)	(0.1)	(0.2)	(0.1)	(0.2)
Return after costs (kg^{-1})	9.0	3.1	6.1	−5.8	8.2	−1.5	8.2	1.0	10.4	4.5
	(0.4)	(1.3)	(0.6)	(1.8)	(0.4)	(1.4)	(0.4)	(1.4)	(0.4)	(1.3)

associated with SRI make the demonstration of additionality difficult to prove.

Alternatively, a subsidised insurance scheme could provide farmers that switch to SRI with a low risk/high reward farming system, saving a large quantity of carbon at a relatively low price with wider societal environmental gains, although at the expense of labour.

3.5. Limitations of this approach

Several of the results described in this paper are dimensionless and static. Dimensionless results are insensitive to location or time while in reality the relative importance of specific issues will vary according to geography and season. For example SRI uses considerably less water than control, but while water is scarce in much of semi-arid India, there are places and seasons when the key concern is tolerance to flooding. Similarly, the demand for labour varies considerable between locations and seasons, so while in some areas/seasons the lower employment associated with SRI could be a crisis, in others it could allow rice production to continue.

The static nature of these results restricts the ability to model feedbacks. It is possible that if SRI spread then the increased production of rice would free up land for more labour demanding crops, or that the price of rice will fall dramatically substantially reducing poverty.

And finally, while this project was ambitious in scope there remains the potential for major trade-offs against unmeasured metrics.

4. Conclusions

Rice is a key Indian crop but carries a range of important sustainability burdens, including excessive water and energy use, high GHG emissions and poor social and economic returns to farmers and labourers. This research has demonstrated that SRI production systems offer substantial environmental benefits – reducing water and energy use by 60% and 74% per kg respectively, reducing GHG emissions by 40% per kg, reducing reliance on nutrient inputs – as well as improving farmer returns by over 400% through increasing yields while reducing costs.

However these benefits come at the expense of employment, which is reduced to 45% of the control employed labour hours per hectare. Until there are sufficient alternative sources of employment, this is an important social sustainability trade-off against the environmental and farm return benefits of SRI.

The model demonstrates that the reduced remuneration to landless labour from lower labour demand can be mitigated by increasing pay with minimal impact for the farmer. If rates of pay are doubled the total remuneration to landless labour will remain the same per hectare as in control production systems, and the net economic return to the farmer remains over three times greater for SRI than control farms per hectare. In reality, though, the reduced demand for employment may result in the opposite. Rather than paying labour more, the reduced demand for labour can weaken the labours' negotiating power, potentially resulting in lower wages. Consequently if SRI sweeps across large areas of rural India it could potentially lead to reduced pay and increased unemployment.

Internalising the cost of electricity increases costs for both sets of farmers, but significantly more for control farms due to higher electricity use, reducing their return to negative. A modest carbon price again impacts the economic return of control farmers more than SRI. Modelling an increase in the farm gate price of 10% increases control farm returns by 38% ha^{-1}, but these returns remain less than a third of the SRI farms' returns *without* a farm gate price increase. This demonstrates that switching to SRI is substantially more effective at increasing farmer profits than increasing farm gate prices; farm gate prices have to increase by 180% before control farms are as profitable as SRI.

This research highlights the importance of multidisciplinary sustainability research, as the sustainability analysis of SRI is contrasting when approached from the environmental compared to the labourist perspectives. While identification of trade-offs is only the first step, without it no policies can be put in place to mitigate negative trade-offs.

Acknowledgements

The authors wish to express their gratitude to the helpful comments from two anonymous reviewers.

With thanks to the ESRC/Dfid Joint Scheme award RES-167-25-MTRUYG0; ES/1033768/1 for funding. The views expressed are those of the authors.

References

Adusumilli, R., Bhagya Laxmi, S., 2011. Potential of the system of rice intensification for systemic improvement in rice production and water use: the case of Andhra Pradesh, India. Paddy Water Environ. 9, 89–97.
Aldaya, M., Muñoz, G., Hoekstra, A., 2010. Water Footprint of Cotton, Wheat and Rice Production in Central Asia.
Ali, S.Z., Sidhu, R., Vatta, K., 2012. Effectiveness of Minimum Support Price Policy for Paddy in India with a Case Study of Punjab. Agric. Econ. Res. Rev. 25, 231–242.
Anonymous, 2013. Climate, AP Climate. Directorate of Economics and Statistics. http://www.ap.gov.in/Other%20Docs/CLIMATE.pdf.
Barrett, C.B., Carter, M.R., Timmer, C.P., 2010. A century-long perspective on agricultural development. Am. J. Agric. Econ. 92, 447–468.
Berkhout, E., Glover, D., Kuyvenhoven, A., 2015. On-farm impact of the System of Rice Intensification (SRI): evidence and knowledge gaps. Agric. Syst. 132, 157–166.
Biggs, S., Justice, S., Lewis, D., 2011. Patterns of rural mechanisation, energy and employment in South Asia: reopening the debate. Econ. Polit. Wkly. 46, 79.
Binswanger, H.P., 1985. Agricultural Mechanization: A Comparative Historical Perspective. World Bank Research Observer. World Bank, Washington, DC, USA.
Bouman, B.A.M., Humphreys, E., Tuong, T.P., Barker, R., 2007a. Rice and Water. In: Donald, L.S. (Ed.), Advances in Agronomy. Academic Press, pp. 187–237.
Bouman, B.A.M., Lampayan, R.M., Tuong, T.P., 2007b. Water Management in Irrigated Rice: Coping With Water Scarcity, Los Baños (Philippines).
Canakci, M., Topakci, M., Akinci, I., Ozmerzi, A., 2005. Energy use pattern of some field crops and vegetable production: case study for Antalya Region, Turkey. Energy Convers. Manag. 46, 655–666.
Carriger, S., Vallee, D., 2007. More crop per drop. Rice Today 6, 10–13.
Carswell, G., De Neve, G., 2014. MGNREGA in Tamil Nadu: a story of success and transformation? J. Agrar. Chang. 14, 564–585.
Cassman, K.G., 2007. Editorial response by Kenneth Cassman: can organic agriculture feed the world-science to the rescue? Renew. Agric. Food Syst. 22, 83–84.
Centre for Science and Environment, 2009. Green rating project, fertilizers. http://www.cseindia.org/userfiles/79-90%20Fertilizer%281%29.pdf (New Delhi).
Chand, R., 2003. Minimum support price in agriculture: changing requirements. Econ. Polit. Wkly. 3027–3028.
Chandramouli, D.C., 2013. Census of India 2011 release of primary census abstracts and data highlights. censusindia.gov.in/…/PRIMARY%20CENSUS%20ABSTRACT_Final.ppt.
CIDS, 2014. State of Indian Farmers: A Report Centre for the Study of Developing Societies.
Corbridge, S., Harriss, J., Jeffrey, C., 2014. 'Lopsided', 'Failed', or 'Tortuous': India's problematic transition and its implications for labour. In: Davin, D., Harriss-White, B. (Eds.), China–India: Paths of Economic and Social Development. Published for The British Academy by Oxford University Press, Oxford.
CSE, 2012. In: CSE (Ed.), Into the Furnace. Green Rating Project of Indian Iron and Steel Sector. CSE, Delhi, India, p. 256.
Dasgupta, P., Goldar, B., 2006. Female Labour Supply in Rural India: An Econometric Analysis. Ind. J. Labour Econ. 49, 293–310.
Dawe, D., 2000. The contribution of rice research to poverty alleviation. In: J.E. Sheehy, P.L.M., Hardy, B. (Eds.), Studies in Plant Science. Elsevier, pp. 3–12.
Directive 2009/28/EC., (2009) On the Promotion of the Use of Energy From Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC, in: Union, O.J.o.t.E., (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=Oj:L:2009:140:0016:0062:en:PDF).
Dobermann, A., Fairhurst, T.H., 2002. Rice straw management. Better Crops International 16, Special Supplement.
Dumortier, J., Hayes, D.J., Carriquiry, M., Dong, F., Du, X., Elobeid, A., Fabiosa, J.F., Tokgoz, S., 2011. Sensitivity of carbon emission estimates from indirect land-use change. Appl. Econ. Perspect. Policy 33, 428–448.
Elsayed, M.A., Matthews, R., Mortimer, N.D., 2003. Carbon and energy balances for a range of biofuels options. Project No. B/B6/00784/REP URN 03/836. Project Carried Out as Part of the DTI Sustainable Energy Programme (http://airburners.com/PUB/Sheffield-studie-mei2003.pdf).
Environmental Defence Fund, A new crop for rice farmers: carbon offsets, Environmental Defense Fund, Accessed March 2015 (http://www.edf.org/ecosystems/new-crop-rice-farmers-carbon-offsets).
EU, (2009) On the Promotion of the Use of Energy From Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC, in: Official Journal of the European Union, (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=Oj:L:2009:140:0016:0062:en:PDF).
European Commission, 2010. International Reference Life Cycle Data System (ILCD) Handbook, General Guide for life Cycle Assessment, Joint Research Centre Institute for Environment and Sustainability.

FAO, 2011. Harvested Area of Rough Rice, By Country and Geographical Region-FAO. IRRI. http://solutions.irri.org/index.php?option=com_content&task=view&id=250&Itemid=186.

FAOSTAT, 2008. Rough Rice Production, By Country and Geographical Region-FAO. http://solutions.irri.org/index.php?option=com_content&task=view&id=250&Itemid=186.

Gathorne-Hardy, A., 2013. Greenhouse Gas Emissions From Rice, Working Paper, South Asia Program, School of Interdisciplinary Area Studies. Oxford University, UK (http://www.southasia.ox.ac.uk/sites/sias/files/documents/GHG%20emissions%20from%20rice%20-%20%20working%20paper.pdf).

Gathorne-Hardy, A., Reddy, D.N., Harriss-White, B., 2013. A Life Cycle Assessment (LCA) of greenhouse gas emissions from SRI and flooded rice production in SE India. Taiwan J. Water Conservancy 61, 120–125.

Geethalakshmi, V., Ramesh, T., Palamuthirsolai, A., Lakshmanan, A., 2011. Agronomic evaluation of rice cultivation systems for water and grain productivity. Arch. Agron. Soil Sci. 57, 159–166.

GoI, 2013. India rural development report 2012|13. In: Ministry of Rural Development (Ed.), Government of India (http://rural.nic.in/sites/downloads/annual-report/MoRDEnglish_AR2012_13.pdf).

GOI, 2014. All India Report on Number and Area of Operational Holdings. Agriculture Census Division, Department of Agriculture & Co-Operation.

Gumaste, S.G., 2006. Embodied Energy Computations in Buildings Department of Civil Engg. Walchand College of Engineering, Vishrambag, Sangli.

Harriss, B., 1977a. Paddy milling: problems in policy and the choice of technology. In: Farmer, B.H. (Ed.), Green Revolution? Macmillan, pp. 276–300.

Harriss, B., 1977b. Piecemeal Planning in Rice Markets: The Effects of Partial Government Intervention on Marketing Efficiency in a South Indian District. School of Development Studies, University of East Anglia Norwich.

Harriss-White, B., Gooptu, N., 2009. Mapping India's world of unorganized labour. Soc. Regist. 37.

Harriss-White, B., Janakarajan, S., Colatei, D., 2004. Heavy agriculture and light industry in South Indian villages. In: Harriss-White, B., Janakarajan, S. (Eds.), Rural India Facing the 21st Century: Essays on Long Term Change and Recent Development Policy. Anthem Press, London, pp. 3–47.

Heller, M.C., Keoleian, G.A., 2000. Life Cycle-based Sustainability Indicators for Assessment of the U.S. Food System, Report No. CSS00-04. Center for Sustainable Systems, University of Michigan.

Hull, K., 2009. Understanding the relationship between economic growth, employment and poverty reduction. In: DAC Network on Poverty Reduction (POVNET) (Ed.), Promoting Pro-Poor Growth: Employment OECD (http://www.oecd.org/dac/povertyreduction/43514554.pdf).

ILO, 1999. Decent work: report of the director general. International Labour Conference, 87th Sessions, Geneva.

IPCC, 2006. National Guidelines for Greenhouse Gas Inventories.

IRRI, 2011. Rice Calorie Supply as Percentage of Total Calorie Supply by Country and Geographical Region, 1961–2005. IRRI. http://solutions.irri.org/index.php?option=com_content&task=view&id=250&Itemid=186.

IRRI, 2013. Rice Production and Processing. http://www.irri.org/index.php?option=com_k2&view=item&layout=item&id=9151&lang=en.

Islam, M., Peng, S., Visperas, R., Bhuiya, M., Hossain, S., Julfiquar, A., 2010. Comparative study on yield and yield attributes of hybrid, inbred, and NPT rice genotypes in a tropical irrigated ecosystem. Bangladesh J. Agric. Res. 35, 343–353.

ISO, 2006. Environment Management – Life Cycle Assessment – Principles and Framework. EN ISO 14040 2006. International Organization for Standardization (ISO), Geneva.

John Deere, 2012. Tractor Specifications. http://www.deere.com/en_IN/home_page/ag_home/products/5104_45HP/5104_45HP.html.

Khush, G.S., 2001. Green revolution: the way forward. Nat. Rev. Genet. 2, 815–822.

Kögel-Knabner, I., Amelung, W., Cao, Z., Fiedler, S., Frenzel, P., Jahn, R., Kalbitz, K., Kölbl, A., Schloter, M., 2010. Biogeochemistry of paddy soils. Geoderma 157, 1–14.

Lerche, J., 2011. Agrarian crisis and agrarian questions in India. J. Agrar. Chang. 11, 104–118.

Li, C., Salas, W., DeAngelo, B., Rose, S., 2006. Assessing alternatives for mitigating net greenhouse gas emissions and increasing yields from rice production in China over the next twenty years. J. Environ. Qual. 35, 1554–1565.

Linquist, B., van Groenigen, K.J., Adviento-Borbe, M.A., Pittelkow, C., van Kessel, C., 2012. An agronomic assessment of greenhouse gas emissions from major cereal crops. Glob. Chang. Biol. 18, 194–209.

Lorano, E., 2005. Quality in work: dimension and indicators in the framework of the European employment strategy. In: UNECE/ILO/Eurostat Seminar on the Quality of Work (Ed.), Working Paper no. 2., Geneva.

Mahindra, 2012. Tractor Specifications. http://www.mahindratractorworld.com/Bangladesh-en/Products-Tractors-MKM-NBP-SERIES-30-50HP/575-DI-MKM-NBP-45HP.

María, A., Muñoz, B., Petesch, P., Turk, C., 2013. Strategic life decisions: who has the final say? On Norms and Agency: Conversations about Gender Equality with Women and Men in 20 Countries. World Bank, Washington DC, pp. 87–125

Markussen, M., Østergård, H., 2013. Energy analysis of the Danish food production system: food-EROI and fossil fuel dependency. Energies 6, 4170–4186.

Mekonnen, M.M., Hoekstra, A.Y., 2014. Water footprint benchmarks for crop production: a first global assessment. Ecol. Indic. 46, 214–223.

Mishra, S., 2006. Farmers suicide in Maharashtra. Economic and Political Weekly, pp. 1538–1545.

Mody, G., Mani, M., Sukumar, M., 2013. Labour Patterns Within the Informal Food Sector, Technology, Jobs and a Lower Carbon Future: Methods, Substance and Ideas for the Informal Economy (The case of rice in India). http://www.southasia.ox.ac.uk/sites/sias/files/documents/Conference%20Book.pdf (India International Centre, New Delhi).

Mohanty, S., 2013. Trends in Global Rice Consumption, Rice Today. IRRI, pp. 44–45.

Moser, C.M., Barrett, C.B., 2006. The complex dynamics of smallholder technology adoption: the case of SRI in Madagascar. Agric. Econ. 35, 373–388.

Nelson, G.C., Robertson, R., Msangi, S., Zhu, T., Liao, X., Jawajar, P., 2009. Greenhouse Gas Mitigation. Issues for Indian Agriculture. IFPRI Discussion Paper 00900. International Food Policy Research Institute, Washington DC.

Noltze, M., Schwarze, S., Qaim, M., 2013. Impacts of natural resource management technologies on agricultural yield and household income: the system of rice intensification in Timor Leste. Ecol. Econ. 85, 59–68.

Patel, V., Ramasundarahettige, C., Vijayakumar, L., Thakur, J.S., Gajalakshmi, V., Gururaj, G., Suraweera, W., Jha, P., Million Death Study, C., 2012. Suicide mortality in India: a nationally representative survey. Lancet 379, 2343–2351.

Pimentel, D., Pimentel, M., 1983. The future of American agriculture. AVI Publishing Co. Inc., Westport, Connecticut, USA.

Planning Commission, (2008) Eleventh Five Year Plan, (2007–2012). Agriculture, Rural Development, Industry, Services and Physical Infrastructure, in: India, G.o.(New Delhi).

Prasad, R., Nagarajan, S., 2004. Rice-wheat cropping system — food security and sustainability. Curr. Sci. 87, 1334–1335.

Reddy, D.N., Venkatanarayana, M., 2013. SRI cultivation in Andhra Pradesh: achievements, problems and implications for GHGs and work. Work in Progress Paper 13: Project on Measuring Materiality in Informal Production–Distribution Systems. Oxford University, Delhi, pp. 160–192 2013.

Rodell, M., Velicogna, I., Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. Nature 460, 999–1002.

Roy, S., Bisht, P.S., 2012. System of rice intensification: a possible way to sustainable rice production. Int. J. Agric. Environ. Biotechnol. 5, 171–177.

Sainath, P., 2014. Maharashtra Crosses 60,000 Farm Suicides. http://psainath.org/maharashtra-crosses-60000-farm-suicides/.

Schramski, J.R., Jacobsen, K.L., Smith, T.W., Williams, M.A., Thompson, T.M., 2013. Energy as a potential systems-level indicator of sustainability in organic agriculture: case study model of a diversified, organic vegetable production system. Ecol. Model. 267, 102–114.

Schramski, J.R., Rutz, Z.J., Gattie, D.K., Li, K., 2011. Trophically balanced sustainable agriculture. Ecol. Econ. 72, 88–96.

Sen, A., 2002. Agriculture employment and poverty recent trends in rural India. In: Ramachandran, V.K., Swaminathan, M. (Eds.), Agrarian Studies: Essays on Agrarian Relations in Less-developed Countries. Tulika Books, New Delhi.

Senthilkumar, K., Bindraban, P.S., Thiyagarajan, T.M., de Ridder, N., Giller, K.E., 2008. Modified Rice Cultivation in Tamil Nadu, India: Yield Gains and Farmers' (Lack of) Acceptance. Agric. Syst. 98, 82–94.

Shah, T., 2009. Climate change and groundwater: India's opportunities for mitigation and adaptation. Environ. Res. Lett. 4, 035005.

Shah, T., Bhatt, S., Shah, R.K., Talati, J., 2008. Groundwater governance through electricity supply management: assessing an innovative intervention in Gujarat, western India. Agric. Water Manag. 95, 1233–1242.

Sinha, S.K., Talati, J., 2007. Productivity impacts of the system of rice intensification (SRI): a case study in West Bengal, India. Agric. Water Manag. 87, 55–60.

Singh, H., Mishra, D., Nahar, N.M., 2002. Energy use pattern in production agriculture of a typical village in arid zone. India––part I. Energy Convers. Manag. 43, 2275–2286.

Slade, R., 2009. Imperial College London.

Stoop, W.A., Adam, A., Kassam, A., 2009. Comparing rice production systems: a challenge for agronomic research and for the dissemination of knowledge-intensive farming practices. Agric. Water Manag. 96, 1491–1501.

Stoop, W.A., Uphoff, N., Kassam, A., 2002. A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers. Agric. Syst. 71, 249–274.

Sumberg, J., Andersson, J., Giller, K.E.N., Thompson, J., 2013. Response to 'Combining sustainable agricultural production with economic and environmental benefits'. Geogr. J. 179, 183–185.

Suryavanshi, P., Singh, Y.V., Prasanna, R., Bhatia, A., Shivay, Y.S., 2013. Pattern of methane emission and water productivity under different methods of rice crop establishment. Paddy Water Environ. 11, 321–329.

Takahashi, K., Barrett, C.B., 2014. The system of rice intensification and its impacts on household income and child schooling: evidence from rural Indonesia. Am. J. Agric. Econ. 96, 269–289.

Tennakoon, N.A., Hemamala Bandara, S.D., 2003. Nutrient content of some locally available organic materials and their potential as alternative sources of nutrients for coconut. COCOS 15, 23–30.

Toung, T.P., Bouman, B.A.M., 2003. Rice production in water scare environments. In: Kijne, J.W., Barker, R.D.M. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement. CABI, Wallingford, pp. 55–67.

Uphoff, N., 2008. The System of Rice Intensification (SRI) as a System of Agricultural Innovation. http://repository.ipb.ac.id/handle/123456789/43778.

Uphoff, N., Kassam, A., Harwood, R., 2011. SRI as a methodology for raising crop and water productivity: productive adaptations in rice agronomy and irrigation water management. Paddy Water Environ. 9, 3–11.

Wang, M., Xia, X., Zhang, Q., Liu, J., 2010. Life cycle assessment of a rice production system in Taihu region, China. Int. J. Sustain. Dev. World Ecol. 17, 157–161.

Wang, Y., Li, Y., Liu, F., Li, Y., Song, L., Li, H., Meng, C., Wu, J., 2014. Linking rice agriculture to nutrient chemical composition, concentration and mass flux in catchment streams in subtropical central China. Agric. Ecosyst. Environ. 184, 9–20.

Wood, S., Cowie, A., 2004. A review of greenhouse gas emission factors for fertiliser production. In: IEA Bioenergy Task 38 (Ed.), Cooperative Research Centre for Greenhouse Accounting, Research and Development Division, State Forests of New South Wales, Beecroft, NSW, Australia (http://www.ieabioenergy-task38.org/publications/GHG_Emission_Fertilizer%20Production_July2004.pdf.).