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Abstract

There are strong interdependencies between water use in agriculture and energy consumption as water saving technologies can require increased pumping and pressurizing. The Chinese Government includes water efficiency improvement and carbon intensity reduction targets in the 12th Five-Year Plan (5YP. 2011–2015), yet the links between energy use and irrigation modernization are not always addressed in policy targets. Here we build an original model of the energy embedded in water pumping for irrigated agriculture and its related processes. The model is based on the physical processes of irrigation schemes and the implication of technological developments, comprising all processes from extraction and conveyance of water to its application in the field. The model uses data from government sources to assess policy targets for deployment of irrigation technologies, which aim to reduce water application and contribute to adaptation of Chinese agriculture to climate change. The consequences of policy targets involve co-beneficial outcomes that achieve water and energy savings, or trade-offs in which reduced water application leads to increasing greenhouse gas (GHG) emissions. We analyze irrigation efficiency and energy use in four significant provinces and nationally, using scenarios based on the targets of the 12th 5YP. At the national scale, we find that expansion of sprinklers and micro-irrigation as outlined in the 5YP would increase GHG emissions from agricultural water use, however, emissions decrease in those provinces with predominant groundwater use and planned expansion of low-pressure pipes. We show that the most costly technologies relate to trade-offs, while co-benefits are generally achieved with less expensive technologies. The investment cost per area of irrigation technology expansion does not greatly affect the outcome in terms of water, but in terms of energy the most expensive technologies are more energy-intensive and produce more emissions. The results show that water supply configuration (proportion of surface to groundwater) largely determines the potential energy savings from reductions in water application. The paper examines the importance of fertigation and highlights briefly some policy implications.

1. Introduction

China faces its own 'perfect storm' as rapid economic transition drives increasing per capita demand for water, energy and food. Whilst national food production has increased substantially in recent decades the agricultural sector has become responsible for nearly two-thirds of total water use and 17%–20% of China's greenhouse gas (GHG) emissions (Wang *et al* 2012). Agricultural water use is declining due to increasing competition for urban and industrial uses, but the agricultural sector still consumes roughly 60% of total water use (Wang *et al* 2005, MWR 2014). Groundwater use in China increased from around 10 km^3 during the 1950s to more than 110 km^3 in 2010 (Shah 2009) causing increases in pumping-related emissions of GHGs (Wang *et al* 2012). The interdependencies between water and energy are increasingly recognized by researchers (e.g. Hoff 2012), however, they often remain absent in planning and operation. One example is the potential for co-benefits or trade-offs to occur when attempting to reduce water application in irrigated agriculture, because energy is generally required for increased pumping, pressurizing and conveyance: situations with groundwater use for irrigation might provide co-benefits via energy savings from reduced pumping and water application (Zou *et al* 2013); while situations with surface water might induce trade-offs between reductions in water application and increases in emissions when energy-intensive irrigation technology is deployed. Outcomes can be quantified and explored using a water–energy nexus perspective (WEF 2011, Sanders and Webber 2012, Hightower *et al* 2013, Scott 2013, DoE 2014, Finley and Seiber 2014, Frumhoff *et al* 2015, Healy *et al* 2015, Iseman and Tidwell 2015). Irrigation comprises the second largest contribution (22%) to the total carbon footprint of crop production in China (Cheng *et al* 2011). Jackson *et al* (2010) reported emissions savings of 12%–44% could be achieved through the adoption of irrigation technology in groundwater fed conditions. Optimal management measures such as dynamic regulation of pressure may also lead to additional energy savings of 20% (Díaz *et al* 2009). Irrigation technologies can reduce the non-productive consumption (Perry 2011) of water in different ways; they can minimize leaching and evaporation and improve application control to optimize water uptake in plants. Canal lining and pipelines are measures to avoid non-productive evaporation and leaching of water during conveyance; sprinkler and drip systems limit the application of water to the fields/crops. By reducing applied water and potentially helping to cope with climate change (e.g. precipitation variability and more intense droughts), irrigation technology can contribute to adaptation and, in some contexts, irrigation technology might simultaneously contribute to carbon intensity reduction and mitigation of climate change.

The Chinese Government included water efficiency, farming modernization and improved risk management in agriculture as priorities in the 12th Five-Year Plan (5YP, 2011–2015) (CPC 2011) and the No. 1 Central Document in 2011 (CPC 2010). The 12th 5YP was the first to set targets for carbon intensity reduction. Water pumping is a major input for Chinese agriculture, yet the links between energy use and the modernization of irrigation are not addressed directly in these policy plans. In fact, vertical planning processes often fail to integrate water–energy considerations (Yu 2011). The 12th 5YP targeted increases in irrigation efficiency of 3% and included objectives for increasing the area under four irrigation technologies, which are the focus of this study: sprinkler irrigation, micro/drip irrigation, canal lining for seepage control, and low pressure pipelines. The policy targets were intended to be realised by giving incentives to and supporting farmers to adopt irrigation technology through extension activities, subsidies, discount loans for equipment and water pricing (NEA 2012, Cremades *et al* 2015). At the provincial level the 12th 5YP sets targets for increases in the area using irrigation technology of 26% in Hebei, 54% in Heilongjiang, 33% in Shandong and 53% in Xinjiang (CPC 2011).

This paper examines how to decrease energy consumption linked to irrigation, whilst reducing irrigation water application and maintaining food security. This objective is challenged by the diversity of situations in China, meaning that similar policies can produce either trade-offs or co-benefits. We develop an original model of the main components of the water–energy nexus of irrigation modernization and assess the consequences of sectoral policy targets in China's 12th FYP (Scott *et al* 2011). First, our assessment focuses on co-benefits, to identify win–win outcomes which achieve reductions of water applied and energy savings. Second, our assessment focusses on trade-offs, in which reductions of water applied lead to increasing GHG emissions from energy use. Third, our study assesses the possible trade-offs and co-benefits in provinces with different contexts to understand the consequences of sectoral policy goals. Fourth, our analysis considers economic aspects linked to co-benefits and trade-offs. The study uses data from government sources and develops a method to estimate changes in water use efficiency and energy use emissions. The analysis is done nationally and in four provinces with contrasting water–energy endowments (figure 1). Our assessment concludes by suggesting policy recommendations for improved management of the irrigation water–energy nexus.

2. Methodology

We develop an original model of the energy embedded in water pumping for irrigated agriculture and related processes. The model is based on the physical processes of irrigation schemes and their technological developments. The model comprises all processes, from extraction and conveyance of water to its application in the field (figure 2), and their implications in fertigation and tillage. There are many other factors that come into play in determining overall system efficiencies for the water–energy nexus. Our analysis focuses on irrigation technology—an

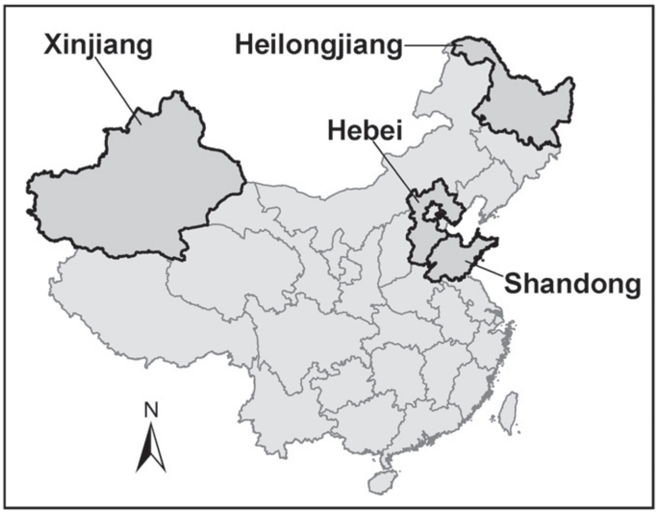

Figure 1. Map of the provinces selected, on the basis of the largest areas of irrigation modernization in the 12th Five Year Plan of China.

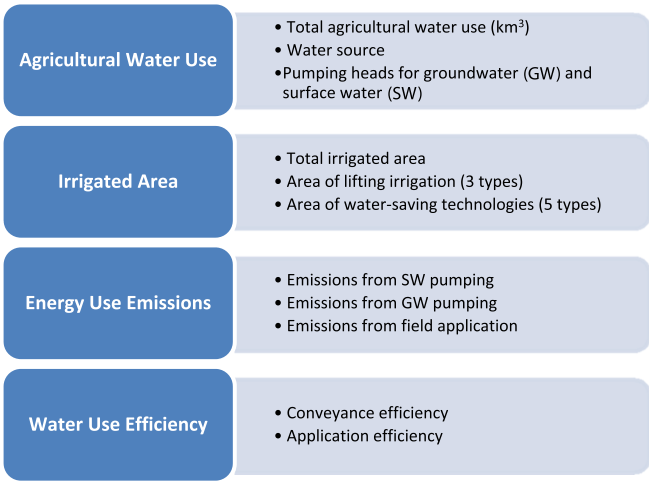

Figure 2. The main data elements in the water–energy assessment.

important (and less studied) component. The model captures changes in energy and water related to the operation of the irrigation system that are affected by technological change. The model uses data to assess water use efficiency and emissions in irrigation schemes and their technological changes. These processes may require energy (e.g. for pumping, pressurizing) and unavoidably involve some consumption of non-productive agricultural water use through evaporation, runoff and seepage.

Data inputs and calculations are based on provincial and national level data:

- Statistical Yearbook of China's Water Resources (Ministry of Water Resources, 2011).
- Groundwater Level Yearbook of China, GEO-Environmental Monitoring Institute (year 2006).
- Extensive survey data collected by the Center for Chinese Agricultural Policy (2004–2014).
- Additional data from the Ministry of Water Resources.

Using these sources we calculate the scheme irrigation efficiency and energy use emissions for the year 2010 and use these as a baseline. The scheme irrigation efficiency, defined as the fraction of water 'pumped or diverted through the scheme inlet which is used effectively by the plants' (FAO 1989), is the combined efficiency of the conveyance and the application (see equation (1)). Conveyance efficiency represents the efficiency of water transport in canals and field application efficiency represents the efficiency of water application in the field

$$\eta = \eta c \times \eta a, \quad (1)$$

$$\eta c = \sum_i A_i \eta c_i, \quad (2)$$

$$\eta a = \sum_j B_j \eta a_j, \quad (3)$$

Table 1. Pressure ranges of irrigation systems.

	kPa	Head (m)	Irrigation system
Low pressure	0–172.37	0–17	Most surface and some drip/micro systems
Medium pressure	179.26–406.79	18–41	Some drip/micro and some sprinkler systems
High pressure	⩾413.69	⩾42	Some sprinkler systems

Source: USDA (2012).

where i is the set that includes the following delivery facilities: unlined canal, lined canal and low pressure pipeline; j is the set that includes flood, sprinkler, micro-irrigation and other kinds of irrigation technologies; A_i is the percentage of irrigated areas using the ith kind of delivery facility; B_j is the percentage of irrigated areas using the jth kind of irrigation technologies in the field; ηc is the conveyance efficiency for non-lined canal (0.30), seepage controlled canals (0.75), low pressure pipelines (0.95); ηa is the field application efficiency for flood (0.50), sprinkler (0.75), micro-irrigation (0.90) and other technologies for application (0.70), and η is the scheme irrigation efficiency.

According to the Food and Agriculture Organization of the United Nations (FAO 1989) a scheme irrigation efficiency of 50%–60% is good, 40% is reasonable, whereas 20%–30% is poor. The combined irrigation scheme efficiency depends on the type of conveyance and application system all of which have different water use efficiencies. If well maintained, long, sandy soil canals have maximum conveyance efficiencies of 60%. Taking into account poor maintenance of canals the conveyance efficiency of earthen canals is set to 30%, and the conveyance efficiency of canals with seepage control is set to 75% (FAO 1989). For low pressure pipelines, we assume a conveyance efficiency of 90%. For application efficiencies we adopt a mid-value of 50% for flood systems, 75% for sprinkler, 90% for drip and 70% for other field practices that enhance efficiency.

To calculate the scheme irrigation efficiencies (equation (1)), we use national statistics for irrigated areas by province. For conveyance efficiency, the total irrigated area is divided according to the areas supplied by seepage controlled canals, low pressure pipelines and the remaining area is assumed to be supplied by traditional non-lined canals (see equation (2)). For field application efficiency, the total irrigated area is divided according to areas of sprinkler, micro and other field measures; the remaining is classified as flood (see equation (3)). Flood irrigation comprises all types of surface water irrigation (basin, furrow, border). It is important to note that Chinese government metrics for irrigation efficiency do not consider conveyance and application practices separately. While areas supplied by water through lined canals and pipelines are counted as irrigation technologies, water might still be applied through flooding practices. Hence, we argue it is important to acknowledge that water can leave the irrigation scheme through non-productive evaporation and seepage both during conveyance and application and therefore both steps should be incorporated in any assessment.

For the energy use emissions, we divide the energy used for an irrigation scheme into pumping and conveyance (equation (5)), and pressurizing water for application to the fields (equation (6)). For both calculations we consider the two main types of engines used for water pumping in China: according to Wang *et al* (2012) the proportion of engines used is set to 76% for electric and 24% for diesel. Similarly, pump engine efficiencies of electric and diesel driven systems are set to 0.40 and 0.15, respectively, and the efficiency of the electric system incorporates transmission and distribution losses assumed at 15% (Wang *et al* 2012). Derating efficiency is considered and set at 80% for electric driven systems and 75% for diesel. Pump head is the most crucial factor, noting that efficiency of the power generation and supply and the pump and pipeline system also influence energy use. To calculate the energy used in the pumping and conveyance of groundwater and surface water we use equation (5) (Rothausen and Conway 2011). Conveyance consumes energy in the case of low pressure pipes. Even so, results from a large-scale field survey (see Cremades *et al* 2015) show low pressure pipes are used in 91% of cases in areas irrigated exclusively with groundwater, only 2% of cases in areas irrigated exclusively with surface water, and the remaining 7% in areas with a mix of both. We therefore assume that the expansion of low pressure pipelines will occur in areas irrigated exclusively with groundwater. Since the adoption of low pressure pipes implies lower extraction of groundwater, the final effect is less water pumped and less energy consumed, as found by Zou *et al* (2015).

We use equation (4) to calculate the groundwater pump heads for each of the provinces, according to regression estimates from survey data in Wang *et al* (2012) relating groundwater levels with pump heads

$$\text{Pump head} = 0.906 \times \text{groundwater level} + 21.75. \quad (4)$$

The energy necessary for groundwater pumping and conveyance, and resulting emissions, is calculated using equation (5). The characteristics of the energy supply in the provinces are taken into account in the calculation of groundwater pumping.

$$\text{Emissions from groundwater pumping and conveyance } (\text{kgCO}_2\text{e}) = \sum_{k,m,r}\left[\frac{9.8(\text{ms}^{-2}) \times \text{Pump head}_{k,r}(\text{m}) \times \text{Water pumped}_{k,r}(\text{kg})}{3.6 \times 10^6 \times \text{Derating }\%_m \times \text{Pump efficiency }\%_m} \times \text{Conversion factor}_{m,r}\left(\text{kgCO}_2\text{e kWh}^{-1}\right) - A_r(\text{ha}) \times \text{LP}\left(\text{kgCO}_2\text{e ha}^{-1}\right)\right], \quad (5)$$

where k is the set of energy intensive water sources, comprising pumping of groundwater and pumping of surface water; m is the set including both engine types, diesel and electric; r is the set that includes the regions studied, i.e. the provinces of China; emissions from groundwater pumping and conveyance are the comprising emissions caused by energy-intensive water sources and decrease of emissions related to conveyance using low pressure pipes, the calculation is analogous for each province and the result is shown at country level, summing over all the provinces; pump head: also referred as lift or pump lift, vertical distance over which water is lifted, or the combined effect on pressure of elevation and/or distance over which water is pumped prior to application, in groundwater extraction the pump head is larger than the groundwater level, because a lowering is created in the level of the aquifer, pump head varies for different water sources (groundwater and surface water) and provinces; water pumped is the the weight of the water pumped, its amount varies for different water sources (groundwater and surface water) and provinces; pump efficiency is the performance of the pump in terms of conversion to mechanical energy; conversion factor: as per the calculation in equation (6) below, which varies for different provinces and engines; A is the area with conveyance through low pressure pipes, which varies for different provinces, LP is the reduction of emissions due to adoption of low pressure pipelines. According to a literature review by Zou *et al* (2015) low pressure pipes reduce emissions by 177 kgCO_2e per hectare of application.

Next, we use equation (6) to calculate the emissions associated with pressurizing water for application to the fields with sprinklers and micro-irrigation. Based on information in table 1 we set the pressure of the pump head at 45 m for sprinklers and 20 m for drip. We apply standard flow rates for sprinkler and drip systems at 40 l s^{-1} and 20 l s^{-1}, respectively. As derived from the flow rate, time is calculated using the duration required to pressurize and apply the volume of water applied with each technology. This volume is obtained from table 2 in proportion to the area used by each technology against total agricultural water and total irrigated area , taking into account the relative reductions of water application when compared to flood irrigation, 0.453 for sprinkler and 0.527 for micro-irrigation, as detailed by Zou *et al* (2015). The distribution between efficiencies and derating coefficients of electric and diesel driven systems are set similarly to the pumping calculation.

$$\text{Emissions from application} (\text{kgCO}_2\text{e}) = \sum_{\text{en},m,r}\left[\frac{9.8(\text{m s}^{-2}) \times \text{Pump head}_{\text{en}}(\text{m}) \times 1(\text{kg l}^{-1}) \times \text{Flow rate}_{\text{en}}(\text{l s}^{-1})}{3.6 \times 10^6 \times \text{Derating}_m\ \% \times \text{Pump efficiency}_m\ \%} \times \text{time(s)}_{\text{en},r} \times \text{Conversion factor}_{m,r}\left(\text{kgCO}_2\text{e kWh}^{-1}\right)\right] - \text{AD}_r(\text{ha}) \times D\left(\text{kgCO}_2\text{e ha}^{-1}\right) \quad (6)$$

Wherein, en is the subset of j, irrigation technologies, including its energy-intensive elements, sprinkler and micro-irrigation; emissions from application are the emissions due to pressurizing water for its application in the fields; AD is the area with application with drips, which varies for different provinces; D is the reduction of emissions due to changes in ploughing and tilling operations after the adoption of drips, 20 kg of diesel per ha as reported by Li *et al* (2016).

In equation (7) we create conversion factors to derive the emissions per energy use for diesel and electricity produced in China with a provincial detail

$$\text{Conversion factor}_{m,r}\left(\text{kgCO}_2\text{e kWh}^{-1}\right) = \text{Engine}_m \times \text{Emission factor}_{m,r}\left(\text{kgCO}_2\text{e kWh}^{-1}\right), \quad (7)$$

where conversion factor is the emissions for the two main types of energy use for water pumping in China, diesel and electricity, engine is the distribution of

Table 2. Estimates of irrigation efficiency and emissions from irrigation and their main parameters for the baseline scenario (values based on data for 2011).

	Units	National	Hebei	Heilongjiang	Shandong	Xinjiang
Agricultural water						
Total agricultural water	km^3	383.16	15.43	25.65	22.19	50.49
Groundwater	%	17	77	52	29	16
Surface water	%	83	23	48	71	84
Pumped surface water	%	13	2	16	9	1
Average groundwater pump head	m	27.2	47.9	17.9	23.2	34.9
Average surface water pump head	m	32.2	43.8	14.6	30.5	50.0
Irrigated area						
Total irrigated area	Mha	66.35	4.97	3.88	5.55	5.39
Groundwater irrigated area	Mha	17.81	3.79	1.81	2.37	0.76
Irrigation technology area	Mha	27.31	2.70	2.66	2.26	2.89
Conveyance						
Surface water canal	Mha	48.09	2.69	3.75	3.82	4.15
Canal lining	Mha	11.58	0.28	0.12	0.57	1.17
Low pressure pipes	Mha	6.68	2.00	0.01	1.16	0.07
Application						
Flood/surface	Mha	57.29	4.51	1.34	5.01	3.64
Sprinkler	Mha	3.03	0.24	0.92	0.15	0.09
Microirrigation	Mha	2.12	0.03	0.13	0.06	1.60
Other field measure	Mha	3.91	0.19	1.49	0.33	0.06
Irrigation efficiency						
Conveyance	%	44.40	58.69	31.56	48.21	40.61
Application	%	53.60	52.21	64.95	52.30	62.51
TOTAL	%	23.80	30.65	20.50	25.21	25.39
Energy emissions						
Groundwater pumping	$MtCO_2e\ yr^{-1}$	22.88	6.83	4.30	2.38	2.92
Surface water pumping	$MtCO_2e\ yr^{-1}$	12.02	0.11	0.51	0.56	0.14
Pressurizing water for conveyance (low pressure pipes)	$MtCO_2e\ yr^{-1}$	−1.18	−0.35	0.00	−0.21	−0.01
Pressurizing water for application (sprinkler)	$MtCO_2e\ yr^{-1}$	3.22	0.17	1.33	0.13	0.14
Pressurizing water for application (micro irrigation)	$MtCO_2e\ yr^{-1}$	0.86	0.01	0.07	0.02	0.97
Decrease in tillage operations (micro irrigation)	$MtCO_2e\ yr^{-1}$	−0.13	0.00	−0.01	0.00	−0.10
Total emissions from energy consumption	$MtCO_2e\ yr^{-1}$	37.66	6.76	6.20	2.89	4.06

engines used, 76% for electric and 24% for diesel, as detailed above, emission factor is the emissions for electricity produced in china with a detail on the provinces (Lindner *et al* 2013) and conversion factors for diesel (DEFRA and DECC 2010).

The nexus between water use and emissions is captured for pressurized application and for pressurized conveyance. First, the emissions caused by irrigation in areas adopting pressurized conveyance are represented in equation (4); when these areas vary, the change is also reflected in equations (2) and (1). Second, the emissions caused by irrigation in areas adopting pressurized application technologies are represented in equation (5); when these areas change, it is also reflected in equations (3) and (1). Therefore, the method captures the implications in terms of both irrigation efficiency and emissions.

Using this procedure, we calculate a baseline and simulate the water and energy use associated with increasing the area that adopts irrigation technology as described in the 12th 5YP targets. Then, by distributing the reductions of water applied from the estimated increases in irrigation efficiency, according to the supply sources in each province, we evaluate the potential GHG emission savings. Finally, we quantify the influence of key parameters in the formulae above to understand their impact on irrigation efficiency and energy use. Figure 2 shows the main data sets used in the methodology.

This approach is used to analyze the outcome of the 12th 5YP targets in four Chinese provinces: Hebei, Heilongjiang, Shandong and Xinjiang (figure 1). The provinces have been chosen because they had the highest planned increases in area under irrigation technology according to the 12th 5YP. The four selected Chinese provinces differ substantially in key parameters like agricultural water use, sources of water, irrigated area, area under irrigation technology, and conveyance and or application type (more information in supplementary section 1). These differences in key variables lead to very different values of fundamental aspects of the water–energy nexus such as energy emission rate, total emissions, irrigation efficiency, water savings and the costs of the related investments.

3. Results and discussion

3.1. Baseline situation

Overall, GHG emissions from China's irrigation for a baseline scenario of 2010 are estimated to be 37.66 MtCO_2e (table 2). This result comprises energy use from groundwater pumping and pumped surface water, including conveyance and application in irrigation systems. This result is similar to previous findings by Zou *et al* (2015), however, our estimate for groundwater pumping on its own (22.37 MtCO_2e) is significantly lower than previous estimates of 28.65 MtCO_2e by Zou *et al* (2015), and of 33.1 Mt CO_2e by Wang *et al* (2012). The contrasting results are likely to be due to the cumulative effects of minor differences in methods between the studies, and perhaps more importantly, due to our inclusion of updated data at the provincial level from the energy sector, which is rapidly evolving.

The irrigation efficiency value calculated for the baseline is 23.80% (table 2), which is lower than the FAO estimate for East Asia (33%; FAO 2002), and much lower than the Chinese official irrigation efficiency figure for 2010 (50%; MWR 2011). It should be noted that estimates of irrigation efficiency are notoriously uncertain at all scales and they are subject to strong debate. Differences in the definition and/or calculation method can greatly influence results. Our definition of irrigation efficiency is the fraction of water 'pumped or diverted through the scheme inlet which is used effectively by the plants' (FAO 1989), while the Chinese government definition is the ratio between water available for crops and water extracted (Han *et al* 2009, MWR 2009). The definition we use includes conveyance efficiency, which is absent in the official Chinese definition (i.e. we include water abstracted from source to crop, whereas the government definition only includes water from irrigation scheme source to crop). Hence, the two irrigation efficiencies are not directly comparable.

The socio-ecological contexts of the four provinces are reflected in *contrasting* relative distributions of water supply sources and adoption levels of different irrigation technologies and therefore show considerable differences in both the overall efficiency and between conveyance and application types (table 2). Hebei has a very efficient conveyance system partly attributed to widespread use of low pressure pipelines but predominantly to the high proportion of groundwater use for irrigation (77%). CO_2e emission rates show even larger differences as rates vary considerably between groundwater and surface water pumping, depending on the pump head. Hebei has high total emissions from irrigation because of its large proportion of groundwater use. The relatively extensive use of sprinkler systems in Heilongjiang leads to higher emissions than other provinces, whereas the greater pump head in Xinjiang causes its high emissions.

3.2. Scenario results

We next project the effects of expanding the area under irrigation technology according to the 12th 5YP plan.

3.2.1. Irrigation efficiency and reductions in water application

Table 3 shows an increase in irrigation efficiency from 23.80% to 26.76% which is consistent with the 3% increase targeted by the national 12th 5YP. Hebei and Heilongjiang show higher increases in irrigation efficiency than the target (Hebei 3%, Heilongjiang 3%, Shandong 4%, and Xinjiang 6%). If realised, these changes would provide reductions of applied water of nearly 11 km^3 that could be used to intensify or expand irrigated cropping to help meet the 5YP target of increased grain production. The national average reduction in applied water is 170.93 $m^3\ ha^{-1}\ yr^{-1}$ and the studied provinces range from 139.40 to 502.09 $m^3\ ha^{-1}\ yr^{-1}$. Hebei, with the highest irrigation efficiency, has the lowest reduction in water application, whereas Xinjiang, with an irrigation efficiency slightly above the national value, has the highest reduction in water application. These differences highlight the importance of increasing efficiency in areas with high water use and low efficiency.

3.2.2. Emissions from fuel consumption

The expansion of pressurized irrigation systems leads: first, to increases in water pressurization for sprinklers and drips, which consume energy that comes from different provincial mixes; second to changes in farming operations, namely a decrease in tillage requirements in areas with drips; and third to reductions in emissions due to smaller water conveyance losses resulting in smaller water pumping needs with the use of low pressure pipes in groundwater contexts. Hence, energy savings directly related to pressurization by irrigation technology are primarily due to reductions in water use, so pressurization-related energy is saved chiefly if less water is pumped and/or pressurized. These aspects cause an increase in the GHG emissions of 0.26% (0.10 MtCO_2e) for China as a whole. Table 3

Table 3. Increase in the area adopting irrigation technology as targeted in the 12th 5YP for 2015 and the effects on scheme irrigation efficiency and GHG emissions.

	Units	National	Hebei	Heilongjiang	Shandong	Xinjiang
Targeted expansion of irrigation technology						
Sprinkler	1000 ha	2001	19	1115	33	90
Microirrigation	1000 ha	2011	19	87	33	1297
Low pressure pipes	1000 ha	2453	559	1	522	27
Canal lining	1000 ha	3535	108	242	162	172
Total	1000 ha	10000	705	1445	750	1586
Irrigation efficiency achieved with the targeted areas under advanced irrigation technology						
Conveyance	%	48.37	66.98	34.39	55.63	42.38
Application	%	55.32	52.46	73.03	52.69	72.56
TOTAL	%	26.76	35.14	25.11	29.31	30.75
% Total increase	%	12.45	14.67	22.53	16.27	21.11
Absolute figure of total increase	%	2.96	4.49	4.62	4.10	5.36
Change in emissions from energy consumption						
Groundwater pumping	$MtCO_2e\ yr^{-1}$	22.37	6.83	4.30	2.38	2.92
Surface water pumping	$MtCO_2e\ yr^{-1}$	11.75	0.11	0.51	0.56	0.14
Pressurizing water for conveyance (low pressure pipes)	$MtCO_2e\ yr^{-1}$	−1.62	−0.45	0.00	−0.30	−0.02
Pressurizing water for application (sprinkler)	$MtCO_2e\ yr^{-1}$	4.99	0.18	2.93	0.16	0.29
Pressurizing water for application (micro irrigation)	$MtCO_2e\ yr^{-1}$	1.58	0.01	0.12	0.03	1.76
Decrease in tillage operations (micro irrigation)	$MtCO_2e\ yr^{-1}$	−0.26	0.00	−0.01	−0.01	−0.18
TOTAL	$MtCO_2e\ yr^{-1}$	38.81	6.68	7.84	2.83	4.91
% Total variation from baseline	%	3.07	−1.21	26.61	−1.84	20.80
Absolute figure of variation from baseline	%	1.16	−0.08	1.65	−0.05	0.85
Change in emissions from fertigation						
Reduction in emissions due to smaller nitrogen application	$MtCO_2e\ yr^{-1}$	−1.06	−0.14	−0.15	−0.13	−0.25
Overall effects of irrigation technology on emissions, including fertigation, compared with baseline						
TOTAL	$MtCO_2e\ yr^{-1}$	37.75	6.54	7.70	2.70	4.66
% Total variation from baseline	%	0.26	−3.23	24.23	−6.35	14.77
Absolute figure of variation from baseline	$MtCO_2e\ yr^{-1}$	0.10	−0.22	1.50	−0.18	0.60
Overall effects of irrigation technology on emissions, assuming technology is used consuming same amounts of water and fertilizer, compared with baseline						
TOTAL	$MtCO_2e\ yr^{-1}$	44.71	6.68	7.84	2.83	4.91
% Total variation from baseline	%	18.72	−1.21	26.61	−1.84	20.80
Absolute figure of variation from baseline	$MtCO_2e\ yr^{-1}$	7.05	−0.08	1.65	−0.05	0.85

shows that the effects on emissions from energy use for pressurization vary substantially among the provinces. Heilongjiang experiences increases of around 25%; Hebei and Shandong, on the other hand, show small decreases due to their adoption of low pressure pipes and proportionally lower increases in sprinkler and micro-irrigation systems.

3.2.3. The economics of the water–energy nexus of irrigation technology

A review of the investment costs of different irrigation technologies in 13 Chinese studies (see supplementary table S6) allows an estimate of average cost (CNY ha^{-1}) for each of the four irrigation technologies that can be used to calculate the reduction in water application per unit cost. Improving conveyance by canal lining costs roughly 4300 CNY ha^{-1}, low pressure pipes cost roughly 3750 CNY ha^{-1}, sprinklers 9700 CNY ha^{-1} and micro-irrigation is the most expensive at 14 500 CNY ha^{-1}. Figure 3 shows varying investment costs per area in different provinces, according to different areas adopting the technologies. In the same figure, when investment per area is compared with the change in water use per area across the provinces, they

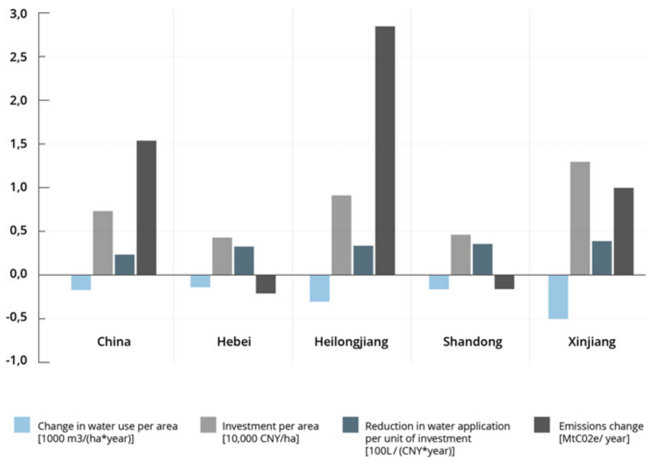

Figure 3. Economic implications of irrigation modernization and impact on emissions and reductions in water application.

visibly follow a similar proportion. Strikingly the actual reduction in water application per unit of investment remains very similar across the case studies (figure 3): in the studied provinces the reduction in water application per unit of investment varies from 0.33 (Hebei) to 0.38 (Xinjiang) hectolitre yr^{-1} CNY^{-1}. That is to say, that in the studied provinces the output has a similar proportion to the investment whatever technological change is made. Importantly, the relative investment returns in terms of water remain similar, but different technological changes create different outcomes in terms of emissions, which are strongly related to the level of expenditure, because lining canals is cheaper than installing drips or sprinklers. Summarizing, the investment cost per area does not have large implications for the outcome in terms of water, but in terms of energy the most expensive technologies listed above are more energy-intensive and therefore produce more emissions.

3.2.4. Regional details strongly influence outcomes

The characteristics of the water supply systems strongly determine the potential for energy savings from reductions in water application. Hebei and Shandong show modest co-benefits, with lower emissions compared to the baseline, which can be explained by the characteristics of their water supply system. A high proportion of groundwater and deep groundwater pump lift make Hebei's water supply very energy intensive, so that reductions in applied water tend to reduce emissions. This finding is consistent with the potential for energy savings in Hebei presented by Zhang *et al* (2013).

In Shandong the increase in areas adopting low pressure pipes offsets the increase of emissions due to larger areas adopting micro-irrigation and sprinklers. Both Heilongjiang and Xinjiang exhibit increases in emissions. For instance, despite the relatively large reductions in water application in Xinjiang, emissions show a significant trade-off, increasing by 15%. Co-benefits are lacking as the main water supply in Xinjiang is gravity-fed surface water. In terms of GHG emissions, pressurized irrigation technology such as sprinklers and micro-irrigation is best implemented in areas with energy-intensive water supply. Where this is not the case, it is important to recognize the energy trade-offs associated with implementing energy-intensive irrigation technology, as seen in the case of Heilongjiang where emissions increase nearly 25%, despite reductions in water application.

Prioritizing low pressure pipes in contexts dominated by groundwater sources, like Hebei, is cheaper and leads to co-benefits. A similar result can be expected from canal lining; although it is not a technology strongly targeted in the analyzed provinces, it could play a significant role. In contrast, prioritizing more expensive technologies like sprinklers and micro-irrigation leads to costly trade-offs, due to increased energy consumption when using surface water and/or increasing the pressure for sprinkler devices.

3.2.5. The potential influence of reduced emission from fertigation

The changes in irrigation systems that we describe have implications for the amount of nitrogen fertilizer used (a key contributor to overall agricultural emissions). Fertilizer is applied jointly with irrigation in the pressurized schemes, which improves the efficiency of the application, and a reduction of nitrogen application would be expected. This additional trade-off is not included in the baseline because there is no detailed data on the actual amount of nitrogen fertilizer used in different provinces and management systems. Moreover there is no strong empirical evidence to estimate the reduction of fertilizer use that would be implemented by Chinese farmers (who are known to generally use much more nitrogen than needed, Qiu 2009). Indeed, the adoption areas of

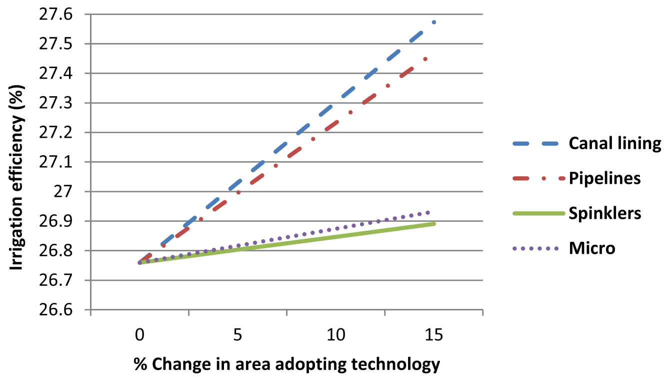

Figure 4. Influence of incremental percent changes in the area using irrigation technology on irrigation efficiency.

sprinklers and drips in the field in China are very limited and many are still in pilot project sites. In the literature there are estimates of ranges of nitrogen application values for different crops (Yang *et al* 2015), but they lie below the values shown by the few sources that do provide survey based data for such technologies (Wang *et al* 2008). Given this uncertainty about how fertigation will be managed and with a note of caution, we provide an estimate (table 3) by assuming a 30% reduction as proposed in government guidelines for fertigation (MA 2013), taking as departure point the application values reported by Yang *et al* (2015) for those areas where pressurized irrigation technology is adopted. Following IPCC guidelines, the emission factors used are country specific (Zhou *et al* 2015), according to Tier 2 methodology and differentiated between rice and cropland (Stocker 2014), and the values are converted to CO_2 equivalent using global warming potential values for 100 years (Stocker 2014). Importantly, in cases where there is a large expansion of micro-irrigation, like in Xinjiang (table 3), the decrease of emissions due to reduced application of nitrogen fertilizer makes a visible difference, but it does not change the overall picture.

3.2.6. Perverse outcomes: maximizing production

The relative advantage created by the adoption of drips and sprinklers and the related decrease in marginal costs of water can create an unexpected outcome, namely that drips and sprinklers are used for maximizing production rather than for decreasing water application; an outcome that is being documented in, for example Pakistan and the US (Ahmad *et al* 2007, Ward and Pulido-Velazquez 2008); water use actually increases after technology adoption creates a rebound effect. This is likely in situations of weak water governance structures and implementation, with neither effective control of water use nor economic mechanisms to regulate overuse, conditions typical in much of China. A scenario in which technology improvements are associated with the same consumption of water and fertilizer shows that co-benefits would still appear in the provinces with less drip and sprinkler technology, but for the whole of China it would mean a significant increase of emissions (table 3, last row).

3.3. Influence of key parameters on the water–energy nexus of irrigation modernization

Finally we examine the influence of incremental changes in some key parameters at the national scale. Increases in the area of canal lining for conveyance and micro-irrigation for application produce the highest proportional effect on raising irrigation efficiency (figure 4). The analysis of the influence on emissions from irrigation technology, and water and energy sources, shows that expansion of sprinkler systems strongly increases the emission rates (figure 5); this would not be the case, however, in areas where the groundwater pump head would be greater than the critical energy saving head (Zou *et al* 2012). There are other important messages: pumping groundwater is clearly the most energy intensive process and changing the distribution of energy sources towards more electric pumps produces a reduction in emissions.

The predominant use of surface water and traditional unlined canals is the main reason for the relatively low irrigation efficiency in China. Consequently, improving conveyance efficiency through canal lining and pipelines may be the most effective way of achieving the co-benefit of reducing water application with a low carbon footprint. Only in groundwater fed areas is micro-irrigation a suitable irrigation technology for both improving irrigation efficiency and decreasing GHG emissions, in situations where the pumping head value allows it (Zou *et al* 2012).

4. Conclusions and policy implications

Quantifying the trade-offs and co-benefits is just part of the nexus story; to successfully manage the water–energy nexus in China, a critical set of socio-economic and policy issues also need to be addressed. These include: improving communication amongst ministries

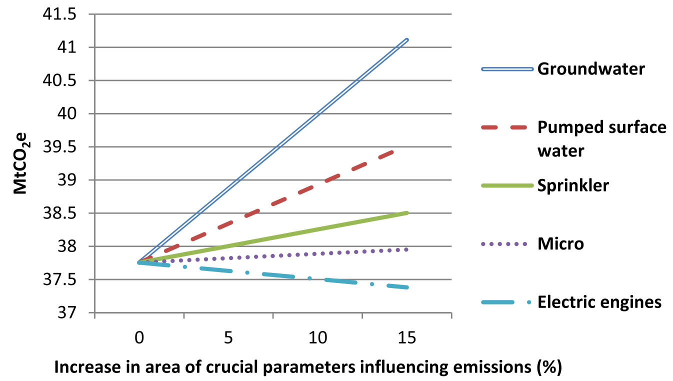

Figure 5. Influence of incremental percent changes in key factors on energy use emissions.

with responsibility for different aspects of the water–energy nexus, creating clear incentives to decrease water application and adopt irrigation technology, establishing reliable water rights, and improving groundwater governance and use (Zhang 2007, Zhang *et al* 2008, Calow *et al* 2009, Shiferaw *et al* 2009, Yu 2011). This study enhances our understanding of co-benefits and trade-offs in the irrigation water–energy nexus, across a set of diverse provincial cases in China using targets defined in the 12th 5YP. The approach applies a suite of assumptions about water use efficiency for various stages and technologies in the process of irrigation at the provincial level, although estimates for the energetic implications of low pressure pipes were only available on a per area basis at the national scale.

We find that expansion of sprinklers and micro-irrigation as outlined in the 12th 5YP could increase GHG emissions from agricultural water use by just 0.10 $MtCO_2e\ yr^{-1}$, however, under the existing weak governance this could increase to 7.05 $MtCO_2e\ yr^{-1}$ if unplanned rebound effects occur. Where pressurized irrigation technology is used in surface water irrigated areas (Xinjiang) or where the energy consumption to pressurize water (Heilongjiang) is high, emissions increase substantially. The results show that water supply configuration largely determines the potential energy savings from reductions in water application. An implication of this is that co-benefits of irrigation technology for energy saving only appear in areas irrigated with energy intensive supply (Hebei, Shandong). Trade-offs appear in surface water irrigated areas (Xinjiang), where emissions due to expansion plans for pressurized irrigation technology could increase significantly. Taken together, these results suggest that in situations where policy makers seek to optimize both water and energy use they should encourage the adoption of low pressure conveyance pipes in groundwater irrigated areas, and canal lining in surface water areas, since these increase efficiency with lower emissions than other methods. Another important implication is that sprinklers and micro-irrigation appear as a suitable means to increase efficiency only in groundwater irrigated areas. Regarding the costs, the most expensive technologies appear linked to trade-offs, while co-benefits result from lower-priced technologies. These insights are relevant to make adaptation policies consistent with mitigation goals in the irrigation sector. Further work needs to be done at the sub-provincial scale, including collection of data at smaller administrative units, and examining in greater detail which governance schemes are needed to achieve co-beneficial outcomes in different contexts.

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