Assessing the externalities of SABMiller's barley extension program in Rajasthan

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This is a 'working paper'. We welcome any comments and feedback

Contents

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Preface & Acknowledgements

The origin of this working paper lies in a case study prepared for the Valuing Nature Network (VNN) "Valuing Externalities in a Business Context" project, run by the Cambridge Programme for Sustainability Leadership with funding from the UK Natural Environment Research Council (NERC). Within the context of this project Colm Bowe (Liverpool John Moores University) and Dan Van der Horst (University of Edinburgh) were partnered with SABMiller to develop a method to evaluate the impacts on natural capital externalities of SABMiller's Saanjhi Unnati (Progress through Partnership) Barley production extension program in Rajasthan India. The initial desk study by Colm Bowe and Dan van der Horst was completed in September 2012, but all parties involved felt that the analysis had been hampered by a shortage of data. The work was further developed through a continuing collaboration between Bowe, Van der Horst and SABMiller with important new data being produced by Chintan Meghwanshi, who acted as a free-lance agricultural consultant. Chintan carried out and reported on a series of focus group meetings with SABMiller extension officers in Rajasthan in February 2013.

The initial desk study was funded by Cambridge Programme for Sustainability Leadership and Valuing Nature Network (VNN). SABMiller funded Chintan Meghwanshi's report on the views and practices of extension officers. The continued contribution by Bowe and Van der Horst was not externally funded; we acknowledge the freedom granted to us by our respective universities to pursue research of academic interest and potential societal relevance. In the same vein, we also acknowledge that with our limited resources came a limited focus. For example we have no direct verification of farmers' perspectives and experiences, no fieldwork data to examine local socio-economic context, no assessment of downstream processing, indirect impacts or displacement effects. For all intents and purposes, ours is an initial desk study of the barley production programme alone, largely based on secondary data.

Earlier drafts of this working paper were shared with members of the "Valuing Externalities in a Business Context" project, who expressed an interest to use it as a worked example in the company guidelines they are developing. More information about VNN and this particular project can be found at http://www.valuing-nature.net/sustainability-leadership

The authors would also like to acknowledge the following people for their assistance in providing information, ideas, feedback and project facilitation: Alexandre Le Vernoy, Anna Swaithes and Tom Salisbury from the SABMiller Water and Food Security Policy team; Kiran Reddy and Nawlendu Ranjan from SABMiller India; Gemma Cranston, Maarten van der Kamp and Fergus Kirkpatrick from University of Cambridge Programme for Sustainability Leadership; Marije Schaafsma from the University of East Anglia, Bhaskar Vira from University of Cambridge and Steve Albon for the James Hutton Institute.

As per usual, any errors and omissions are ours alone.

Executive Summary

This report examines the externalities associated with the increased production of malting barley for a brewery in Rajasthan, India. The company has been working with independent small scale farmers to increase yields through better crop management and increased adoption of new barley varieties that are more beneficial to the brewing process than the feed barley which has traditionally been grown in Rajasthan. The environmental externalities associated with farm operations are described and quantified, using information from farm extension worker focus groups as well as publicly available data. Four crop growing scenarios are developed for a typical 2.8 ha farm.

Comparison of the baseline scenario (i.e. non-participating farmers) to the company scenarios (i.e. participating farmers) shows a reduction in externalities as well as an increase in farm income. The agronomic advice provided by the company's extension services has helped farmers to achieve a reduction in blue water use and GHG emissions (CO_2e) and grey water whilst increasing barley production extent, yield per hectare and farm profit. The establishment of a historical scenario allowed a comparison of the two temporal trends, historic-to-baseline and historic-to-company. This shows that over the time period of the study GHG emissions (CO_2e) and grey water emissions have increased, but these increases are lower under the impact of the company. In this time period there has also been a reduction in water use by farmers, but under the company scenario, that reduction is much bigger than what would have happened in the absence of the company. This reduction in water use over time could indicate that that farmers are concerned water availability and are moving towards crops that require less irrigation; this being facilitated by the impacts of the company. There has also been an increase in farm income, but under the company scenario, this increase has been much higher than what would have happened in the absence of the company.

When summed across the 6000 participating farmers in Rajasthan, the annual reduction of water use and GHG emissions amounted to 3.4 million m^3 and 1980 tCO_2e respectively. The total value of these externalities was estimated at $300k/y. Despite these benefits, the study also showed that the water use reductions achieved by farmers participating in SABMiller's barley growing programme are insufficient to address the unsustainable depletion of the aquifer in the area. Systemic changes to the entire agricultural system would be required to address the rapid fall in groundwater resources.

Farmers under the guidance of the company's agricultural extension services showed both reduction in negative externalities and increases in farm income. Such analysis indicates that well developed extension services can have a positive impact on both environmental and development objectives. In cases where farm management changes may lead to reduction of negative externalities at the expense of farm income such analysis allows decision makers to explore the trade-offs between farm income and environmental externalities. This study could be extended to examine the opportunity costs for farmers to further reduce water use and greenhouse gas emissions, and the extent to which the (effective) provision of best practice agronomic advice can off-set these costs.

1. Introduction

1.1 Background; valuation of natural capital in a business context

Increased emphasis is being placed on the link between business and natural capital with the aim of achieving sustainable development (Trucost and TEEB for Business 2013). Recent guidelines have been published to encourage business to value their impacts on and benefits from ecosystem services (World Business Council for Sust. Dev. 2011). Companies are becoming increasingly aware of the environmental costs and the impact on natural capital that are involved in the production of goods. In the absence of regulation, these costs in the short term do not affect company balance sheets and so remain as externalities. There is also increasing evidence that ecosystem degradation, over-exploitation of increasingly scarce, un-priced natural capital at a time of rapid population growth has a material impact and increases risks for companies – undermining performance, profits, their license to operate and access to new markets (World Business Council for Sust. Dev. 2011).

A number of international (the UN 'Natural Capital Declaration' - Mulder et al 2013) and national policies (UK Natural Environment White Paper) and reports (State of Natural Capital report - Natural Capital Committee 2013) have highlighted the importance of natural capital accounting and reporting. Such accounting allows businesses to identify hotspots of environmental externalities within the commodity chain, or identify areas of best practices within the organisation. Such work allows the company to adapt management practices to reduce externalities or develop methods to internalize these costs and avoiding sudden shocks or risks around natural resources in the future (i.e. drought). Thus positioning themselves for a natural capital constrained world. Such studies also advise policy makers on identifying the distribution of natural capital risk across the economy. It will allow government and investors to understand how business sectors' global competitive position may change in the future as a result of natural capital costs and develop policies that efficiently and effectively internalize these costs (Trucost and TEEB for Business 2013).

While a lot of emphasis is being placed on the need to quantify environmental externalities, methods are still under development. A recent regional scale study to identify the world's top 100 Externalities of Business (Trucost and TEEB for Business 2013) called for a strengthening of methodologies based on bottom-up analysis which attempts to capture intra-national differences in impacts, or differences between specific technologies and business practices.

This study aims to develop a method to quantify business externalities based on management changes brought about by business intervention through its extension services This work is based on the result of collaboration between business and academia to develop methods to value business externalities using data easily available within the company structure in combination with secondary data. This study has directed the development of and is included as the worked case study in E.Valu.A.Te: The Practical Guide[1] (Cambridge Programme for Sustainable Leadership 2013).

[1] E.Valu.A.Te: The Practical Guide can be accessed at www.cpsl.cam.ac.uk/natcap

1.2 Business Context

Barley had traditionally been grown in India as a fodder and feed crop with low input requirements. Due to its low market value barley production has lacked investment and over the last 4 decades has seen a decrease in area due to a shift toward wheat or mustard production (Verma et al 2010). More recently however Indian domestic demand for barley has been increasing for industrial uses such as brewing and the malting process. Indian beer consumption rate is growing at a robust rate of 15 to 17 per cent each year (Verma et al 2010). However, the majority of the 1.5 million tons of barley produced each year in India are feed grade quality varieties as opposed to the malting quality preferred by the brewing industry. Higher-quality malting barley reduces the cost of the brewing process, while also improving the quality and extending the shelf life of products.

This has led to an investment in the barley production chain with increased distribution of higher quality government certified seeds and agronomic extension by industry. This has resulted in increases in production area and yield. SABMiller's Saanjhi Unnati (Progress through Partnership) project initiated in Rajasthan in 2006 aims to promote sustainable livelihoods through the development and improvement of local supply chains for barley. In order to increase barley production and stimulate the cultivation of the most suitable varieties of barley, the company employs a team of 30 agronomists in India. The agronomists liaise with farmers and sensitize them to the adoption of varieties that are more suitable to brewing. They have identified promising barley varieties (i.e. K551 from Uttar Pradesh) and imported and promoted the uptake of these in Rajasthan. Through the program, farmers also benefit from extension workshops on topics of interest such as water management (including time of irrigation, method of fertilizer application, weeding practices, harvest timing, and storage practices).The overall aim is to secure a long-term reliable source of locally grown malt-quality barley and test new strains of barley that offer better yield and price to the farmers. Farmers had traditionally used their own seed for cultivating barley. This is due to a combination of reasons - lack of availability of quality certified seed, lack of knowledge and awareness of the benefits of usage of certified seed, lack of knowledge on varieties etc. The company buys barley from (otherwise independent) farmers. In the last 7 years it is estimated that this has resulted in more yield for the participating farmers, whilst the company got a better malting variety. This case study focuses on the externalities associated with this project in Jaipur, Rajasthan.

1.3 Biophysical Context

The major crops grown in the region include barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum*), mustard (*Brassica juncea*) and gram (*Cicer arientinum*) grown in the Rabi (winter, dry) season and soybean (*Glycine max)*, guar gum (*Cyamopsis tetragonoloba*), bajra millet (*Pennisetum glaucum*) and groundnut (*Arachis hypogaea*) during the Kharif (summer, rainy) season.

Agricultural inputs into the system include synthetic fertilisers DAP and Urea. Organic matter is added to the system in the form of farm yard manures, crop residues and the soil is tilled. Pesticides and herbicides are also applied to the crops. Water sources for crop growth come from rainwater and irrigation predominantly from ground water (some canal and river water is used).

This results in a number of externalities; Water is pumped from wells using electric pumps, resulting in decline in groundwater reserves and CO_2 production. DAP, urea and organic fertiliser result in nitrogen volatilisation to N_2O an important GHG's which influence global processes and impacts climate change. Rainfall and irrigation can lead to runoff and leaching of nitrate and phosphate from fertiliser additions leading to eutrophication of local water bodies and a reduction in water quality and biodiversity. Addition of crop residues and organic manure lead to an increase in the amount of carbon stored in the soil, while tillage leads to the violation of carbon and release of CO_2.

Ground water extraction is of particular concern in the region. Groundwater extraction by farmers significantly exceeds natural recharge and the current agricultural system is clearly not sustainable in the long term. It is anticipated that the continued depletion of groundwater resources will eventually result in the abandonment of dry season farming (which is dependent on irrigation) and the reduction of yields in the rainy season (currently, Kharif crops are partially dependent on irrigation).

2. Methodology

2.1. Externality Selection, Data Collection and Scenario Development

Data Collection and sources

Within the context of this project the authors were partnered with SABMiller to develop a method to evaluate the impacts on natural capital externalities of SABMiller's Saanjhi Unnati (Progress through Partnership) Barley production extension program in Rajasthan India. An initial desk study was completed in September 2012, but all parties involved felt that the analysis had been hampered by a shortage of data. The work was further developed through a continuing collaboration with important new data from a series of focus group meetings with SABMiller extension officers in Rajasthan in February 2013 carried out and reported on by an external consultant.

Data used in this study on agronomic inputs was provided by farm extension worker focus groups along with secondary data sources (table 2). Values used to calculate outputs such as emission factors were mainly derived from standardised methods and guidelines such as the IPCC guidelines (table 2). Where available, uncertainty values are provided (see quantifying externalities section for further details).

It is acknowledged that the project had limited resources and therefore a limited focus. For example we have no direct verification of farmers' perspectives and experiences, no fieldwork data to examine local socio-economic context, no assessment of downstream processing, indirect impacts or displacement effects. For all intents and purposes, ours is an initial desk study of the barley production programme alone, largely based on secondary data.

Selection of externalities to quantify

This project focuses on a number of externalities where data on inputs and methods to calculate impact/outputs were available (Table 1; figure 1).This led to carbon balance (greenhouse gases and soil carbon storage) and water balance (green, blue and grey water) being included (table 1 and table 2). Impacts on biodiversity and corresponding services and function such as nutrient recycling could not be quantified due to lack of available data on level of pesticide application and any measure of biodiversity from the system. Also the effect of eutrophication on provisioning and supporting services from biodiversity such as fish stocks are not considered due to lack of available data.

Although total loss of biodiversity and the pollution caused by excessive use of agricultural chemicals is probably quite high in Rajasthan the disappearance of the shallow aquifer and (as we assume) the associated destruction of fresh water and riparian habitats has already taken place before the company became active in the area. In this case study we seek to capture values at the margin and it does not make sense to attribute historical losses of biodiversity to activities by an actor which arrived later.

Table 1 Quantified inputs and outputs to the study agricultural system

Inputs to the system	Output		
	Atmospheric	Water	Soil
Urea $CO(NH_2)_2$	Green house gas emissions CO_2 + Volatilisation of nitrogen to N_2O	NO_3 - release of nitrates through runoff and leaching to local water bodies resulting in Eutrophication	
DAP (Diammonuim Phosphaste) $(NH_4)_2HPO4$	Green house gas emissions N_2O	NO3 + P_2O_5 – Nitrate and Phosphates resulting in Eutrophication	
Organic matter (Animal manure and crops residues)	Green house gas emissions N_2O	NO3 + P_2O_5 Nitrate and Phosphates resulting in Eutrophication	Increased organic matter
Fossil Fuels (ground water pumps)	Green house gas emissions CO_2		
Ground water (blue water)		Reduction in water availability and quality. Runoff and leaching resulting in Eutrophication	
Rain water (green water)		Runoff and leaching resulting in Eutrophication	

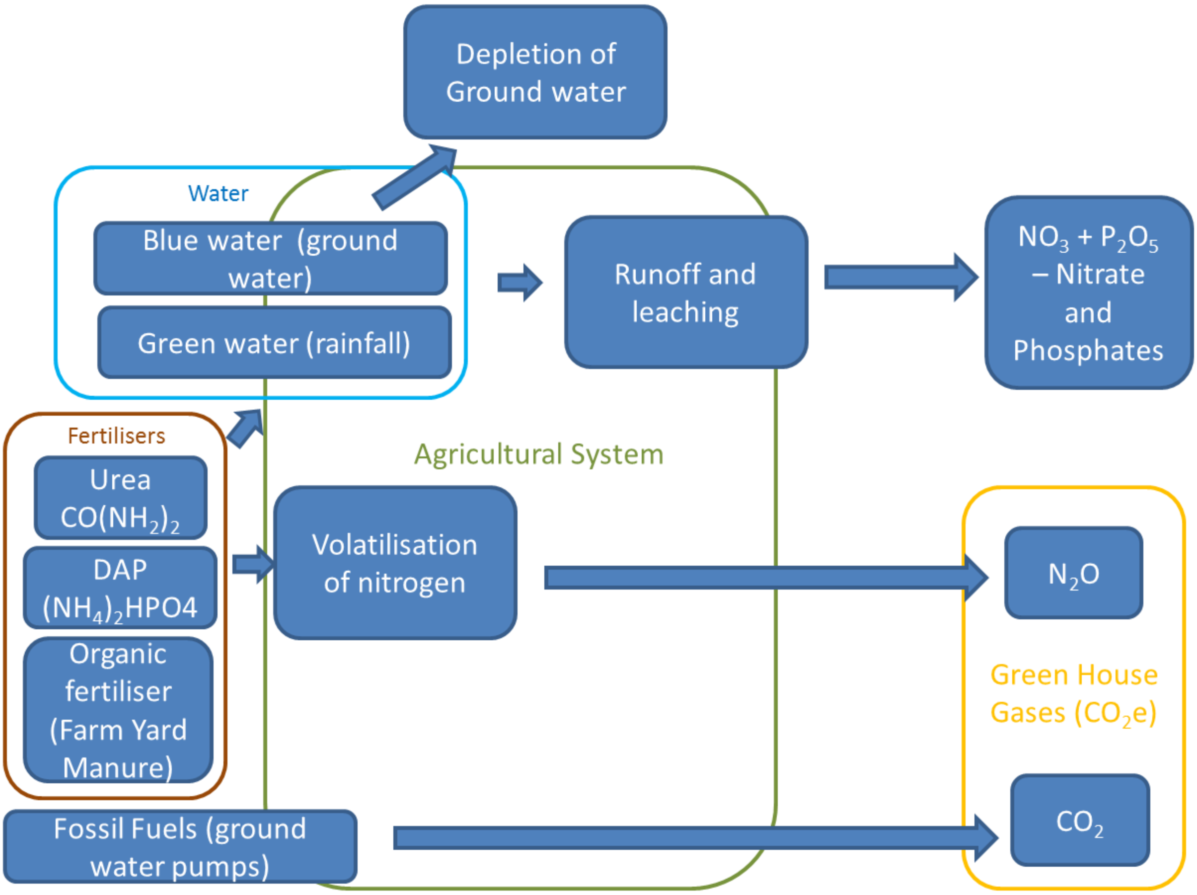

Figure 1 Quantified inputs and outputs to agricultural system

Table 2 Ecosystem service – goods, impact/externalities quantified and data source and method applied in this study

Ecosystem service (MEA Category)	Externality		Units	Method
Regulating	Green house Gas Emissions	N_2O Urea/DAP/FYM	kg/ha kg/ton	**Method:** emission factor 0.01 IPCC tier 1 guidelines (De Klien et al 2006) **Data:** Kg/ha of Urea, DAP and FYM derived for extension worker focus groups
		CO_2 ground water pumping	kg/ha kg/ton	**Method:** Emissions 1000m^3 -1m 0.665kg C – diesel/3.873 kg C electric pumps. **Data:** Blue CWU (ground water) derived this study (see below) Ground water level/Well depth (Central Groundwater Board 2007)
Regulating	Carbon storage		Tonnes/ha	**Method:** (0 – 30cm) IPCC tier 1 guidelines (Aalde et al 2006) $SOC = SOC_{REF} \bullet F_{LU} \bullet F_{MG} \bullet F_I$
Regulating (grey) Provisioning	Water Consumption/Water quality As the water foot printing method is used both are measured in terms of water consumption (m^3).	Green Water	m^3/ha m^3/ton	**Method:** Crop evapotranspiration CROPWAT model (Allen et al 1998) CWU - Hoekstra et al 2011 **Data:** Kc and LGP (various see section 3.2)
		Blue Water	m^3/ha m^3/ton	
		Grey Water	m^3/ha m^3/ton	**Method:** Run off and leachate values (Lv et al 2010; Chapagain and Orr 2010) **Data:** Kg/ha of Urea, DAP and FYM derived for extension worker focus groups. EU water quality standards (Liu et al 2012)

2.2 Scenario approach and baseline selection

The purpose of the scenarios (table 3) was to estimate the change in production and yield levels based on the impact of the company and to use this to estimate change in externalities. Four scenarios were developed. An historical pre-company scenario (2005-2006) predating the companies establishment in the area and three present time scenarios (2012-2013). The present time scenarios include the current baseline scenario representing farmers which are not working with the company and two current company scenario representing farmers which have benefited from the companies extension programme. Selection of base line scenario should be carefully considered. In this case this it was selected as the current state (business as usual). However over a longer time frame, this current state will not be sustainable given the shrinking ground water resources in the region.

Ministry of Agriculture district level yield and production area data (Ministry of Agriculture, Govt. of India) was used to set historical (Scenario 1) and baseline scenarios (Scenario 2) and account for change in yield and production due to factors other than the presence of the company (i.e. environmental or market factors). SABMiller works with 6000 farmers in Rajasthan, approximately 3000 of which are in Jaipur. Jaipur has a population of over 6.5million, so we assume that the company's activities have a negligible effect on district level yield or production area data. To account for year to year variation in the Ministry of Agriculture, Govt. of India district data on yield and production area data a regression model was run to model a line of best fit to the data. The precompany scenario and no company scenario (baseline) production and yield values were read off this line for the 2005-2006 and 2012-2013 growing seasons respectively.

For the company scenarios (Scenario 3a and 3b) values for production area and yield were derived from the SABMiller farmer extension workers (based on the results of the focus group). Scenario 3a assumes that the effects of the extension workers only influence Barley yield and not that of the other crops. While 3b assume the SABMiller extension service has an impact on all rabi crops in the system due to improved management techniques and access to information. Scenario 3a is considered the more conservative of the two scenarios (3a and 3b). This is because it is assumed that as the farm extension workers who work directly with the farmers on the production and sale of barley will have a greater knowledge of this crop over the others.

Based on comparison between the yield data expressed by the focus group studies and the government district level data yield, differences were found between the baseline and the company scenarios. While these increases are substantial they are with in the 45 – 70% yield gaps for major crops identified by Mueller et al (2012).

The drive for increased agricultural intensity in coexistence with fertiliser subsidies has led to an increase in fertiliser applications across India (Sharma 2012). Rajasthan showed a 26.2% increase in fertiliser use in kg/ha between 2000 – 2010 (Sharma and Thaker 2011). Based on this we assume a 13% fertiliser increase between the historical and current scenarios (table 3). Based on data on ground water levels in Jaipur and rate of decline in ground water (worst affected agricultural blocks have experienced a drop 2.2m/y in groundwater for the period 2001-2006 (CGWB 2007)) depths of 30m are estimated for the historical and 40m for the baseline and company scenarios. For barley, the company provides farmers a 5% price premium above the market rate. This is incorporated into the scenarios (table 3).

Although the high quality malt barley has proved more productive for the company in terms of quality and processing, at the farm production level no quantifiable differences between 6 row feed and 6 row malt Barley have been identified so these are not considered separately. Although there has been some interest in 2 row malt varieties these are not currently in production so are not considered.

Additional Management influences[2] (not described in table 3)

The focus group discussions identified a number of agronomic management changes brought about by farmers' exposure to Farmer extension officers. UREA usage for barley was reduced from 45 kg/acre to 36kg/ha (32 - 40 kg/acre). The extension officer noted that urea added height to the barley plant so higher plants were more lodge prone in case of excess irrigation or rain, leading to a yield reduction due to losses. Seed rate for barley was reduced from 60 kg per acre to 45-55 kg/acre. The effect of this was a small reduction in the cost of production for Barley. These effects are incorporated into the scenarios.

Scenario scale and study boundaries: The study is implemented on a model farm in the district of Jaipur. Based on farmer extension focus group data and government data (Ministry of Agriculture, Govt. of India) the average holding size for Rajasthan is estimated to 2.8ha. An assumption is made that 100% of all production area for each crop is irrigated during the Rabi season. While the choice of Rabi crops can influence the choice of Kharif crops externalities from the Kharif crops are not considered within the study as the company has less influence over this.

[2] Irrigation timing for barley has been modified by farmers due to the influence of the extension officers. The irrigation previously conducted at approx 30 days after sowing is now conducted between the 21st to 25th day. This is thought to improve growth and reduce number of irrigation applied to crop. In some cases there has also been a reduction in the depth of irrigation to address the consideration of barley as shallow root depth plant. The direct effect of irrigation timing and depths have not been considered in the scenarios due to lack of data. Indirect effects for both reduction in urea application and irrigation timing and depth have been accounted for though changes in yield.

Based on the above the following scenarios were derived:

Table 3 Jaipur Scenarios

Scenario	**Proportion of crop area (%)**				**Yield change from Baseline (%)**				**Barley price change (%)**	**Inorganic Fertiliser application change (%)**	**Ground water level change**
	Barley	*Wheat*	*Gram*	*Mustard*	*Barley*	*Wheat*	*Gram*	*Mustard*			
Scenario 1 (2005-2006) Historical - Precompany	14	41	15	30	- 15	- 19	-22	- 22	Current	-13%	-10m
Scenario 2(2012_2013) baseline No company	15	36	14	35	0	0	0	0	Current	0	0
Scenario 3a (2012-2013) Company (conservative)	35	30	10	25	+55	0	0	0	Current+5	0	0
Scenario 3b (2012-2013)Company (non conservative)	35	30	10	25	+55	+24	+11	+66	Current+5	0	0

3. Quantification of Externalities

The first part of this section seeks to quantify various emissions of greenhouse gasses as well as carbon storage in the soil. The second part focuses on quantifying blue, green and grey water.

3.1 Greenhouse gasses and carbon storage

N_2O Emissions

IPCC guidelines (De Klein et al 2006) provide 2 standard conversion factors for determining nitrous oxide emissions based on mineral fertiliser and organic amendments, for flooded rice (0.003, uncertainty range 0.000 – 0.006) and for all other crops (0.01, uncertainty range 0.003-0.03).

The amount of synthetic fertilisers (Urea and DAP) and farm yard manure (FYM) applied per hectare of land was provided form the farm extension worker focus groups. The amount of nitrogen applied per hectare was based on its proportion based on molecular weight (Urea 46% ($CO(NH_2)_2$/DAP 18% $(NH_4)_2HPO4$) multiplied by the conversion factor from De Klein et al (2006). The amount of N_2O produced from farm yard manure was derived assuming nitrogen made up 6% of the material (Chambers et al 2001). The level of nitrogen emitted was converted to the amount of N_2O produced based on molecular weight.

Table 4 N_2O emissions from Urea fertilisers

Crop	Urea application kg ha^{-1}	Amount of nitrogen kg ha^{-1}	Conversion factor	N_20_N emissions kg ha^{-1}	N_20 emissions kg ha^{-1}	N_20 emissions kg ha^{-1} uncertainty*
Barley	90	41.4	0.01	0.414	0.6505596	0.195 - 1.95
Wheat	100	46	0.01	0.46	0.722844	0.216 - 2.16
Mustard	50	23	0.01	0.23	0.361422	0.108 - 1.08
Gram	344	158.24	0.01	1.5824	2.48658336	0.746 - 7.476

*Conversion factor uncertainty (0.003 – 0.03).

Table 5 N_2O emissions from DAP (Diammonuim Phosphate) fertilisers

Crop	DAP application kg ha^{-1}	Amount of nitrogen kg ha^{-1}	Conversion factor	N_20_N emissions kg ha^{-1}	N_20 emissions kg ha^{-1}	N_20 emissions kg ha^{-1} uncertainty*
Barley	100	18	0.01	0.18	0.282852	0.085 - 0.85
Wheat	100	18	0.01	0.18	0.282852	0.085 - 0.85
Mustard	100	18	0.01	0.18	0.282852	0.085 - 0.85
Gram	185	33.3	0.01	0.333	0.5232762	0.156 - 1.56

*Conversion factor uncertainty (0.003 – 0.03).

Table 6 N_2O emissions from farm yard manure

crop	Farm Yard Manure application kg ha^{-1}	Amount of nitrogen kg ha^{-1}	Conversion factor	N_20_N emissions kg ha^{-1}	N_20 emissions kg ha^{-1}	N_20 emissions kg ha^{-1} uncertainty*
Barley	22239	133.434	0.01	1.33434	2.096782	0.629 - 6.29
Wheat	24711	148.266	0.01	1.48266	2.329852	0.699 - 6.99
Mustard	24711	148.266	0.01	1.48266	2.329852	0.699 - 6.99
Gram	2670	16.02	0.01	0.1602	0.251738	0.076 - 0.76

*Conversion factor uncertainty (0.003 – 0.03).

The amount of N_20 produced from urea (table 4), DAP (table 5) and farm yard manure (table 6) were summed to give total amount (table 7)

Table 7 Total N_2O emissions from fertilisers

Crop	Urea - N_20 emissions kg ha^{-1}	DAP - N_20 emissions kg ha^{-1}	FYM - N_20 emissions kg ha^{-1}	Total - N_20 emissions from fertilisers kg ha^{-1}	Total - N_20 emissions from fertilisers uncertainty* kg ha^{-1}
Barley#	0.6505596	0.282852	2.0967819	3.030193476	0.91 - 9.1
Wheat	0.722844	0.282852	2.3298519	3.335547924	1 - 10
Mustard	0.361422	0.282852	2.3298519	2.974125924	0.9 - 9
Gram	2.48658336	0.523276	0.2517383	3.26159784	0.98 - 9.8

*Sum of min and max values from uncertainty range (see tables 4,5 and 6).

CO_2 - Emissions from Urea

Adding urea to the soil during fertilisation leads to a loss of CO_2 that is fixed in the industrial process. However as CO_2 is fixed in the industrial process therefore there is no overall net addition or removal in the atmosphere. It is possible that bicarbonate could leach to deep ground water, and or lakes and oceans and is thus not contributing to CO_2 emissions immediately. However for the purposes of this study it was assumed that this has led to no net gain or loss in atmospheric CO_2.

CO_2 emissions from pumping ground water for irrigation

In order to derive the amount of CO_2 produced from pumping ground water (table 8) it is necessary to identify the amount of water and depth from which it is extracted and the pump power sources. Values on consumptive water use (CWU) for blue water were calculated based on Hoekstra et al (2011) using the CROPWAT modelling software (FAO 2009) (see section 3.2). Depth of the well was based on data from Central Groundwater Board, Jaipur (2007). In 2006, 90% of wells were considered to be dug wells or dug-cum bore wells and the majority of the 13 blocks which constitute Jaipur district, ground water stood at of 20-40m. 9% of the wells were considered not to have pumps and 2% of wells were considered to be tube wells. Due to the likely low proportion of the water pumped from tube-wells and pump less wells these are not considered in the analysis. The worst affected agricultural blocks have experienced a drop 2.2m/y in groundwater for the period 2001-

2006. Therefore for the historical scenario all wells are assumed to be electric and 30m in depth and for the current scenarios to account for the effects of the drop in the water table 40m in depth. All pumps are assumed to be electric. Nelson et al (2009) estimated that carbon emissions to lift a $1000m^3$ of water 1m to be 3.873 kg C with electric pumps. Electricity grid transmission losses (5%) and efficiency of electrical and diesel pumps (30%) are taken into account (Nelson et al 2009).

Table 8 CO_2 emissions from pumping ground water

Crop	Well depth (m)	Ground water pumped (m^3)	Emissions to pump $1000m^3$ 1m (kg)	C carbon produced (kg ha^{-1} CO_2_C)	CO_2 (kg ha^{-1})*
Barley	40	4230	3.873	655	2403
Wheat	40	5820	3.873	902	3306
Mustard	40	4900	3.873	759	2783
Gram	40	4760	3.873	737	2704

*Note on sensitivity - This set of assumptions is likely underestimate the contribution of electricity use to CO_2 emissions. For example, the transmission electricity losses are believed by some observers to be in the order of 25 percent. The efficiency losses in pumps are likely to make the conversion from actual to theoretical pump efficiency 20 percent or lower (Nelson et al 2009).

Global warming potential

Global warming potential (GWP) is an index defined as the cumulative radiative forcing between the present and some chosen later time "horizon" caused by a unit mass of gas emitted now. It is used to compare the effectiveness of each GHG to trap heat in the atmosphere relative to some standard gas, by convention CO_2. The GWP for CH_4 (based on a 100-year time horizon) is 21, while that for N_2O, it is 310 when GWP value for CO_2 is taken as 1 (Lv et al 2010).

The GWP of different treatments were calculated using the following equation (Watson et al., 1996). GWP (CO_2e) = CO_2 emission+CH_4 emission*21+N_2O emission*310 (Pathak 2005).

In this study we quantify N_2O (table 4-7) and CO_2 (table 8). Based on the equation above global warming potential is calculated as CO_2 equivalent (CO_2e) (Table 9)

Table 9 Total CO_2e emissions

Crop	N20 emissions	Total CO2	CO_2e per hectare	CO_2e per hectare uncertainty
			(kg ha^{-1})	
Barley	3.0302	2403	3342	2685 - 5221
Wheat	3.3355	3306	4340	3616 - 6408
Mustard	2.9741	2783	3705	3059 - 5549
Gram	3.2616	2704	3715	3007 - 5737

*Uncertainty only accounts for N_2O emissions. For details on potential sensitivity analysis for CO_2 emissions for pumping see above and Nelson et al (2009).

Carbon storage

In order to estimate the effects each crop has on carbon storage IPCC tier 1 guidelines were used (Aalde et al 2006; Lasco et al 2006). Above ground biomass is not considered for annual crops under IPCC guidelines as there is no net accumulation of above ground carbon stocks (Lasco et al 2006). Influences on soil carbon stocks include crop choice and management practices including residue, tillage and fertilizer management and intensity of cropping management (Lasco et al 2006). IPCC guidelines provide reference values for soil organic carbon (SOC_{REF}) for soil organic carbon stocks (0 – 30cm) for different climatic regions (under native vegetation) and soil types. Under tier 1 guidelines the stock change factors land use type (F_{LU}), management regime (F_{MG}) and input of organic matter (F_I) are used (Lasco et al 2006).

$$SOC = \sum_{c,s,i} \left(SOC_{REF_{c,s,i}} \bullet F_{LU_{c,s,i}} \bullet F_{MG_{c,s,i}} \bullet F_{I_{c,s,i}} \bullet A_{c,s,i} \right)$$

To derive the Soil organic carbon reference value (SOC_{REF}) for crop production, the Jaipur region was defined climatically as Tropical dry and a Soil with High Activity Clay. Soil class was assigned based the majority of the Jaipur district being dominant soil type being classified as a Cambisols soil type based on the Harmonised World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012)

All crops were classified under the same landuse (F_{LU}) category as long term cultivated, tropical and dry, management system (F_{MG}) as full tillage and input level (F_I) (high with manure). Stock change factor categories was assigned based on information from the extension worker focus groups (addition of manure and residues) using the classification scheme in Lasco et al (2006).

Based on this criteria the reference carbon stock for all crops was calculated as:

$SOC = SOC_{REF} \bullet F_{LU} \bullet F_{MG} \bullet F_I =$

Crop SOC 30.42 TONNES C HA^{-1} = 38• 0.58 • 1.38 (over 20 years)

Under IPCC tier 1 stock change factor classification all crops in this study are assigned the same value. The IPCC guideline broad classifications do not consider quantity of fertiliser or residue inputs. Process orientated models which include soil carbon storage such as the Denitrification-Decomposition (DNDC) model (University of New Hampshire 2012) have been used to identifying variation in soil organic carbon based on crop type and management (Liu et al 2006). In this study such a model was not used due to lack of detailed information on tillage and residue management.

3.2 Water

For crop plants, the water footprint is mainly determined by evapotranspiration occurring during the timespan between sowing and harvest. While the water applied through rainfall and irrigation may be greater than that evaporated, the water that has percolated into the soil or lost as runoff is not classified as utilised or consumed water, because it will be re-added to the system as groundwater (Schubert 2012). Water use from effective rainfall (green water) ($CWU^{\text{Effective rain}}$) and from irrigation (blue water) ($CWU^{Irrigation}$) are estimated based broadly on the Water Footprint Network Standard methods in Hoekstra et al (2011) using the CROPWAT 8 modelling tool (FAO 2009).

The water depletion due to pollution ($DEP^{Pollution}$) (grey water) is calculated by quantifying the dilution water volumes required to dilute waste flows (runoff and leachate) to such extent that the quality of the water remains below agreed water quality standards (Hoekstra et al 2011). The rationale for including this water component in the definition of the water footprint is similar to the rationale for including the land area needed for uptake of anthropogenic carbon dioxide emissions in the definition of the ecological footprint. Land and water do not function as resource bases only, but as systems for waste assimilation as well (Chapagain et al 2006).

Green and Blue Water

Hoekstra et al (2011) estimates green and blue water use by calculating the crop evapotranspiration values (ET_c) (mm/growing period) based on method described in Allen et al (1998). This is achieved by combining the crop coefficient and the estimated reference evapotranspiration. The evapotranspiration met by irrigation (ET_{Blue}) is estimated based on the deficit water requirement when evapotranspiration from rainfall (ET_{Green}) does not meet full water requirements. Evapotranspiration values are then multiplied by a factor of 10 to provide the consumptive water use values (m^3 ha^{-1}) ($CWU^{Effective\ rain}$ and $CWU^{Irrigation}$).

The CROPWAT programme uses local climate data to derive the reference evapotranspiration for the reference surface (a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23) for the study location using the Penman-Monteith method. This is multiplied by the crop coefficient (K_c) which incorporates crop characteristics for the study crop based on albedo, crop height, aerodynamic properties, and leaf and stomata properties.

Allen et al (1998) provides K_c values and length of growth period (LGP) for a number of major crops. However they do not consider varietal differences and are estimated for standardised environmental conditions. The importance of using locally derived Kc values to account for variation in crop variety selection as well as local climate conditions has been highlighted by a number of authors (i.e. Tyagi et al 2000; Singandhupe and Sethi 2005; Ko et al 2009). Local crop evapotranspiration values (ET_c) and crop coefficients ($K_{c)}$ have been derived based on lysimeter studies (Alazba et al 2003; Ko et al 2009), however such studies have been conducted for a limited number of locations and varieties.

Changes in vegetation and ground cover mean that the crop coefficient (K_c) varies during the growing period. Three K_c values are required to describe the crop coefficient curve over the growth period. The initial stage ($K_{c\ ini}$), the mid-season stage ($K_{c\ mid}$) and at the end of the late season stage ($K_{c\ end}$). Allen et al (1998) provides generic values information for length of growth period (LGP) as well as the length of each stage for a number of crops, however this can also vary dependent on variety and location.

To identify suitable K_c and length of each growth stage values for this study a literature search was conducted. For all study crops no lysismeter studies or local K_c values were identified for Jaipur or even in Rajasthan. Therefore K_c values were selected from the studies; conducted locally, in the same agro climatic zone and/or which include the same varieties as those grown in the study area were selected (table 12 and 13). In order to test the robustness of the K_c values selected a sensitivity analysis was conducted using K_c values derived from the wider literature (Appendix A and table 14). K_c values were included in the sensitivity analysis from sources in which studies had been conducted in India or outside India in a similar climatic zone to that found in Jaipur (semi-arid). For studies which provided data on length of growth period and length of each growth stage, ET_{Blue} and ET_{Green} were calculated using the LGP provided by that study as well as the LGP provided in the farmer extension focus groups. The planting date for all crops was acquired from the farm extension workers.

The CROPWAT model offers two different options to calculate evapotranspiration: the 'crop water requirement (CWR) option' and the 'irrigation schedule (IrrS) option'. Hoekstra et al (2011) indicate that the 'irrigation schedule option' is more accurate as the underlying model includes a dynamic soil water balance which keeps track of the soil moisture content over time using a daily time step. This method requires soil data. The CWR option does not consider a soil water balance but uses the concept of effective precipitation. This is the part of the total amount of precipitation that is retained by the soil so that it is potentially available for meeting the water need of the crop. The default setting in CROPWAT using the USDA SCS equation (United States Department of Agriculture, Soil Conservation Service) to measure effective rainfall was used. Outputs for both analysis types are presented below and in the sensitivity analysis (Appendix A and table 14). For the irrigation schedule (IrrS) option the default was used, 'irrigate at critical depletion' and 'refill soil to field capacity' which assumes 'optimal' irrigation where the irrigation intervals are at a maximum while avoiding any crop stress[3].

The CROPWAT software requires a number of data files (Climate, Crop and Soil files). Climate data was downloaded from CLIMWAT for CROPWAT (Grieser 2006). Crop files for Barley, Wheat, Mustard and Gram were developed based on the K_c and length of growth stage as described above. Most values for rooting depth, critical depletion fraction and yield response all necessary to calculate the 'irrigation schedule option' were derived from appropriate crop files provided with the software (FAO 2009) unless stated otherwise (table 10).

[3] An alternative method is proposed in Hoekstra et al (2009), using the irrigation schedule option in CROPWAT in which the green and blue water use is calculated by performing two different soil water balance scenarios. This method is used in a number of published reports and papers (FAO 2005; Siebert and Döll 2010; Liu and Yang 2010; Mekonnen and Hoekstra 2010; Gerbens-Leenes and Hoekstra 2012). However this method has been superseded by the Water Footprint Network Standard (Hoekstra et al 2011), which has been used in many recent papers published by the Water Footprint network (Mekonnen et al 2012; Vanham et al 2013). and is used in this study as described above

Table 10 Sources of data required for CROPWAT Crop file for water use analysis and sensitivity test

Variable	Source of data			
	Barley	*Wheat*	*Mustard*	*Gram*
K_c values	Various see sensitivity analysis			
Lengths of growth period	Farm extension workers and various			
Length of each growth period stage	Various see sensitivity analysis			
Rooting depths	FAO Barley	FAO Winter Wheat	Kar et al 2007	FAO Pulse
Critical depletion fraction	FAO Barley	FAO Winter Wheat	FAO Cabbage Brassica	FAO Pulse
Yield Response	FAO Barley	FAO Winter Wheat	FAO Cabbage Brassica	FAO Pulse
Crop height	FAO Barley	FAO Winter Wheat	Shankar et al 2006	FAO Pulse

FAO – corresponding crop file available with CROPWAT 8 software (FAO 2009)

The CROPWAT soil file was created based on the dominant soil type classification for the Jaipur district Eutric Cambisol derived from the World Harmonised Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). Soil characteristics for Eutric Cambisol were utilised to populate the CROPWAT soil file (table 11). The maximum infiltration rate was derived based on medium texture soil (loam) file provided with the CROPWAT software (FAO 2009). The initial soil moisture depletion was set to 100% assuming no available soil moisture within the soil at the start of the Rabi season (due to water use from Kharif crops).

Table 11 HWSD data used to populate CROPWAT soil file for Jaipur

HWSD Characteristic	Eutric Cambisol – HSWD Value	CROPWAT soil file	Jaipur soil file
Soil Texture	Medium	Maximum rain infiltration rate (mm/day)	40 (medium texture soil file from CROPWAT (FAO2009))
Soil Depth (cm)	100	Maximum rooting depth (cm)	100
Available Water Capacity (AWC) (mm/meter)	150	Total available soil moisture (mm/meter)	150

Table 12 Source for Kc values selected and rational

Crop	Source	Rational for selection
Barley	Sabu et al 2000	Study area in Pujab, India – same agroclimatic zone as study site (semi-arid)
Wheat	Tyagi et al 2000	Study area Haryana, India – same agroclimatic zone as study site (semi- arid). Study Variety HD 2329 grown in Jaipur
Mustard	Sabu et al 2000	Study area in Pujab, India – same agroclimatic zone as study site
Gram	Sabu et al 2000	Study area in Pujab, India – same agroclimatic zone as study site

Table 13 Selected Length of growing period and Crop coefficients

Crop	Sowing date	Length of growing periods (days)					Crop coefficients in growth periods			
		Initial	Develo pment	Mid-Season	Late Season	Total	Initial	Develo pment	Mid-Season	Late Season
Barley	10/11	15	25	50	30	120	0.34	0.69	1.05	0.65
Wheat	20/11	16	27	54	33	130	0.5	1.36	1.24	0.42
Mustard	15/10	15	45	65	25	150	0.34	0.61	0.88	0.82
Gram	15/10	23	47	52	28	150	0.26	0.63	1	0.63

Table 14 Crop evapotranspiration, evapotranspiration met by irrigation (ETblue) and rainfall (ETgreen) for Crop Water Requirement (CWR) and Irrigation Schedule (IrrS)

Crop	Method	ETa	ET_{Blue}	ET_{Green}
Barley	CWR	455 (461, 80)	425 (432, 77)	30 (28, 4)
	IrrS	448 (455, 75)	423 (430, 71)	25 (24, 4)
Wheat	CWR	618 (622, 63)	584 (586, 62)	35 (35, 1.2)
	IrrS	612 (614, 57)	582 (583, 56)	30 (32, 2)
Mustard	CWR	532 (520, 116)	496 (489, 109)	35 (31,7)
	IrrS	523 (508, 103)	490 (480, 98)	33 (27,7)
Gram	CWR	515 (447, 109)	480 (415, 103)	35 (31, 7)
	IrrS	508 (442, 102)	476 (413, 96)	32 (28,6)

Values in brackets represent mean values and standard deviation respectively from sensitivity analysis.

In order to account for recharging of ground water from rainfall a “Ground Water Loss” values is calculated. The amount of “Rain recharge” is estimated by combining the green water not used and “Total Rain Loss” calculated by CROPWAT. The green water not used is estimated by subtracting the CWU_{green} for each crop from the maximum CWU_{green} for all crops in the study (in this case mustard). This difference in CWU_{green} takes account of differing amount of rainfall being used in evapotranspiration by the plant and rainfall during times in which the crop is not yet planted or has already been harvested while other crops are still growing. “Total Rain Loss” is estimated by CROPWAT based on the soil water balance model. This is the amount of rain water which is estimated to runoff or be lost to deep percolation. The “Rain recharge” is then subtracted from the blue water (CWU_{Blue}) to estimate the “Ground Water Loss” (table 15).

Table 15 Green and Blue Consumptive Water Use (CWU) total rain loss, rain recharge and groundwater loss based on selected Kc Values (table 11) and Irrigation Schedule CROPWAT option

Crop	Eta	ET_{Blue}	ET_{Green}	CWU_{Blue}	CWU_{Green}	Total rain loss	Rain recharge	Ground water loss
	mm/growing period					$m^3\ ha^{-1}$		
Barley	448	423	25	4230	250	30	110	4120
Wheat	612	582	30	5820	300	30	60	5760
Mustard	523	490	33	4900	330	0	0	4900
Gram	508	476	32	4760	320	10	20	4740

Pollution/Grey water

To estimate the impacts of water pollution from fertiliser application the concept of grey water is used. The method used here broadly follows the guidelines for grey water foot printing described in Hoekstra et al (2011). Grey water consumption is quantified based on the dilution water volumes required to dilute waste flows to such extent that the quality of the water remains below agreed water quality standards (Chapagain et al 2006; Mekonnen and Hoekstra 2010).

Nutrient loss rates

When a chemical is applied to the soil only a fraction seeps into the groundwater or runs off over the surface to a surface water stream. The nutrient loss rate or pollutant load is the fraction of the total amount of chemicals applied that reaches the groundwater or surface water. This fraction of applied chemicals that reaches the groundwater or surface water cannot be measured directly, since it enters the water in a diffuse way. Estimates can be made of the fraction of applied chemicals that enter the water system by using simple or more advanced models. In this case we assume a fixed fraction of the applied chemicals finally reach the ground- or surface water (Hoekstra et al 2011).

Different Nutrient loss rates have been estimated by various authors for different crops, for both leaching and runoff.

Nitrate: Hoekstra et al (2011) assume the quantity of nitrogen that reaches free flowing water bodies has been assumed to be 10% of the applied fertilization rate (in kg/ha/yr). Estimated rates of nitrogen loss through leaching and runoff have been made for various crops such as rice (5%) (Chapagain and Hoekstra 2011), wheat (10%) (Chapagain and Orr 2009) and maize (10%) (Gerbens-Leenes and Hoekstra 2009). Mekonnen and Hoekstra (2011) assumed an average of 10% of total nitrogen for all crops included in the study. De Klein et al (2006) give a generic value of 30% for runoff and leachate.

Country specific values have been provided by some authors such as rice –wheat production system in China (Lv et al 2010) which provide specific values for runoff (4.8% (1.0 – 8.6)) and leaching (3.8% (1.0 – 6.6)) and Zhu et al (2000) have suggested the leaching losses to be 2% for rice-wheat rotation. No local data could be derived for Rajasthan or India so a value of 10% was assumed for all crops.

Phosphate: Few authors provide loss rates for phosphate. Lv et al (2010) gave the loss rate of leaching and runoff for phosphorous fertilizer is 0.6% and 0.4%, respectively. In this study a loss value of 1% was assumed for all crops.

Water pollution standards

Care should be made when selecting permissible limits of nitrates and phosphates. Within Europe there is a large range of target values for different nitrogen and phosphorus compounds (Laane et al 2005) and the worldwide range is even larger. Liu et al (2012) identified European target level based on scattered information on target levels for N and P concentrations from the literature. Using this method, they provide values for dissolved inorganic, dissolved organic and particulate forms of nitrogen and phosphorous

Various permissible limits have been used in previous studies. Based on EU Nitrate Directives safe maximum limits should not exceed 50 mg/l (Chapagain and Hoekstra 2011). The EPA (2005) recommendations for nitrate in drinking water is 10 mg/l (Chapagain et al 2006). Van Riesen et al (2005) gives maximum permissible levels total phosphorous within the EU of between 1-2mg/l. Liu et al provide values for total Phosphorus is given as 0.95 mg/l and Laane (2005) 0.048 – 0.9. In this case EU standards were selected for both Nitrates (50mg/l) and Phosphorous (1mg/l) (table 19).

Based on urea and DAP application the amount of nitrogen and phosphorous applied is multiplied by the nutrient loss conversion factors to calculate the levels of N and P in the runoff and leachate (table 16 and 17). It is assumed that FYM contains 6% nitrogen and 3.5% Phosphate P_2O_5 (Chambers et al 2001). Phosphate levels are converted to phosphorous based on molecular weight (table 18).

The grey water consumption was then estimated based on the amount of water required dilute waste flows to such extent that the quality of the water remains below agreed water quality standards. As in this case if more than one pollutant is considered the most critical one is accounted for (highest water volume) (table 19). Total consumptive water use from blue, green and grey water is given in table 20.

Table 16 Urea $CO(NH_2)_2$ leachate and runoff emissions Nitrogen (Based on the molecular weight basis urea is 46% nitrogen

Crop	Urea application kg ha^{-1}	Amount of nitrogen kg ha^{-1}	Conversion factor	$N0_3$_N emissions kg ha^{-1}
Barley	90	41.4	0.1	4.14
Wheat	100	46	0.1	4.6
Mustard	50	23	0.1	2.3
Gram	344	158.24	0.1	15.824

Table 17 DAP Diammonuim Phosphaste - $(NH_4)_2HPO4$ leachate and runoff emissions (Based on the molecular weight basis DAP is 18% nitrogen and 46% Phosphorous).

Crop	Fertiliser application kg ha^{-1}	Amount of nitrogen kg ha^{-1}	Amount of P kg ha^{-1}	Conversion factor (nitrogen)	Conversion factor (phosphorus)	$N0_3$_N runoff and leachate kg ha^{-1}	P runoff and leachate kg ha^{-1}
Barley	100	18	46	0.1	0.01	1.8	0.46
Wheat	100	18	46	0.1	0.01	1.8	0.46
Mustard	100	18	46	0.1	0.01	1.8	0.46
Gram	185	33.3	85.1	0.1	0.01	3.33	0.851

Table 18 Farm Yard Manure leachate and runoff emissions

Crop	FYM application kg ha^{-1}	Amount of nitrogen kg ha^{-1}	Amount of P_2O_5 kg ha^{-1}	Amount of P	Conversion factor (nitrogen)	Conversion factor (phosphorus)	$N0_3$_N runoff and leachate kg ha^{-1}	P runoff and leachate kg ha^{-1}
Barley	22,239	133.434	77.8365	33.4697	0.1	0.01	13.3434	0.334697
Wheat	24711	148.266	86.4885	37.19006	0.1	0.01	14.8266	0.371901
Mustard	24711	148.266	86.4885	37.19006	0.1	0.01	14.8266	0.371901
Gram	2670	16.02	9.345	4.01835	0.1	0.01	1.602	0.040184

Table 19 Total Grey water

Crop	Total - N from fertilisers kg ha^{-1}	Total NO_3 from fertilisers kg ha^{-1}	Grey water consumption m^3 NO_3	Total P runoff and leachate kg ha^{-1}	Grey water consumption m^3 P ha^{-1}	Grey water consumption m^3 P/NO_3 ha^{-1}*
Barley	19.2834	85.39791	1707.95829	0.794697	794.69695	1707.958286
Wheat	21.2266	94.00351	1880.07029	0.831901	831.90055	1880.070286
Mustard	18.9266	83.8178	1676.356	0.831901	831.90055	1676.356
Gram	20.756	91.91943	1838.38857	0.891184	891.1835	1838.388571

*the most critical pollutant is accounted for (highest water volume). EU standards were selected for both Nitrates (50mg/l) and Phosphorous (1mg/l)

Table 20 Total Consumptive water use

Crop	Eta	ET_{Blue}	ET_{Green}	CWU_{Blue}	Ground water loss	CWU_{Green}	GWU_{Grey}
	mm/growing period			m^3 ha^{-1}			
Barley	448	423	25	4230	4120	250	1708
Wheat	612	582	30	5820	5760	300	1880
Mustard	523	490	33	4900	4900	330	1676
Gram	508	476	32	4760	4740	320	1838

CWU: consumptive water use

3.3 Crop price and production costs

Crop and fodder prices, crop/fodder ratios and cost of production were derived from the farm extension worker focus groups. Crop and fodder prices were based on farm gate prices (table 21). A breakdown of production cost for barley is given in table 22. DAP and Urea costs were adjusted to account for reduction in fertiliser use for the historical scenario (Scenario 1).

Table 21 Crop yield and farm gate prices and cost of production

	Barley	*Wheat*	*Mustard*	*Gram*
Baseline crop yield tons/ha-1	2.9	3.3	1.1	1.1
Market price Rs/ton (US$/ton in parentheses)*	13250 (221)	12800 (213)	33000(550)	43000(717)
Crop/fodder weight ratio	1:1.5	1:2	1:2	
Baseline fodder yield	4.35	6.6	2.2	-
Fodder Rs/ton (US$ ha^{-1} in parentheses)*	8000 (133)	6500 (108)	2000 (33)	-
Company scenario Cost of production Rs ha^{-1} (US$ ha^{-1} in parentheses)*	32120 (535)	33360 (556)	18540 (309)	29650 (494)

*1$ = 60Rs

Table 22 Breakdown of the production costs of Barley

S.No.	Cost Heads	Amount Rs ha^{-1}
1	Land Preparation (Tractor + Labour)	4942
2	Seed Cost	1235
3	Labour for sowing (2)	741
4	DAP Cost	2965
5	Urea Cost	741
6	FYM	1977
7	Labour for Fertilizer application	741
8	Interculture operation (Manual- 5 in number)	1853
9	Pesticides (Cost+ Labour)	494
10	Irrigation charges	5189
11	Labour for irrigation	371
12	Harvesting labour (Manual)	5189
13	Threshing machine charges	19761482
14	Labour Threshing	600
	TOTAL	**32120**

Assumptions - Variety: 6 Row Feed/Malt, Seed Rate: 97 Kg/Acre Seed Cost: 12000 Rs/ton Labour cost: 150 Rs/Day. Unit per hectare

3.4 Scenario Outputs

Table 23 results of scenarios All values per 2.8 ha farm

Scenarios	Crop	Carbon storage	CO2e	CWUBlue	CWUGreen	Ground water loss	GWUGrey	Income	Income + Fodder	Cost of production	Farm Profit
		Tonnes $20yr^{-1}$	Kg yr^{-1}			m3 yr^{-1}			Rs farm $year^{-1}$		
Scenario 1 (historical)	*Barley*	12	1076	1658	98	1615	671	12842	14065	12851	1214
	Wheat	35	3989	6681	344	6613	2074	41144	45002	37719	7283
	Mustard	26	2507	4116	277	4116	1367	24948	25250	15191	9757
	Gram	13	1226	1999	134	1991	679	16254	16254	7595	8659
	Total	**85**	**8798**	**14455**	**854**	**14334**	**4791**	**95188**	**100571**	**73355**	**26913**
Scenario 2 (Current - Baseline)	*Barley*	13	1423	1777	105	1730	752	15347	16808	13817	2991
	Wheat	31	4375	5867	302	5806	1895	42578	46570	33627	12943
	Mustard	30	3631	4802	323	4802	1643	35574	36005	18169	17405
	Gram	12	1456	1866	125	1858	721	18542	18542	7268	11274
	Total	**85**	**10885**	**14311**	**856**	**14197**	**5010**	**112040**	**117925**	**72881**	**44613**
Scenario 3a (Current - Company - Conservative)	*Barley*	30	3275	4145	245	4038	1674	58433	63725	31478	32247
	Wheat	26	3646	4889	252	4838	1579	35482	38808	28022	10786
	Mustard	21	2594	3430	231	3430	1173	25410	25718	12978	12432
	Gram	9	1040	1333	90	1327	515	13244	13244	5191	8053
	Total	**85**	**10555**	**13797**	**818**	**13633**	**4941**	**132568**	**141495**	**77669**	**63517**
Scenario 3b (Current - Company - Non conservative)	*Barley*	30	3275	4145	245	4038	1674	58433	63725	31478	32247
	Wheat	26	3646	4889	252	4838	1579	43008	47040	28022	19018
	Mustard	21	2594	3430	231	3430	1173	39270	39746	12978	26292
	Gram	9	1040	1333	90	1327	515	14448	14448	5191	9257
	Total	**85**	**10555**	**13797**	**818**	**13633**	**4941**	**155159**	**164959**	**77669**	**86813**

Comparison of the baseline scenario (scenario 2) to the company scenarios (scenario 3a and 3b) shows a reduction in externalities as well as an increase in farm income due to effect of the extension services (table 23). In comparison to farmers not exposed to SABMiller's extension workers, there has been a shift in production area to barley (wheat (6%), mustard (10%) and gram (4%) - table 3) and a change in agronomic practices brought about by the availability of high quality barley seeds and extension advice. The impact of the extension services has led to a 4% reduction in blue water use, brought about by the shift to barley, which has the lowest blue water requirements. A 3% reduction is seen in GHG emissions (CO_2e), brought about by the lower energy requirement to pump ground water and the lower nutrient requirements of barley in comparison to wheat and gram. This is also influenced by the change in agronomic management brought about by the company to reduce the amount of UREA applied to Barley. Grey water is also reduced by 1.4% due to the shift from wheat and gram and the decline in fertiliser application to barley. The smaller reduction in the grey water externality in comparison to the other externalities is due to mustard having a slightly lower nitrogen input than barley across the 3 fertiliser types (table 19). The increase in farm income seen in the company scenarios has be brought about by the increase in yield due to improved varieties and management practices, good crop and fodder price for barley and the SABMiller premium.

It should be highlighted that the baseline (scenario 2) is subject to the same economic and environmental effects as the company scenario; this provides a robust counterfactual to the impacts of the extension services. The historical scenario (scenario 1) was included to look at the general trends occurring with the agricultural system in Jaipur. Comparison between the historical scenario and the baseline indicates a shift from wheat to mustard (and a very small shift to Barley) in the period 2006 – 2012 which reflects the aggregate behaviour of all farmers in Jaipur, in the absence of the company. As a consequence of this trend, there in a small decline in blue water (1%) externalities but an increase in GHG production and grey water likely due to the increase in fertiliser use brought about by fertiliser subsidies and intensification. Farm income has increased. The small reduction in blue water use could indicate that farmers are concerned about water use and are moving towards crops that require less irrigation, although they are also driven by the high value of mustard in comparison to wheat. The use of the historical scenario allows changes in externalities to be assessed relative to the historic trend for non-participating farmers (table 24). This indicated that over time of the study 2006 - 2013 GHG emissions (CO_2e) and grey water emissions have increased, but these increases are a lower under the company scenario; 16% (GHG emissions) and 31% (grey water) less than what would have happened in the absence of the company. Over this time, there has been a reduction in water use by farmers, but under the company scenario, that reduction is much bigger (409%) than what would have happened in the absence of the company. There has also been an increase in farm income, but under the company scenario, that increase has been much higher (107%) than what would have happened in the absence of the company.

Table 24 Differences between Scenarios

Differences between scenarios	C02 (kg/y)	Groundwater loss (use) (m^3/y)	Grey water (m^3/y)	Farm income
Historic to current baseline	+2087	-138	220	17700
Historic to company (cons)	+1757	-701	151	36604
from current baseline to company (cons)	-330	-563	-69	18905
company trend compared to historic trend (%)	-15.81	409.00	-31.37	106.81

Non - Quantified aspects

As well as the quantified effects described above, a number of non quantifiable aspects related to the biophysical aspects and the shift in Barley should be noted. With increasing variability of the timing of summer rains in the area, Kharif crops (mainly food crops) end up being harvested at a later date than planned by the farmers. As Barley can be sown later in the Rabi season (when predominantly commercial crops are grown) in comparison to mustard and gram this provides the farmer greater flexibility with Kharif crops. As Barley and wheat are sown later in the season they are also less prone to lodging. If the farmers choose to sow the mustard later in the season it will incur yield loss due to predation by aphids that benefit from lower temperatures at the flowering stage. The shift from wheat to barley also means farmers are less dependent on minimum support prices (MSP). Wheat is mainly purchased by MSP while barley has a competitive market. The MSP operation is bureaucratic. If they can achieve the same level of income, farmers would likely opt for the market rather than for MSP.

4. Valuation of externalities

4.1 How to value greenhouse gas emissions?

The cost of carbon may vary hugely, depending on the valuation method and the local context in which a carbon emissions reductions project might be carried out. The options for valuing greenhouse gas emissions externalities include the prices in artificial markets (if these exist), the marginal abatement cost and the social cost of carbon. Cap-and-trade schemes (the prime example being the EU-ETS) have been put in place in order to create a market for large scale carbon emissions reductions, but it is widely accepted that these artificial markets have not been working well enough to date, resulting in carbon being traded at prices that are far too low (often below $10/tC) to provide genuine incentives for investments in carbon emissions reduction projects. Prices have been much higher in the non-traded sector, but this is not exactly an open market; voluntary off-setting largely consists of one-off transactions between a limited number of (sometimes) trusted offset providers and private consumers who are driven by morality to pay high prices for relatively small amounts of carbon. In short, at this point in time, we cannot derive a value for carbon emissions reductions in a case study like ours by looking at the trade-price of carbon. The marginal abatement cost (MAC) of carbon looks at the cost to reduce emissions without taking account of the damage that these emissions have caused, such as negative impacts on health and mortality. The social cost of carbon (SCC) does measure "the full global cost today of an incremental unit of CO_2e emitted now, summing the full global cost of the damage it imposes over the whole of its time in the atmosphere" (Price et al., 2007, p. 1). In a Defra report, Price et al (2007) argue in favour of using a shadow price of carbon (SPC) which is based on the SCC for a given stabilisation goal, but can be adjusted to reflect the policy and technological environment. However a more recent DECC (2011) document draws on MAC modelling exercise to produce 'central' values of £70 in 2030 and £200 in 2050 (/tC). Tol (2010) provides estimates of SCC based on an extensive literature review, with mean values between 80 and 299 $/tC (assuming a zero rate of time preference). Tol's analysis shows that mode and median values are much lower than the mean – which is pulled up by some studies with very high estimated social costs. This wide range makes it very difficult to justify a particular price. For illustrative purposes, we will use the value of $75/t$CO_2$. This is high in comparison to most studies, but it is lower than the Stern (2007) report or the DECC (2009) carbon valuation approach.

4.2 How to value ground water use

In this report, we value groundwater loss, which takes account of blue and green water. We are reluctant to value grey water because strictly speaking it does not represent real water. The grey water calculation could be seen as a method to value the externalities of agricultural inputs not in monetary units but in water units. We could decide to monetise grey water on the basis of abatement cost, using green or blue water, but would need to be aware of the potential risk of double counting. i.e. replenishing the aquifer can in theory be combined with resolving the grey water problem.

With regards to valuing the externalities of groundwater use, Turner et al. (2004) state that we need to calculate the sum of marginal direct cost (what it costs the farmer to extract water) plus marginal external cost (the costs faced by others) plus marginal user cost (the cost of irreversible depletion of the aquifer). These three categories are generic, and refer to historic costs, costs to others and future costs respectively. In the more empirical literature on groundwater depletion externalities, a number of different and partially overlapping externalities are recognised. Santiago & Begon (2001) make the distinction between 'pumping cost externality' (pumping costs increase with depth) and 'strategic externality' (farmers competing with each-other by digging deeper wells). Provencher & Burt (1993) distinguish between cost externality (as Santiago & Begon, 2001), 'stock externality' (uncontrolled exploitation of a common pool resource) and 'risk externality' (e.g. of subsidence, of salt-water intrusion). Reddy (2005) uses different labels again, referring to uneven farmer access to deeper wells and/or stronger pumps as a 'technology externality', which is exacerbated by the existence of a 'legislative externality', i.e. the lack of property rights for water abstraction for the poorer farmers who cannot afford to invest in deeper wells. Wasantha Athukorala (2007) points out that in addition to externalities associated with water quantity, groundwater depletion under intensive agriculture can also lead to water quality externalities, as the remaining groundwater becomes saltier and more polluted (e.g. by nitrates). And finally, if the depletion of the aquifer results in the drying up of springs and wetlands and reduction of the base-flow in rivers (Strand, 2010), then this has a number of further externalities related to down-stream use of the water.

In this working paper we will focus mainly on two water-related externalities; increased pumping costs and the loss of shallow wells that have dried up. At some stage, falling ground water levels are likely to affect agricultural production, at the farm level if not on aggregate: the amount of water that is pumped up is likely to fall for some farmers, because their pumps are no longer strong enough, the well is falling dry more often, or the remaining wells that can produce more water, are too far from some fields. The comparison between the historic scenario and the (current) baseline scenario shows a reduction in irrigation (i.e. blue) water used. We can interpret this as an indication that irrigation is indeed becoming a constraining factor in agriculture in Jaipur, certainly compared to fertiliser input, which continues to grow. However we felt that this drop is too small to allow us to make assumptions about the likely near future reductions in the area that is under irrigation or the yields of crops that depend on irrigation. In the long run, and assuming unchanged irrigation practices, we could anticipate very significant reductions of irrigation. While we will not quantify potential crop yield losses due to reduced irrigation, based on the assessment of Jaipur agricultural and hydrological data, we can draw on a study in Andhra Pradesh (Reddy, 2005) to demonstrate how a benefit transfer approach could work (see Appendix B for further details).

Pumping cost externality

For our case study, we assume that water can only exit the aquifer by being pumped up by farmers, and that the only water that is entering the aquifer comes from precipitation (rain) which has managed to percolate through to the water table (= rainfall minus evapotranspiration and run-off). In this simple model we have no information on water quality issues and we assume that rainfall run-off has no value and no externalities associated with it. In principle this would leave us with three types of externalities; the externalities of increased pumping efforts, the externalities of reduced irrigation as water becomes less accessible and the externalities of dried up wells.

Table 25 energy use of pumping up groundwater

Lifting 1liter of water (i.e. 1kg) up by 1m = 9.8J or $2.72*10^{-6}$ kWh. This value needs to be corrected for pumping efficiency and grid losses (30% and 5% respectively according to Nelson et al., 2009), so that lifting $1m^3$ of water by 1m by electric pump = $9.534*10^{-3}$ kWh

Given that an average farm growing barley for SABMiller is using a total of 13,797 m^3/y of water in irrigation, a drop of 1m of the groundwater table, would require 131.540 kWh extra electricity for pumping up this water. In 2013, domestic consumers were charged a maximum of 5.45 rupees/ kWh in Rajasthan[4], and 60 rupees = $1 so that 131.540 kWh = $11.94. This annual cost increase in pumping is not huge for individual farmers, but it is a cost that is felt by all farmers and it is a cost that is increasing year on year as the water table drops further. Data from the Rajasthan Groundwater Department (CGWB, 2007) show that groundwater levels are declining across Jaipur. The worst affected agricultural blocks have experienced a drop of 0.7m/y in the period 1984-2006, 1.4m/y in the period 1996-2006 and 2.2m/y in the period 2001-2006. In other words groundwater depletion is not just systemic, it is actually accelerating over time. If we assumed that consumer electricity prices and irrigation water use have not changed in the last 20 years but that during the same period, the water level has dropped by an average of 20 metres across the whole of Jaipur district, a farmer today would be spending $220/y more on pumping than he/she would have done 20 years ago.

If we assume that groundwater has to be pumped up from 40m below the surface, then the total electricity costs of pumping amount to $477.6/year/farm, or $0.0346/$m^3$. However, electricity prices are subsidised in India. A recent report on energy subsidies in India (IISD, 2012, p. 13) estimates that only about 75% of the electricity production costs are recovered by the utilities. By assuming that consumer prices are only 75% of the real cost of production, we arrive at a real cost of $ 0.0433/m^3 of water pumped to the surface.

Dried wells externality

If x wells are lost in the region as the groundwater level drops by y meter, then the lost well externality can be calculated as:

$((P * x) / F)/y$ per farm, per m of reduced ground water level,

Where P is the price of a well and F is the number of farms in the region. Since we want to know the lost well externality value of a unit of groundwater that is pumped up, we need to multiply this equation by the annual groundwater level drop (G) and then divide by the amount of water that is over-extracted every year. The latter can be calculated as the average irrigation water use per farm per year (I), divided by the aquifer exploitation rate (R):

$[((P * x) / F)/y] *G/(I/R)$

[4]Price obtained at http://www.bijlibachao.com/Calculators/online-electricity-bill-calculator-for-all-states-in-india.html

For Jaipur we used the following values (CGWB, 2007 unless stated otherwise):

P = \$1500 (based on costs reported in Reddy, 2005)

x = 9463 (these are all the low yield wells in Jaipur – CGWB did not report well depth)

F = 316041 (80% of the district is arable[5], which we divided by a farm size of 2.8 ha)

y = 10m (we assume that the x wells have all fallen dry over the course of a 10 m groundwater level drop)

G = 2.2 m/y (the worst case figures in 2004, we assumed them to be common now)

I = 14311 m^3/y (irrigation used by baseline farms – taken from the cropwat model)

R = 2 (i.e. 200% - we took an upward figure from the 2004 exploitation rate of 186%)

This gives us a marginal dry well externality of \$0.00138/m^3 based on shallow wells that we assume have largely fallen dry already; the CGWB (2007) report contains data that is now almost a decade old, and we have no reason to believe that the hydrological situation has become any better. This is small amount masks a very uneven distribution: farmers who have no shallow wells lose nothing whilst those who do have such a shallow well, have lost \$1500. These are also the farmers who are least likely to be extracting lots of water.

The value of the marginal dry well externality is 31x smaller than that of the marginal pumping cost externality. Together, the two water over-extraction externalities amount to \$0.0447/m^3.

If we were to add the crop yield losses based on the benefit transfer approach in Appendix B, this value would go up to \$0.0456/m^3. One thing to bear in mind when considering this small difference, is that total crop production statistics may mask underlying problems related to income distribution and trends in externalities. The distributional effects of crop yield losses are likely to be highly significant. As poorer farmers will stop irrigating, their increased poverty may force them into leasing or sell their land to wealthier farmers who can invest in deeper wells and stronger pumps so they can irrigate larger areas of land. These wealthier farmers may be able to increase production and thus (in terms of regional crop production statistics) make up for the reduced production by poorer farmers. Under this scenario, it is quite possible that total groundwater extraction actually increases.

4.3 Valuing externalities based on the different scenarios

Having established a value for carbon (\$75/tCO_2) and ground water (\$0.0447/m^3), we can convert table 24 into monetary values (table 26). We also convert rupees to dollars (\$1=60 rupees), and for illustrative purposes we value grey water as groundwater loss, i.e. we assume that grey water

[5] http://agricoop.nic.in/Agriculture%20contingency%20Plan/Rajasthan/RAJ1-Jaipur%203.2.2011.pdf

represents the amount of ground water that would be used to dilute pollution. In table 26, positive signs of the externalities of carbon and water indicate an increase in pollution, whilst a negative sign indicates a reduction in pollution. The positive signs for farm income simply indicate an increase in farm income.

The findings in table 26 show that the environmental externalities show a positive trend (i.e. less carbon emitted, less blue water used) under the company scenarios, but that under the prices we use for carbon and blue water, their positive monetary values are low at the farm level in comparison with the (from the company's perspective) positive externality of increased farmer income. In the non-progressive (conservative) company scenario, the farm advisors are simply doing their job in terms of promoting the production of malted barley. The non-conservative company scenario represents the optimal positive impact that the company could have on farmer income (and thus also on the sum total of positive externalities) through the advice and services provided by their agricultural extension officers with regards to all major crops grown by the farmer (not just malting barley).

Table 26 Monetised differences between the scenarios. All values are in US dollar

Monetised differences between scenarios ($)	C02 (neg. externality)	Groundwater loss (neg. externality)	Grey water (neg. externality)	Farm income (pos.)
Historic to current baseline	+156.53	-6.17	+9.83	295
Historic to company (cons)	+131.78	-31.33	+6.75	610.07
from current baseline to company (conservative)	-24.75	-25.17	-3	315.08
From current baseline to company (non conservative)	As above	As above	As above	703.30

In summary, our calculations indicate that that over a total of 6000 farms participating in SABMiller's barley grower extension programme in Rajasthan, there has been a reduction of water use of 3,414,000 m^3/y (3.4 km^3) and a reduction of CO_2 emissions of 6000x330kg/y = 1980 tCO_2/y. This amounts to a total value of $148,500 of reduced greenhouse gas emissions and a total value of $152,606 of reduced groundwater extraction, making a grand total of $300k/year.

5. Some reflections on groundwater depletion and the role of the company

The positive effects of reduced water use and reduced carbon emissions at the farm level could be enhanced if the company pursued the non-conservative scenario, combined with providing environmentally sound investment advice to farmers for (part of) that additional income. Dependent on local context, these investments could include the construction of surface water runoff retention structures, water storage tanks.

The continued rapid depletion of the aquifer remains the most critical issue with regards to our methodology. More specifically, we have presented scenarios with a relative reduction in water use as positive externalities, whilst strictly speaking they are examples of a reduction in a negative externality, i.e. the changes affected by the company are going in the right direction. But, overall the water uses by all users located in the area are still not considered as sustainable. We will use this section to reflect briefly on the position of the company and its ability to affect water management and governance in the regions where they operate.

An interesting point raised during discussions with SABMiller, was that they found themselves in a position where they recognised that the absence of effective local or regional water governance structures would result in a depletion of groundwater resources which would eventually threaten their operations and expose them to reputational risks - not because they are a particularly big consumer of water, but because they (as a big overseas company) are one of the most visible consumers of water. They subsequently became proactively involved in efforts to create new water governance structures. These efforts are still in an early stage but the relevance of these efforts is reiterated by the literature. Reddy (2005, p552) has looked at the costs of replenishing the aquifer vis-a-vis the cost of depleting it and he concludes that "*it makes economic as well as ecological sense to invest in the replenishment mechanisms. However, there are no private initiatives in this direction [..] Collective action is a prerequisite in tank restoration and management. Such an approach calls for state intervention [..] (also) in terms of a facilitator or catalyst for collective action at the community level*."

A field study (of hydrology and institutions) would be required to assess the extent to which Reddy's findings also hold in the case study area. Hydrological data available to us at the state level and discussions with the company certainly suggest that the need for collective action is overwhelming. The most effective way for the company to safeguard it's access to water and its future in the region, is for it to play a proactive role in forming of new water governance structures.

Collective action around protecting water resources is critical in these situations where the resource is encroached in a tragedy of the commons. In such a context individual water users are merely incentivised to invest in the protection of the resource because either the investment in the protection outweighs the short term profit or because their individual effort would be diluted by inaction from others. Collective action helps avoiding free riding behaviour but also helps trigger meaningful shift in unsustainable water management practices.

An example of such a collaborative approach is provided by a project in Neemarana (NW Rajahastan), where SABMiller have contributed to the development of a recharge structure which has increased the groundwater level in an area where continuous depletion was constraining water usage not only for the company's local operation but also for other users (WWF, GIZ & SABMiller, 2011).

Of course a single stakeholder, no matter how much of a leadership role they play, cannot claim ownership over the positive environmental or social impacts that have been achieved through a cooperative approach. However it could be argued that such an effort would be partially internalised through reduction in reputational risk, increased security of supply an improved public image of the company, an increase in political capital and a growing potential for novel and mutually beneficial business collaborations with other local stake-holders. This is very similar to the concept of 'shared value' (Porter and Kramer, 2011), which is gaining traction in some business circles.

To maximise the positive consequences coming out the company's programme, extension services should continue with the delivery of better practices around water management at the farm level. This may help to leverage the outcome in two ways. First, by making sure that farmers participating in the barley growing programme do indeed consume less water through the continuation and improvement of best practice irrigation approaches, methods of fertilizer application, weeding practices, harvesting timing, and storage practices. And secondly by reaching out to more farmers and providing them with the same quality of extension services in order to create a scale effect.

This study also point to the critical importance of timely collaborative action around the protection of water resources and particularly the aquifers. Collaboration should first look at the implementation of a comprehensive assessment of not only the state of the aquifers and the behaviours of all actors and their respective demand. This cannot be achieved without the full commitment of water users in the area but also the relevant public authorities. We hope that this study, and other studies like it, will serve as a recommendation for all water users and water managers who are drawing on rapidly depleting regional water sources.

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Appendix A Sensitivity analysis for Crop water Use – CROPWAT Analysis

Appendix A1 Length of Growth Periods and Crop coefficients for Crop Water Use Sensitivity Analysis

				Length of growth periods					Crop coefficients in growth periods				**Source (*LGP from extension worker focus group)**
Crop	Location	Climate	Variety	Initial	Development	Mid-Season	Late Season	Total	Initial	Development	Mid-Season	Late Season	
Barley	FAO 56 Barley - India (LGP)	Not stated		15	25	50	30	120	0.3	0.73	1.15	0.25	Allen et al 1998
	Tigray, Northern Ethiopia	Semi Arid		18	20	30	16	85	0.7	0.85	1.05	0.6	Alemie and Fantahun 2010
	Tigray, Northern Ethiopia	Semi Arid		15	25	50	30	120	0.7	0.85	1.05	0.6	Alemie and Fantahun 2010*
	Central region of Saudi Arabia	Arid		15	25	50	30	120	0.6		1.39	0.29	Alazba et al 2003*
	Iran - Gareh Bygone Plain Southern Iran	Arid		15	25	50	30	120	0.45		1.2	0.47	Raes et al 2009*
	Punjab, India	Semi Arid		15	25	55	30	125	0.34	0.69	1.05	0.65	Sabu et al 2000
	Punjab, India	Semi Arid		15	25	50	30	120	0.34	0.69	1.05	0.65	Sabu et al 2000*
Wheat	Wheat (FAO 56 winter wheat)	Not stated		16	27	54	33	130	0.7		1.15	0.25	Allen et al 1998*
	Karnal, India (Haryana)	Semi Arid	HD 2329	16	27	54	33	130	0.5	1.36	1.24	0.42	Tyagi et al 2000
	West Bengal	Semi Humid	Sonalika	16	27	54	33	130	0.33	0.82	1.08	0.64	Bandyopadhyay and Mallick 2003
	central region of Saudi Arabia	Arid		16	27	54	33	130	0.63		1.39	0.29	Alazba et al 2003
	Punjab, India	Semi Arid		25	35	60	30	150	0.34	0.69	1.05	0.65	Sabu et al 2000
	Punjab, India	Semi Arid		16	27	54	33	130	0.34	0.69	1.05	0.65	Sabu et al 2000*

Crop	Location	Climate	Variety	Length of growing periods: Initial	Development	Mid-Season	Late Season	Total	Crop coefficients in growth periods: Initial	Development	Mid-Season	Late Season	Source (*LGP from extension worker focus group)
Mustard	Himachal Pradesh Hill zone India	Sub - tropical		17	30	35	25	107	0.23		1.28	0.66	Kumar et al 2011
	Himachal Pradesh Hill zone India	Sub - tropical		24	42	49	35	150	0.23		1.28	0.66	Kumar et al 2011*
	Dhenkanal Orissa - Eastern India	Humid		16	29	34	24	103	0.39	0.92	1.31	0.42	Kar et al 2007
	Dhenkanal Orissa - Eastern India	Semi Arid		23	42	50	35	150	0.39	0.92	1.31	0.42	Kar et al 2007*
	Punjab, India	Semi Arid		15	45	65	25	150	0.34	0.61	0.88	0.82	Sabu et al 2000
Gram	Tusnia	Semi Arid		20	25	35	25	105	0.28	0.62	0.98	0.16	Mbarek et al 2012
	Tusnia	Semi Arid		29	36	50	35	150	0.28	0.62	0.98	0.16	Mbarek et al 2012*
	Punjab, india	Semi Arid		25	50	55	30	160	0.26	0.63	1	0.63	Sabu et al 2000
	Punjab, india	Semi Arid		23	47	52	28	150	0.26	0.63	1	0.63	Sabu et al 2000*
	FAO 56 Chick Pea FAO	Not stated		30	35	50	35	150	0.4		1	0.36	Allen et al 1998
	Ethiopia	Various		20	30	30	20	100	0.4		1	0.35	Tesfaye and Walker 2004
	Ethiopia	various		30	45	45	30	150	0.4		1	0.35	Tesfaye and Walker 2004*

Appendix A2 Crop evapotranspiration, evapotranspiration met by irrigation (ET_{blue}) and rainfall (ET_{green}) for Crop Water Requirement (CWR) and Irrigation Schedule (IrrS) for Crop Water Use Sensitivity Analysis.

		CWR			**IrrS**		
Crop	**Source (*LGP from extension worker focus group)**	**Eta**	**ETBlue**	**ETGreen**	**Eta**	**ETBlue**	**ETGreen**
		mm/growing period			mm/growing period		
Barley	Allen et al 1998	440	411	29	437	408	29
	Alemie and Fantahun 2010	298	279	19	291	277	15
	Alemie and Fantahun 2010*	490	461	29	482	457	25
	Alazba et al 2003*	554	525	29	549	522	23
	Raes et al 2006*	498	469	29	492	466	26
	Sabu et al 2000	492	461	31	485	458	27
	Sabu et al 2000*	455	425	30	448	423	25
	Mean	461	433	28	455	430	24
	Median	490	461	29	482	457	25
	SD	80	77	4	75	71	4
Wheat	Allen et al 1998*	583	549	35	577	545	32
	Tyagi et al 2000	618	584	35	612	582	30
	Bandyopadhyay and Mallick 2003	571	537	35	564	534	30
	Alazba et al 2003	675	641	35	669	638	31
	Sabu et al 2000	719	682	37	710	674	36
	Sabu et al 2000*	561	527	34	554	524	31
	Mean	621	586	35	614	583	32
	Median	601	566	35	595	564	31
	SD	63	62	1	57	56	2

Crop	Source (*LGP from extension worker focus group)	CWR Eta	CWR ETBlue	CWR EtGreen	IrrS Eta	IrrS ET Blue	IrrS ET Green
		mm/growing period			mm/growing period		
Mustard	Kumar et al 2011	390	368	22	386	364	22
	Kumar et al 2011*	615	580	35	608	575	34
	Kar et al 2007	396	375	22	392	373	19
	Kar et al 2007*	634	598	35	628	600	28
	Sabu et al 2000	532	496	35	523	490	33
	Mean	521	490	31	508	480	27
	Median	532	496	35	523	490	28
	SD	116	109	7	103	98	7
Gram	Mbarek et al 2012	292	269	23	284	262	21
	Mbarek et al 2012*	446	410	35	443	411	32
	Sabu et al 2000	576	539	38	569	536	33
	Sabu et al 2000*	515	480	35	508	476	32
	Allen et al 1998	502	467	35	497	464	33
	Tesfaye and Walker 2004	301	282	20	297	281	16
	Tesfaye and Walker 2004*	499	465	35	494	464	31
	Mean	447	416	32	442	413	28
	Median	499	465	35	494	464	32
	SD	110	103	7	102	96	6

Appendix A3 Literature Sources for Length of Growth Periods and Crop Coefficients for Crop Water Use used in Sensitivity Analysis

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Appendix B: Benefit transfer approach to dry wells and crop yield losses.

Given the initial difficulty in obtaining sufficient empirical data on hydrology and access to groundwater for the case study area in Rajasthan during this desk study, we were also looking to develop a benefit transfer approach (or an 'externality transfer' approach).

The most promising study we have found is that of Reddy (2005). Reddy has calculated the groundwater depletion externalities in three villages in Andhra Pradesh by measuring (a) the costs of wells that have fallen dry and (b) the loss of agricultural income due to diminished irrigation (i.e. he didn't include the pumping externality). Because of the way in which Reddy has aggregated the data, we need to do a benefit transfer of these two externalities combined, and then subtract the dry wells externality which we have already calculated, so that we remain with a benefit transfer value for the stock externality (loss of agricultural income due to reduced irrigation). The challenge we face is to convert Reddy's figures of total externality based on observed loss of assets and income for a whole village, into our case study of marginal reduction of ground water depletion associated with crop change for a participating farmer.

What we have done is to plot the per hectare externalities calculated by Reddy for the 3 villages, against the drop in water table registered at these 3 villages[6]. By fitting a regression (see figure A) we now have a proxy for estimating the per hectare externality as a function of the level of groundwater depletion.

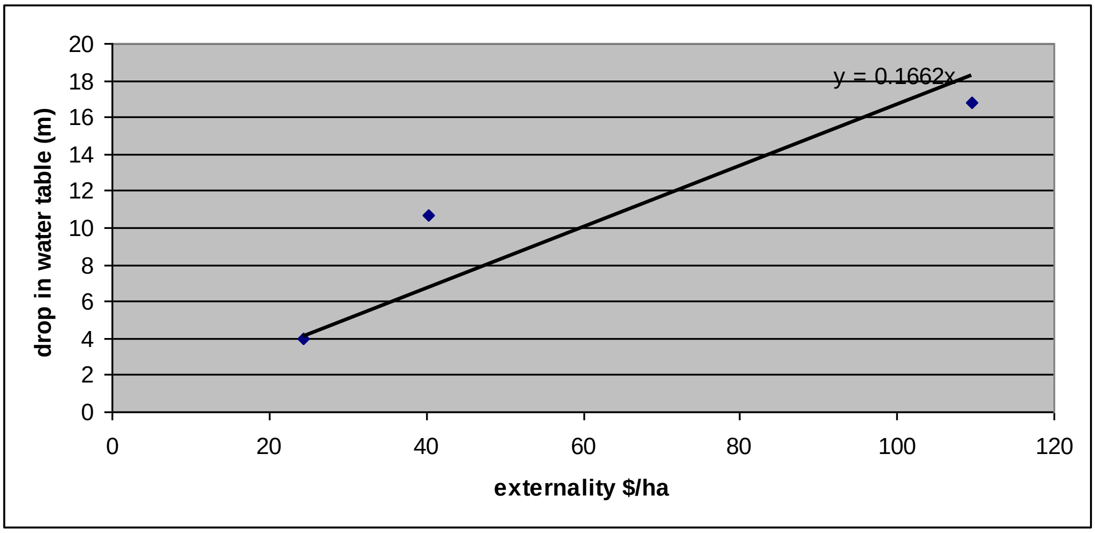

Figure A: Total groundwater depletion externalities as a function of the lowering of the water table (the 3 data points are averages of 3 villages in Andhra Pradesh, provided by Reddy, 2005).

Using this regression it is possible to convert a drop in the level of the water table into an externality cost (see figure A), provided we have the porosity of the aquifer. We don't actually know the porosity for this case study but as this benefit transfer approach is an illustrative example, we

[6] We don't have average ground water levels for these villages. Reddy provides data on the average growth in well depth over a five year period for each village – we have used these numbers on well depth as a proxy for groundwater depth.

assume a value of 25%. This enables us to adopt a working assumption that a crop change which results in a reduction of annual evapotranspiration by (for example) 1mm, or which allows farmers to reduce irrigation by 1mm, is equal to a water table rise of (100/25 * 1mm =) 4 mm, which according to the regression is a positive externality worth 0.004/0.1662=$0.024 /hectare/year[7]. Since 1mm of water spread over a hectare is $10m^3$ in total, one cubic meter is worth $0.0024. This value represents both the dry well externality and the yield loss externality. It is 60% higher than the dry well externality calculated for Jaipur alone (which was $0.00148/$m^3$). If we would extract the (Jaipur) dry well externality from the (Reddy, 2005) benefit-transfer derived value of $0.0024 for dry wells + crop yield loss, we would end with an externality of $0.00092/$m^3$ for the crop yield loss externality alone. The crop yield loss externality is thus only 60% of the size of the dry well externality. Both externalities together, only add 5% to the value of the pumping externality (of $0.0433/$m^3$).

This benefit transfer approach is particularly sensitive to soil porosity. There is also a chance that some of the reduced irrigation is due to the increased cost of pumping up water, thus creating a risk of (some) double counting if we add this figure to the pumping externality. Furthermore, although we have fitted a linear function through our three village data points, we do not have reasons to expect that crop yield losses in the real world will be linearly related to groundwater level reduction. It is likely that farmers will give up high value irrigated crops last, so that the crop yield loss will increase as the groundwater resources become more critically depleted.

In comparison to Rajasthan, the benefit transfer approach may produce values that are on the low side, since Reddy's study is based in a less arid part of India where crop yields are possibly less dependent on irrigation. Finally, it is worth noting that in Reddy's study (which is based on actual crop losses) the damage of being left with a dry borehole is reported to be disproportionally suffered by poor farmers whose agricultural output is already limited due to restrictions on land and capital. In other words, Reddy's assessment is grounded in the real world situation that the poor suffer more but the overall yields are less affected. From a normative perspective, we could consider this to be an undervaluation, both because of the uneven distribution and its consequences (e.g. income loss is more likely to impact directly on the health and development of the poor farmers affected), and because the strategic importance of the aquifer as an agricultural insurance policy, is NOT insensitive to distributional consequences: food security is a key component of national policy in most if not all developing countries. Even from a purely utilitarian point of view, food security for the poor is of strategic importance to better off sections of society.

[7] This is of course a very rough method to estimate the externalities; a hydrological field survey in the barley growing area would be needed, combined with a survey of locally existing wells, crops and irrigation practices.

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