The sustainability of changes in agricultural technology

Citation for published version:
Gathorne-Hardy, A 2016, 'The sustainability of changes in agricultural technology: The carbon, economic and labour implications of mechanisation and synthetic fertiliser use' AMBIO, vol. 45, no. 8, pp. 885-894. DOI: 10.1007/s13280-016-0786-5

Digital Object Identifier (DOI):
10.1007/s13280-016-0786-5

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
AMBIO

The sustainability of changes in agricultural technology - the carbon, economic and labour implications of mechanisation and synthetic fertiliser use

Abstract

New agricultural technologies bring multiple impacts which are hard to predict. Two changes taking place in Indian agriculture are a transition from bullocks to tractors and an associated replacement of manure with synthetic fertilisers.

This paper uses primary data to model social, environmental and economic impacts of these transitions in South India. It compares ploughing by bullocks or tractors and the provision of nitrogen from manure or synthetic urea for irrigated rice from the greenhouse gas (GHG), economic and labour perspective.

Tractors plough nine times faster than bullocks, use substantially less labour, with no significant difference in GHG emissions. Tractors are twice as costly as bullocks yet remain more popular to hire.

The GHG emissions from manure-N paddy are 30% higher than for urea-N, largely due to the organic matter in manure driving methane emissions. Labour use is significantly higher for manure, and the gender balance is more equal. Manure is substantially more expensive as a source of nutrients compared to synthetic nutrients, yet remains popular when available.

This paper demonstrates the need to take a broad approach to analysing the sustainability impacts of new technologies, as trade-offs between different metrics are common.

Keywords: Paddy; Oxen; India; Draught animals; Livelihoods; Life cycle assessment; LCA

Introduction

The history of agriculture is a history of technological change. These changes have brought impacts – often ambiguous in their sustainability - on both society and the environment that go far beyond the initial social, economic, cultural, political, institutional and agro-ecological factors that fuelled the technological change in the first place (Astill and Langdon 1997, Piesse and Thirtle 2010, Montgomery 2012). Key technological changes in today's global agriculture include: mechanisation; seed breeding; and the increase in synthetic fertiliser and pesticide use. Analysing the drivers of change is beyond the scope of this paper. Instead it uses rice production in South India as a case study to highlight the complexity of impacts from two key technological changes taking places in today's global agriculture. Specifically it uses labour-demand, costs and GHG emissions as examples of social, economic and environmental sustainability metrics to analyse (a) the mechanisation of ploughing, and (b) the shift from manure to urea as a source of nitrogen.

The impacts of agricultural technology transitions have been widely studied within individual disciplines, for example the economic implications of farm energy options at the macro-economic level (Musa and Bello , Pearson 1991, Thomas 2000), and energy and the greenhouse gas (GHG) implications at the farm scale (Schramski et al. 2013, Spugnoli and Dainelli 2013, Cerutti et al. 2014, Gathorne-Hardy et al. 2016). However, the wide-reaching social, economic and physical impacts of technology transition requires a multi-disciplinary understanding of sustainability, yet there is a dearth of studies that combine primary data and interdisciplinary research. To the best of our knowledge this is the first study to use primary field data to study technological transitions from an interdisciplinary approach.

Both mechanisation and fertiliser use are energy intensive compared to bullocks or manure, and fertilisers are associated with direct and indirect pollution (Erisman et al. 2008, Starkey 2010, Schramski et al. 2013). Further, transition up the energy ladder is often associated with reduced employment.

This research is based around primary data collected from irrigated rice farms in South India. Rice was chosen due to its global importance; it is the staple food for 50- 60% of the global population (Stoop et al. 2009) and provider of employment for approximately 1bn people (Dawe 2000).

This paper first identifies key sustainability issues associated with different traction and fertiliser options. After describing the methods it presents the results, including discussing the apparently counterintuitive choices made by farmers.

Greenhouse gas emissions

Displacing fossil fuels through the use of draught traction

For centuries bullocks have been emblematic of sustainable agriculture in India, providing draught energy while recycling waste straw into fertiliser and fuel. Today, however, tractors have replaced bullocks over vast tracts of India. From 122,000 per year in 1989, tractor sales increased by 4.4% per year between 1989 to 2009 (Sarkar 2013), and tractors per 1000 hectares increased from 0.19 in 1961 to 27.38 in 2013 (Evenson et al. 1998, Singh 2013). From 2003 to 2012 the number of bullocks decreased from 78m to 61m (GoI 2012).

Ploughing GHG emissions are determined by input: output efficiency, energy source and waste gas composition. Tractors and livestock are approximately equal in their net efficiency, converting about 30% of input energy into useful energy (Pearson (1991) quoted in Fuller and Aye (2012)). While tractors typically use non-renewable fossil fuels and produce CO_2 as a waste gas, bullocks use potentially sustainable biomass fuel, but generate methane in their waste gases, a gas with a 25 times greater global warming potential (GWP) compared with CO_2 over 100yrs (Forster et al. 2007).

Displacement of GHG intensive fertilisers with manure.

Energetically, environmentally and agronomically, nitrogen (N) is the most important plant nutrient (Ladha et al. 2005, Erisman et al. 2008) and this paper focuses on nitrogen. With adequate water supply, and providing damage from pests or diseases is not excessive, then, within a single season, nitrogen availability typically determines yield. In India, synthetic fertiliser use has increased dramatically, augmenting or replacing traditional organic manures. The total quantity of NPK fertiliser expanded 9 fold from 2 to 18 m tonnes from 1969/70 to 1999/00 (FAO 2005, Sarkar 2013) 82% of total synthetic nitrogen is supplied in the form of urea (FAO 2005).

The GHG emissions associated with manure are complex. Globally, slurry and manure are major source of GHGs (IPCC 2007) yet emissions are highly variable depending upon manure composition and environmental conditions: methane emissions increase with high proportions of volatile solids and anaerobic storage conditions (for example wet manure piles or lagoons). Nitrous Oxide (N_2O) emissions increase with N content and in moist but not anaerobic conditions (IPCC 1996).

Most manure-emissions data is from developed-world agricultural systems. Gupta et al (2007) looked at manure emissions in three Delhi-based dairies and found emissions equating to 21.67kg CO_2eq cow^{-1} yr^{-1}. Unfortunately there was no description of manure storage conditions, but the large herd size suggests housed livestock, urine collection and large manure piles or 'lagoons'. In contrast, most rural manure is from small herds, without urine collection, stored in small aerobic mounds, minimising CH_4 and N_2O emissions.

Manure use can also impact soil carbon. In contrast to most arable systems, which through cultivation and disturbance tend to loose soil organic carbon (SOC), the anaerobic soils of irrigated rice inhibits the oxidation of organic matter, encouraging a build-up of SOC (Pan et al. 2004, Ci and Yang 2013). The application of supplementary organic matter such as manure further increases the SOC in paddy systems (Ghosh et al. 2012).

Soil-based GHGs dominate total GHG emissions from arable farming. In aerobic arable systems N_2O dominates emissions, and soils act as a net sink for CH_4. In contrast, the anaerobic nature of rice soils effectively supresses' soil-based N_2O emissions (Hou et al. 2000)and GHG emissions are instead dominated by methane. Under anaerobic conditions, the supply of substrate for the soil methanogenic community is the commonest limiting factor for methane production. Organic matter substrate originates from both direct by-products of rice production (such as sloughed-off root cells and root exudates) and from added materials including manure (Qin et al. 2010).

Yield gains through increased soil fertility

Yield is an important sustainability metric as lower yields increase environmental impacts per unit of production, assuming input factors remain constant. In addition to nutrients, manure is a source of organic carbon which in most arable soils is positively correlated with soil fertility (Bronick and Lal 2005, Mueller et al. 2010).

However it cannot be assumed that the same benefits accrue from increased SOC in paddy fields, especially as many of the key attributes of SOC are associated with their benefits to soil structure. Irrigated rice fields are ‘puddled’ (repeated ploughing under waterlogged conditions) to deliberately break down soil structure and provide a fine, more waterproof soil.

Experiments to understand the contribution of SOC to irrigated rice yields have been inconclusive. Pan (2009) found a positive relationship between SOC and yield, but it is unclear if the SOC is driving the yield advantage, or vice versa. Ghosh et al (2012) found increased yields with increased manure, yet their study methods do not compensate for the additional nutrients imported into the system with the additional organic amendments. In contrast, research in which the nitrogen was compensated for by organic amendments showed yield declines when part or all of the N was applied as FYM (Bhatia et al., 2010). This however was a single year study. These results may be due to lack of N availability from more tightly-bound FYM N compared with mineral N. At present there is insufficient evidence to suggest that higher levels of SOC are likely to be associated with higher yields.

Economic return to the farmer

The economic return to a farm is fundamental to its long-term sustainability and at present the economic conditions for much of Indian agricultural is poor. In a survey of over 8000 farmers, 10% of families had endured days with no food over the previous year, and 45% of the 90% of farmers with ration cards are below the poverty line (CIDS 2014). Agricultural poverty is especially common in the 85% of Indian farms below 2ha in size (GOI 2014). While this is not the place for a detailed discussion about farmer poverty in India, for the 118.9m cultivators in India, an improvement in agricultural returns can help reduce poverty.

Employment

Economic poverty remains endemic in the Indian countryside (GoI 2013) and is especially prevalent amongst landless labour - two thirds of the landless agricultural labour force are below the poverty line (Harriss-White and Gooptu 2000). Poor people derive most of their income from work (Hull 2009) and while recent developments are reducing agriculture’s employment dominance (including the MGNREGA[1] (GoI 2013, Carswell and De Neve 2014)) agricultural employment still represents up to two thirds of India’s rural workforce (Harriss-White et al. 2004).

This alone does not suggest that more agricultural labour demand is a positive sustainability metric, especially as agriculture is arguably some of the worst work in rural India – lowly paid, physically difficult and of low status. But India has followed a unique development pathway, resulting in massive of un- and under-employment nationally. Unlike other developing nations, India has had ‘job-less growth’ with the majority of growth represented by high-paying, low employment service industry (Corbridge et al. 2014). So instead of agriculture mechanisation releasing workers for the industrial economy, it releases people to un- or underemployment. Therefore, in this paper, there is an assumption that while much agricultural employment is very low quality, people are employed in agriculture due to lack of alternative options, and as such, more agricultural employment is better than less.

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[1] 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 days work a year and growing off-farm sources of income

Materials and methods

Streamlined, attributional, Life Cycle Assessment (LCA) was used to determine the GHG emissions based on the standards and criteria of ISO 14040, PAS 2050, and the ILCD handbook (ISO 2006, European Commission 2010). Costs and labour requirements were mapped simultaneously.

Goal and scope definition

The goal of this research was to understand the implications for GHG, costs and labour demand of two independent technological transitions in agriculture: tractors compared to bullocks for traction, and manure compared to urea as a source of nitrogen, in irrigated rice production in India. Two discrete functional units were used:

a. The ploughing of 1 hectare, once, for irrigated rice
b. The application of 1kg nitrogen-N for irrigated rice.

These two functional units were independent of each other. Questionnaire responses demonstrated that neither the quantity or quality of ploughing varied between bullock and tractor.

System boundaries.

The setting of LCA boundaries – what is and what is not included within the analysis - has the potential dramatically to affect the final result, especially when dealing with an input as complicated as the draught power of, and manure from, livestock.

The GHG boundaries associated with ploughing of 1ha of land for flooded rice include the embodied emissions (production emissions for tractors, non-utilised juvenile life for bullocks) and running emissions per hour for bullocks or tractors. The background emissions associated with bullock's enteric fermentation were allocated according to the number of hours of both on- and off-farm jobs per year, and similarly the embodied emissions associated with tractors. The allocation of feed to bullocks would have been important to include except that no dedicated crops were used; the only cropped feed for bullocks in this study was rice straw, an otherwise un-utilised by-product of rice production.

The GHG boundaries associated with the provision of 1kg of N for flooded rice are complicated by the lack of perfect substitutability between the two nitrogen sources. While both provide nitrogen, manure provides a range of alternative nutrients, and is itself typically a co-product with milk, meat and draught power. However the dominant source of manure in the study villages was dairy cows, a situation that is likely to increase as the number of bullocks decreases, so analysis was restricted to these and used economic allocation to accommodate the co-products of manure, including other macro nutrients (see Table 1) - it allocates cow GHG emissions to different co-products according to their price. Thus if the manure and milk produced per year were equally valuable, cow GHG emissions would be split equally between these. For more detail on economic allocation see Kindred et al (2008). Included in the boundary of the second functional unit is: production, transport, SOC impacts, co-products of manure, and soil GHG emissions associated with both input systems. Yield changes associated with the high SOC of manure were excluded from this analysis due to lack of evidence to justify such yield gains in paddy systems.

Indirect N_2O emissions were not included within the manure-N urea-N analysis, as these are constant independent of N source.

Inventory analysis and data sources

This analysis uses a combination of primary and secondary data, collected as part of a larger project examining interactions of social, economic and environmental factors in rice production and supply chains, see http://www.southasia.ox.ac.uk/resources-greenhouse-gases-technology-and-jobs-indias-informal-economy-case-rice.

The primary data used for this analysis was collected from 77 farmers in 2012 using an extensive (31-page) questionnaire. Data collection took place in three semi-arid areas of South: Janagaon region of Warangal District in the state of Andhra Pradesh (n=25); Vanthavaasi of Thiruvannamalai district (n=20), Tamil Nadu state and Nagapattinam district, Tamil Nadu (n=32). Farms were chosen to reflect the distribution of holding sizes in the Indian Agricultural census for each region.

Input assumptions are detailed in Table 1.

Assessment of global warming potentials

To calculate GHG equivalents, we used GWP_{100} as specified by IPCC 2007 (Forster et al. 2007). The gases included in this analysis were carbon dioxide (CO_2, GWP:1), methane (CH_4 GWP:25), nitrous oxide (N_2O GWP:298)

Analysis

Analysis was carried out using a LCA model built in Excel, and statistics (t-tests) were tested in SPSS.

Costs

All costs are given in USD, using September 2012 conversion rate (1USD = 54.415INR)

Ploughing.

No farms hired bullocks for ploughing, so it was not possible to gather the market rate for ploughing with bullocks. However, bullocks were regularly hired for levelling (flattening the ground prior to transplanting) and as bullocks are hired out on an hourly rate independent of task, levelling costs were used as proxy for ploughing costs.

Including hidden costs

The use of family labour is common on small scale farms around the world. While this labour is often treated as ‘free’ by farmers, in reality there is often an opportunity cost – members of the family could be otherwise employed elsewhere at potentially higher rates of pay. This analysis includes both the actual costs (free family labour) and imputed costs (included family labour – based on local casual labour pay).

Description	Figure	Source, comment
Kg of N t manure^{-1} (assuming 20% moisture)	12	Tennakoon and Bandara (2003)
Tractor composition	Assumed to be 100% steel	
Tractor weight (kg)	1952.5	(John Deere 2012, Mahindra 2012)
Embodied emissions associated with steel (kg CO2 –eq kg^{-1})	2.4	(CSE 2012)
Tractor diesel use (l hr^{-1})	4	Response from interviews (interviews rather than tractor specifications for actual rather than factory engine efficiency)
GHG intensity diesel (kgCO2eq l^{-1})	3.0168	(EU 2009)
Tractor life span (yrs)	20	
Average tractor working hours per yr (hrs)	1129	Interview responses
Emission factor for indigenous working bullock (kg CO_2 animal^{-1}yr^{-1})	823.5	(Singh et al., 2002)
Emissions factor for indigenous cows milking (kg CO_2 animal^{-1}yr^{-1})	899.25	(Singh et al., 2002)
Emissions for crossbred females (milking) (kg CO_2 animal^{-1}yr^{-1})	970.75	(Singh et al., 2002)
Manure emissions (kg GHG per animal per yr) (kg CO_2 animal^{-1}yr^{-1})	50	(IPCC 2006)

Bullock life expectancy (yrs)	18	Farmer response
Emissions 1-5 years of bullock life (kg CO_2 animal^{-1})	2270.5	(Singh et al. 2002)
Number of days a bullock works yr^{-1} (days)	175	Interview responses
Working life of a bullock (yrs)	13	Interview responses
Manure produced per cow (kg cow^{-1} yr^{-1})	2344.7	Interview responses
Allocation of the adults' emissions to manure (compared to milk and carcass value).	6%	Economic allocation was using farmer responses.
Allocation of labour and costs of manure to manure-N	0.19	Derived from the costs of mineral alternatives, assuming manure consists of only NPK at the manure nutrient concentration described by Tennakoon and Bandara (2003)
Speed of livestock pulling manure (km/hr)	3.4	Interview responses
DAP production emissions (kg CO2 eq/kg active product (N and P)	1.38	(Wood and Cowie 2004)
Urea production emissions (kg CO2 kg Urea-N^{-1})	0.7	(CSE 2009)
Transport GHG emissions (assumed 4000km)(kg CO2 kg Urea-N^{-1})	0.23	From main project transport data analysis
SOC from manure (kg CO_2 ha^{-1}yr^{-1})		(IPCC 2006)

Family labour costs		Modelling allowed family labour costs to be imputed. Family labour costs were based on local casual labour rates

Table 1. Input assumptions and sources of data

Results and discussion

Ploughing

GHG emissions.

Bullocks are substantially less polluting per hour of work than tractors, producing just 20% of tractors' emissions, see Table 2. Yet bullocks are slow to plough a field – taking an average of 18 hours to plough a hectare (similar to the 23hours in Indonesia, see Teleni et al (1993)). This is 6 times slower than with a tractor. Consequently, there is no statistically significant difference in the GHG emissions between ploughing with bullocks or ploughing with tractors (p=>0.05), see Table 2.

Table 2

	Tractor	Bullocks (pair)
GHG emissions per hour	12.27 (including embodied emissions at 0.21)	2.59
Mean time to plough a hectare once (hrs)	2.8 (0.3)	17.7 (2.1)
GHG emission to plough a hectare (kg CO_2 ha^{-1})	33.9 (3.5)	45.99 (7.4)

Table 2. The GHG emissions associated with ploughing by tractor or bullocks, either per hour or per hectare. Figures in brackets represent standard error.

The composition of emissions from tractors and bullocks differ – tractors' emissions are dominated by use (98%), while bullocks have no specific emissions associated with use. Bullocks have two sets of embodied emissions: firstly the emissions associated with its immature stage (the first 5 years as a calf representing 21% of total emissions) and secondly the emissions associated with staying alive independent of the actual hours of work. In contrast to tractors which, once purchased, only produce GHGs when working, bullocks cannot be 'turned off'. Bullocks from our data-set typically worked for 5 hours a day, on average 175 days a year (similar to Misra and Pandey (2000) who suggest bullocks are typically used for an average of 154 days). Thus every hour worked had an associated 10 hours of non-work emissions.

Emissions from both tractors and bullocks can be reduced through increased ploughing efficiency – better plough designs, more fuel-efficient tractor engines, better harnesses for bullocks. Bullocks can also be made substantially more efficient through working more days: the background emissions associated with enteric fermentation are the dominant GHGs from bullocks. The larger the number of hours worked by bullocks, the smaller the emissions per hour (the small embodied GHG emissions of tractors compared to the diesel based use-emissions minimises the potential to reduce tractor emissions through increased tractor use). For example if the number of days worked by bullocks is reduced to 100 days year^{-1}, the emissions almost double to 80.5 kg CO_2 ha^{-1}. Bullock use from our data ranged from 100 to 280 days yr^{-1}. At 280 days yr^{-1} the emissions to plough a hectare fall below that of the tractor to 28.8kg CO_2 ha^{-1}. Clearly there are limits to this method of efficiency gain. In addition, anecdotally, harder working bullocks have shorter lives.

Thus, while the present working patterns found show no significant difference in GHG emissions, it is possible to modify existing use patterns to radically reduce emissions from bullocks, especially through increasing the workload of individual bullock-pairs (although the potential of sharing between farmers for ploughing is limited due to time pressure at key points in the growing season).

These overall results are in line with Spugnoli and Dainelli (2013), who found tractors reduce GHG emissions compared to bullocks when ploughing in Indonesia. In contrast, when comparing tractors and non-ruminant based draught animal power, livestock reduced GHG emissions, for example Cerutti et al (2014).

Costs

The overall cost for ploughing with bullocks is USD 48.01 hectare^{-1}, less than half of the USD 100.01 ha^{-1} to plough using a rented tractor ($p<0.01$). Yet bullocks are rarely hired to plough when tractors are available. Why is hiring bullocks unpopular, when the cost is substantially lower than tractors? Our data cannot answer this, but it is possible that their slower work and inability to work long days reduces their practical use; rapid work rates are important to prepare fields for subsequent crops in a timely manner (Agarwal 1984).

Labour

Labour requirements for ploughing are directly proportional to the length of time to plough a field. The employment is 100% male for both activities. Importantly, few owners of tractors or bullocks allowed others to use them. Instead the owner tended to manage the animals/machine himself. So while bullocks require substantially more labour, it is unlikely that ploughing by either method is an important source of employment for landless labour. Furthermore, the increased timeliness provided by tractors can increase overall labour demand by allowing cropping in an additional seasons (Sarma 1981).

Nitrogen from manure or urea

GHG emissions

GHG emissions are 30% higher when manure is used as a source of nitrogen compared to urea, yet with very different constituent emissions, see Figure 1. The production of manure, including GHG emissions associated with enteric fermentation and manure storage, has less than half the emissions associated with the production and transport of synthetic urea. Urea GHG production arises largely from fossil energy driven CO_2 emissions, and the use of methane as a source of hydrogen for urea feedstock, ammonia.

Figure 1

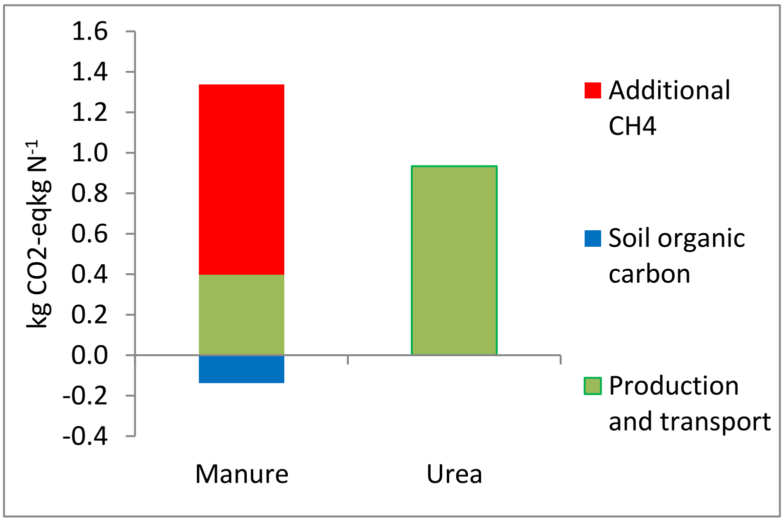

Figure 1 The GHGs associated with 1kg of nitrogen in manure or urea. Additional CH_4 refers to CH_4 produced in response to the organic matter within manure

Urea production in India is already some of the most efficient in the world (CSE 2009), reducing the potential for efficiency-based reductions in urea GHG emissions. The efficiency of India's road network could be improved, reducing GHG emissions in urea transport. In contrast, transport is largely irrelevant to manure due to the small distances travelled, but substantial efficiency gains might be possible, through collecting a greater proportion of the nitrogen excreted from a cow. While solid matter is collected, the urine – which can contain a substantial portion of total N (Rotz 2004) – is often released straight onto the soil.

The high organic matter content of manure, when used under flooded rice production systems, sequesters 0.14kg of CO_2 as SOC. However, the high organic matter also acts as feedstock for methogenic species, increasing methane production from the rice fields and producing the single largest source of GHG associated with manure production. While it is outside the scope of this paper to analyse the relative benefits of manure and urea in dryland agriculture, Figure 1 suggests that in dryland agriculture – including reduce SOC storage and zero CH_4 emissions - manure would offer overall GHG savings compared to urea. Also outside the direct scope of this paper, but important to mention, is that manure has a host of wider environmental qualities compared to urea, most especially concerning biodiversity (Mandal et al. 2008, Rahmann 2011, Gabriel et al. 2013).

The emissions from manure are highly sensitive to a number of variables and assumptions. These include the quantity of N in manure, the value ascribed to N in manure compared with other nutrients, and the economic value of the manure compared to the milk. In the study areas the majority of manure came from cows rather than bullocks (partially reflecting diminishing bullock numbers), and cow GHG emissions between milk and manure were allocated using economic measures (for more details see methods). Due to the relatively high value of milk, manure production represented only 6% of the total cow emissions. If, to take an extreme example, cows were to exist solely for the production of manure, then the production phase of manure alone would be responsible for 6.94 kg carbon kgN^{-1} – an order of magnitude more than urea. In contrast, if the value of milk doubled then the GHG emissions associated with manure reduce by 20%.

Costs

Manure-N is substantially more expensive than urea-N. The costs in Table 3 represent the value of N in the manure rather than the total manure costs (19% of the total value of manure). Many farmers used their own manure but even assuming the manure was free the labour costs of application still make it more expensive per kg N.

If family labour is imputed at the casual labour rate, the cost of urea-N increases by 69% and manure-N by 16%. However manure-N remains substantially more expensive than urea-N, see Table 3.

Table 3

	Family labour at zero cost		Imputed family labour costs	
	Manure –N	Urea -N	Manure –N	Urea -N
Purchase (including transport)	0.02 (0.002)	0.13 (0.021)	0.02 (0.002)	0.13 (0.021)
Application costs	0.0 (0.00)	0.03 (0.010)	0.01 (0.00)	0.05 (0.007)
Total	0.02	0.16	0.04	0.18

Table 3. The accounting costs entailed with applying 1kg nitrogen (USD). Figures in parentheses are standard errors.

The question of why farmers still use manure when a far cheaper source of nutrients is available is hard to answer. For farmers producing their own manure through their own livestock, manure then a free resource. But many farmers were willing to buy manure at considerable cost, demonstrating a high perceived value. Furthermore, as discussed above, there is no clear evidence that manure is associated with yield gains in rice.

Labour

Manure has over three times the labour requirements of synthetic fertilisers, an average of 51.4min to spread 1kg of manure-N compared to 6.5min to spread 1kg of urea-N ($p<0.01$). In a country with a considerable shortage of employment, manure offers the advantage of increased labour provision. Between the different nitrogen sources there were also substantial differences in the proportion of male to female workers, and of wage- labour compared with family labour, see Table 4.

Table 4

	Male		Female		Total
	Family	Employed	Family	Employed	
Manure	15.4**	11.9**	12.4**	11.4**	51.4**
Urea	3.4	1.1	2.0	0.0	6.5

Table 4. Total labour requirements to apply nitrogen (minutes per kg-N). Differences were measured between the different sources of manure. Figures for manure are based on the economic value of manure-N compared to manure-P and manure-K (*=p<0.05, **=p<0.01)

Approximately 50% of the labour for manure-spreading is female, in all sites. However, while in Andhra Pradesh this is also true for synthetic fertilisers, in both Tamil Nadu sites urea-spreading labour was dominated by males (97%), even though the work is less arduous.

Conclusions

Livestock have had a long symbiotic relationship with man, producing: food, manure, clothing, power and companionship in exchange for feed and protection. Yet this relationship is changing as the provision of energy and of nutrients is increasingly taken over by fossil fuels and synthetic fertilisers. This change has not been previously analysed using multi-disciplinary data and primary data.

Results from this analysis show that tractors can plough approximately six times faster than bullocks; offer no, or minimal statistically valid GHG savings per hectare; cost more and reduce labour demand. The GHG results are highly sensitive to key assumptions, especially the number of days that bullocks are used per year. As bullock use per year decreases, bullock emissions per unit of work increase proportionally due to the high background rate of enteric methane emissions. The higher economic cost of tractors seems to be unimportant to farmers. This is likely to be due to the relative convenience, availability and speed of ploughing by tractors - important in the rapid establishment of the next season’s crops. Only male labour was used for ploughing. Due to the speed of tractor ploughing, substantially less labour was required compared with ploughing using bullocks. However, since much of that labour is provided by the owner of the animal/machine, it is rarely an important source of employment for the rural poor.

Manure-N compared to urea-N for irrigated rice generates substantially higher GHG emissions, increases costs and increases labour demand. Manure GHG emissions are dominated by increased methane associated with the high manure organic matter content. This suggests that manure could offer GHG emission savings for dryland crops, compared to urea. The higher cost of manure assumes manure is bought, while many farmers have domestic manure production for direct use. There is a substantially higher labour demand associated with manure, which, unless it is family labour (and therefore a hidden cost), results in high application costs even with free manure. In all areas manure generated roughly equal employment for men and women. The spreading of manure offers substantial employment for non-family labour in most sites, a useful form of income for landless labours, and so a net social benefit to the rural economy.

This study is the first of its kind to use primary data to compare tractors with bullocks, and manure with urea, from a range of disciplinary perspectives. The results highlight the interplay between different measures of sustainability – for even just using three sustainability metrics there is a clear trade-off between labour provision and GHG emissions between the two sources of nitrogen. However, it is important to note that the purpose of this paper was to highlight the need to take broad approaches to sustainability when analysing technological transformations in agriculture rather than to provide a detailed study of the mechanisation or nitrogen: many sustainability metrics were ignored from this study, and so this study should not be used to recommend any particular policy. Further work that increases the number of criteria to include health, gender, biodiversity, national economic impacts and resilience will be important to allow positive policy decisions that accurately identify and mitigate trade-offs.

ACKNOWLEDGMENTS

The author would like to thank the constructive comments from four 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.

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