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Environmental impact assessment of water-saving irrigation systems across 60 irrigation construction projects in northern China

Xiuzhi Chen [a], Kelly R. Thorp [b], Pieter R. van Oel [c], Zhenci Xu [d], Bo Zhou [a], Yunkai Li [a,*]

[a] College of Water Resource & Civil Engineering, China Agricultural University, Beijing, 100083, China
[b] USDA Agricultural Research Service, 21881 N Cardon Ln., Maricopa, AZ, USA, 85138
[c] Water Resources Management Group, Wageningen University, PO Box 47 6700 AA, Wageningen, the Netherlands
[d] School for Environment and Sustainability, University of Michigan, 500 S. State Street, Ann Arbor, MI 48109 USA

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A B S T R A C T

With increasing water shortages partly due to increasing demands, water has become a globally relevant issue especially in arid and semi-arid regions. Water-saving irrigation technologies provide new ways for improving the efficiency of water use for agricultural production. Although efficient irrigation management could lead to water savings and increased yields, the water consumption and greenhouse gas emissions during the construction of irrigation projects also puts pressure on environmental health. However, little research has considered the environmental impact of the construction process and materials. To fill this gap, the water footprint (WF) and carbon footprint (CF) of irrigation projects were calculated using life cycle assessment (LCA) methods. The results for sixty typical irrigation projects in northern China showed that the WF accounted for only 0.2–1.5% of the total agricultural WF and 2.3–8.8% of the water saved. When the WF to construct modern irrigation systems is not considered, the water-saving effects of these systems are generally overestimated by 13%. The CF for irrigation projects was 42.0% of all agricultural activities. Due to the difficulty to obtain detailed information for irrigation projects, this paper established the relationship between financial investment or area and CF for three kinds of irrigation projects. It provided a simple quantitative method for assessing its environmental impacts. By comparing environmental impacts and production benefits under different scenarios, using drip irrigation over the long-term could increase crop yield and reduce water footprint, but carbon footprint was increased at the same time. This study suggests that it is necessary to assess the environmental impacts of irrigation construction projects from a life cycle perspective rather focusing only on yield increases and reductions in irrigation amounts.

1. Introduction

Food security and environmental protection are both important issues of global concern (Godfray et al., 2010). Population growth and improvement of living standards have significantly increased the demands on food, and trends suggests greater consumption and environmental problems in the future (Steffen and Richardson, 2015; Westing, 2010). Investment in irrigation projects that incorporate technologies for efficient water use is regarded as an effective way to solve these problems, although they may also lead to substantial unintended effects on downstream water availability (Di Baldassarre and Wanders, 2018; Grafton and Williams, 2018). Compared with traditional irrigation (e.g. border, furrow, and flood irrigation), efficient irrigation (e.g. sprinkler, micro-spray, and drip irrigation) has obvious advantages for achieving sustainability and developing rural economies (Ricart, 2017), especially in arid or semi-arid regions (Elliott and Mueller, 2014). However, the construction of irrigation projects (including materials, equipment, energy et al.) consumes a considerable amount of water and results in greenhouse gas emissions (Moinet and Cieraad, 2017). Because of the rapid development and popularity of irrigation projects, especially in China, the environmental impacts of irrigation projects cannot be overlooked. Accordingly, it is necessary to quantify the impact of irrigation projects on the environment and discuss food security and environmental protection in the context of productivity gains.

* Corresponding author. College of Water Resources and Civil Engineering, China Agricultural University, No.17 Qinghua East Road, Beijing, 100083, China.
E-mail address: yunkai@cau.edu.cn (Y. Li).

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In the past 20 years, footprint assessments have been conducted to raise awareness on the seriousness of environmental pressure from human activities. Such approaches can also be used to quantitatively assess the environmental impact of irrigation projects. Water footprint (*WF*) was proposed to indicate the total amount of water consumption for producing products and services within a certain period (Hoekstra, 2007), laying the basis for quantitatively analyzing the impacts of human activities (Hoekstra, 2009; Van Aggelen and Ankley, 2010). With climate change and global warming, the greenhouse effect attributed to agriculture and industry has also aroused great concern (Cohn et al., 2014). The carbon footprint (*CF*) for products and services, based on lifecycle assessment (*LCA*) (Pennington et al., 2004; Rebitzer and Ekvall, 2004), is capable of describing greenhouse gas (*GHG*) emissions at all stages of a product's life (Hertwich, 2009). In the past decade, many studies have been conducted on agricultural *WF* and *CF*. For instance, agricultural sustainability has been analyzed by calculating *CF* at regional scales (Al-Mansour and Jejcic, 2017; Lopez et al., 2015; Rebolledo-Leiva et al., 2017). Some scholars preliminarily evaluated the *CF* of crop production systems as well as its driving forces by conducting surveys of four major crops (Chakrabarti and Pathak, 2016; Li et al., 2018; Poje, 2014). These studies provide a basis for *CF* calculation approaches. Current studies on the *WF* for crop production are mostly focused on water consumption by the crop itself and water used to produce the materials and equipment required for crop production (e.g., fertilizer, pesticide and agricultural machinery) (Huang and Qian, 2017; Machado and Maceno, 2017). Since engineering information is lacking, no study has reported on the environmental impacts exerted by large-scale irrigation projects. Thus, the comprehensive benefits of irrigation projects to agriculture could not be analyzed. To fill this gap, *WF* and *CF* calculation methods need to be proposed, and environmental assessments should be performed for irrigation projects as it relates to the overall agricultural production chain.

The objectives of this study were to analyze the *WF* and *CF* of irrigation projects in northern China according to the *LCA* method. Based on the research results, reliable methods for calculation of *WF* and *CF* for irrigation projects were developed. The relative environmental impact among various irrigation methods was also addressed using scenario analysis to assess options for improving agricultural irrigation water management, reducing environmental impact, and achieving agricultural sustainable development.

2. Methodology

2.1. Boundary and assumptions

Based on the principles of *LCA* (Hortenhuber et al., 2014), the *WF* and *CF* assessment boundary for irrigation projects consisted of water consumption and carbon emissions occurring as a result of construction and operation. It primarily included three aspects: upstream, intermediate, and downstream. The upstream aspect incorporated the production and processing of pipe material and equipment (e.g., pipes, emitters, and pumps). The intermediate aspect involved the construction of the irrigation project (e.g., machinery, construction equipment, manual labor and other temporary project requirements). The downstream aspect incorporated the operation and maintenance of the irrigation project (e.g., routine maintenance and equipment replacement). Different irrigation water sources or groundwater levels have great influence on irrigation energy consumption and water consumption, but this is not associated with the environmental effect of irrigation project itself. Therefore, the *LCA* assessment boundary for this study does not include water requirements for crop irrigation and greenhouse gas emissions from power and pumping requirements. This means the energy consumption and irrigation water were not included in calculation.

Three commonly-used irrigation methods were considered in this study: drip irrigation, pipe irrigation and sprinkler irrigation (as shown in Fig. 1). To ensure the reliability of the assessment and reduce uncertainty, the following assumptions were proposed in line with the Technical Specification for Irrigation Projects (GB/T50085—2007, GB/T50485-2009. China) and the Analysis of Resources Consumption in Construction Industry (GB 50189—2015, GB/T 51161—2016. China; PAS 2050; ISO 14067):

(a) To solve the problem of inconsistent construction timeframes among irrigation projects, a uniform calculation of investment was used based on the inflation rate in 2015 (Lopez-Roudergue et al., 2011; Regev et al., 1990).
(b) The coefficient of electricity for *CF* and *WF* assessment was consistent with the power grid at the site for energy use, following the *Provincial Greenhouse Gas Compilation Guidelines*.
(c) The service life of equipment and pipes for various water-saving irrigation systems was determined following the relevant standards (GB/T50085—2007, GB/T50485-2009. China).

2.2. Calculation method for WF and CF

To use *LCA* methods, the total water footprint (WF_{tot}) was partitioned into the water footprints attributed to equipment (WF_{equ}), energy use (WF_{eu}), machinery (WF_{mac}), labor (WF_{lab}), and operation (WF_{ope}). The WF_{equ} component included footprints from materials (WF_{mat}) and products (WF_{pro}). The total carbon footprint (CF_{tot}) included the carbon footprints attributed to equipment (CF_{equ}), energy use (CF_{eu}), machinery (CF_{mac}), labor (CF_{lab}), and operation (CF_{ope}), and CF_{equ} included both materials (CF_{mat}) and products (CF_{pro}).

$$WF_{total} = \sum_{1}^{5} WF_i \tag{1}$$

$$CF_{total} = \sum_{1}^{5} CF_i \tag{2}$$

In addition, WF_{ope} and CF_{ope} considered repair and maintenance processes. Because the energy consumption characteristics of irrigation systems are different, energy consumption of the pumps were considered while the irrigation water was not considered. The WF_{ope} and CF_{ope} are generated by the maintenance or replacement of the equipment for irrigation purposes and exclude water and electricity consumption required for the irrigation process. WF_{ope} represents the sum of actual water consumption for the operating stage, but due to lack of data, CF_{ope} was estimated as 3% of CF_{equ}. The calculation boundaries and equations are given in Table 1.

For the equations in Table 1, m_i denotes the quantity of raw materials or equipment; k_i is the *WF* coefficient of raw materials or equipment; c_i is the *CF* coefficient of raw materials or equipment; w_i is the power consumption at each stage; and WFP_i and CFP_i are the *WF* and *CF* coefficients of different productions. The water consumption during irrigation equipment production were investigated through surveys (see detail in Supporting *Information*); V_i is the *WF* energy coefficient; E_i is the *CF* energy coefficient; pow_i is the *WF* coefficient of mechanical power or fuel consumption; mc_i is the *CF* coefficient of mechanical power or fuel consumption; t_i is the running time of each machine; n is the total number of laborers; w_p is the *WF* coefficient of the laborers; c_p is the *CF* coefficient of the

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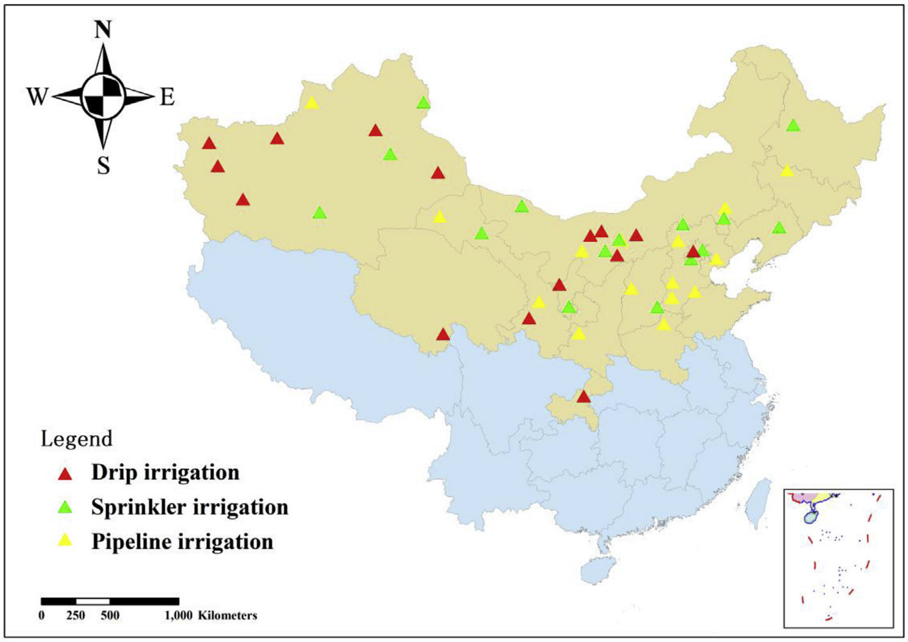

Fig. 1. Geographical location of water-saving irrigation projects.

Table 1
Calculation methods and equations for water and carbon footprints.

Name	Equation		
WF_{equ}	$WF_{\mathrm{equ}} = WF_{\mathrm{mat}} + WF_{\mathrm{pro}}$	$WF_{\mathrm{mat}} = \sum_1^n \mathrm{m_i} \times \mathrm{k_i} WF_{\mathrm{pro}} = \sum_1^n \mathrm{WFP_i}$	(3)
WF_{eu}	$WF_{\mathrm{eu}} = \sum_1^n w_i \times V_i$		(4)
WF_{mac}	$WF_{\mathrm{mac}} = \sum_1^n \mathrm{pow}_i \times \mathrm{t}_i$		(5)
WF_{lab}	$WF_{\mathrm{lab}} = \mathrm{n} \times \mathrm{w_p}$		(6)
WF_{ope}	$WF_{\mathrm{ope}} = \sum_1^n Q_i$		(7)
CF_{equ}	$CF_{\mathrm{equ}} = CF_{\mathrm{mat}} + CF_{\mathrm{pro}}$	$CF_{\mathrm{mat}} = \sum_1^n \mathrm{m_i} \times \mathrm{c_i} CF_{\mathrm{pro}} = \sum_1^n \mathrm{CFP_i}$	(8)
CF_{eu}	$CF_{\mathrm{eu}} = \sum_1^n w_i \times E_i$		(9)
CF_{mac}	$CF_{\mathrm{mac}} = \sum_1^n \mathrm{mc}_i \times \mathrm{t}_i$		(10)
CF_{lab}	$CF_{\mathrm{lab}} = \mathrm{n} \times \mathrm{c_p}$		(11)
CF_{ope}	$CF_{\mathrm{ope}} = CF_{\mathrm{equ}} \times 3\%$		(12)

laborers; and Q_i is the actual water consumption for the operating stage. The calculation of CF_{pro} suffered from a lack of relevant data. Accordingly, a proportional conversion method was used to replace the segmental calculation of *CF*. The routine maintenance primarily involved equipment maintenance, parts replacement, material purchase and renewal as well as other normal maintenance requirements of the irrigation system.

2.3. Investigation and survey

At present, the water and carbon footprints of irrigation equipment and materials have been rarely studied. Thus, there was basically no reference or standard for calculating this portion of the overall footprint. To obtain relevant information for equipment and materials, 23 irrigation production enterprises (e.g., manufacturers of water pumps, drip irrigation components and plastic pipes) were questioned by surveys. The energy consumption and materials used in the production of irrigation equipment were obtained through questionnaires, and results provided basic data for calculating water and carbon footprints (see details in *Supplementary Information*).

Additionally, the acceptance reports of 60 irrigation projects were collected from design institutes, construction enterprises, and other organizations (see details in *Appendix*). These 60 projects are all located in northern China and are in use with complete engineering data. All irrigation projects met the technical specification for irrigation projects (GB/T50085—2007, GB/T50485-2009 (China, 2007, 2009)) and passed the acceptance inspection. All projects are currently in use without any quality problems. From these project acceptance reports, information on labor requirements, consumption of raw materials, and use of water, electricity, and fuel for each project was obtained and employed for calculating water and carbon footprints. Information on the financial investment and scale of the engineering projects were used to build a regression model for estimating the carbon footprint.

2.4. Data sources and mapping

The water footprint calculation coefficient for plastics, cement, and other building materials were obtained from the Global Water Footprint Standard and Network Stat (https://waterfootprint.org/), the Water Footprint Calculator (https://www.watercalculator.org/), the Water Footprint Assessment (IFC, 2010) and the Water Footprint Assessment Manual (Hoekstra, 2011). These parameters and data were used to calculate the water footprint of irrigation projects.

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The carbon footprint calculation coefficient for plastics, cement, and other building materials were obtained from the CLCD (China Life Cycle Database, http://www.ike-global.com), CIAE (China Institute of Atomic Energy, http://www.ciae.ac.cn), IPCC (Intergovernmental Panel on Climate Change, https://www.ipcc.ch), and EIO-LCA (Economic Input-Output Life Cycle Assessment, http://www.eiolca.net) (*Supplementary Information*). These parameters and data were used to calculate the carbon footprint.

All statistical analyses were conducted using the software SPSS software (version 25.0; Statistical Product and Service Solutions, IBM, USA). All maps and GIS shape files for provinces and other major geographical areas were acquired or created by using ArcGIS software (version 10.1 ESRI).

3. Results and analysis

3.1. WF and CF of water-saving irrigation systems

WF_{tot} and the distribution of irrigation projects are shown in Fig. 2 The average *WF* of these projects ranged from 539.46 to 8075.90 $m^3\,yr^{-1}$. There were differences in *WF* among the three types of irrigation projects. The *WF* of drip irrigation projects ranged from 539.46 to 8075.90 $m^3\,yr^{-1}$ with an average of 3916.08 $m^3\,yr^{-1}$. The *WF* of sprinkler irrigation projects ranged from 739.26 to 7276.70 $m^3\,yr^{-1}$ with an average of 3517.81 $m^3\,yr^{-1}$. The *WF* of pipeline irrigation ranged from 599.40 to 6163.80 $m^3\,yr^{-1}$ with an average of 3131.532 $m^3\,yr^{-1}$. From Fig. 3, the distribution of WF_{tot} was relatively random (see details in *Supplementary Information*). Among all irrigation projects, there were only 5 projects with *WF* less than 1000 $m^3\,yr^{-1}$, 32 irrigation projects with *WF* between 1000 and 5000 $m^3\,yr^{-1}$, and 13 irrigation projects with *WF* larger than 5000 $m^3\,yr^{-1}$.

CF_{tot} and its spatial distribution among irrigation projects are shown in Fig. 3 The average *CF* of these irrigation projects ranged from 5.75 to 239.66 $t\,yr^{-1}$. Moreover, the *CF* of drip irrigation projects ranged from 22.52 to 170.75 $t\,yr^{-1}$ with an average of 91.25 $t\,yr^{-1}$. The *CF* for sprinkler irrigation projects ranged from 20.75 to 239.66 $t\,yr^{-1}$. The *CF* for pipe irrigation projects ranged from 5.75 to 46.18 $t\,yr^{-1}$. Among all irrigation projects in this study, only one irrigation project had a *CF* below 10 $t\,yr^{-1}$, 37 irrigation projects had CF between 10 and 100 $t\,yr^{-1}$, and the CF for 17 projects exceeded 100 $t\,yr^{-1}$.

3.2. Composition of WF and CF in water-saving irrigation systems

To compare the impact of *WF* and *CF* for various types of irrigation projects, five components of the construction project were considered, including equipment, energy, machinery, labor, and operation. The results are shown in Figs. 4–7. For different components of irrigation projects, WF_{tot} demonstrated obvious differences (Fig. 4). The WF_{equ} was largest among the five components. The WF_{eu} for pipeline irrigation projects was substantially more than WF_{eu} for the other two types. The WF_{mac} for pipeline irrigation projects was often larger than WF_{mac} for the other two types. Differences in WF_{lab} were small among all three irrigation types. Because the scale of the irrigation projects varied greatly, the proportion of *WF* in each component were calculated to analyze the difference among components (Fig. 6). The proportions of *WF* was substantially different among each component.

The *CF* for the five components of the irrigation projects were also different (Fig. 6). The CF_{equ} was remarkably larger than that for other components. The CF_{equ} for pipeline irrigation was relatively small, only one-sixth of that for drip or sprinkler irrigation. The CF_{eu} was the second largest portion. The CF_{lab} was smaller than that for other components. The *CF* for each component of irrigation projects decreased in this order: $CF_{equ} > CF_{eu} > CF_{mac} > CF_{lab} > CF_{ope}$ (Fig. 7). CF_{equ} was the greatest portion in all three types. In contrast to *WF*, the proportion of CF_{mac} for the three types of irrigation projects was smaller than that of WF_{mac} and WF_{lab}, accounting for 15.5%, 19.5% and 21.3% of CF_{tot}, respectively.

4. Discussion

4.1. WF of irrigation projects

To compare the *WF* of different irrigation projects, the *WF* per

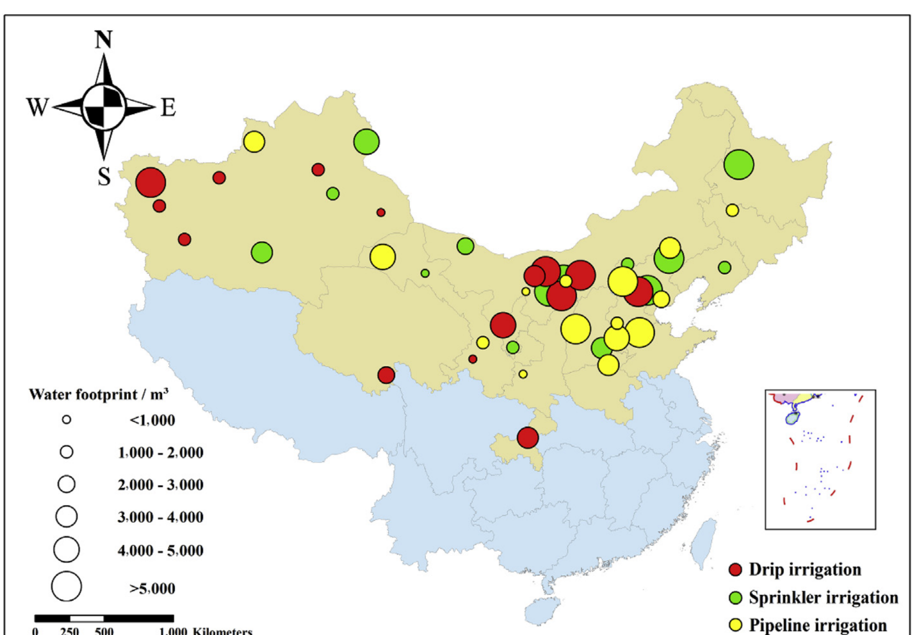

Fig. 2. Water footprint distribution of irrigation projects.

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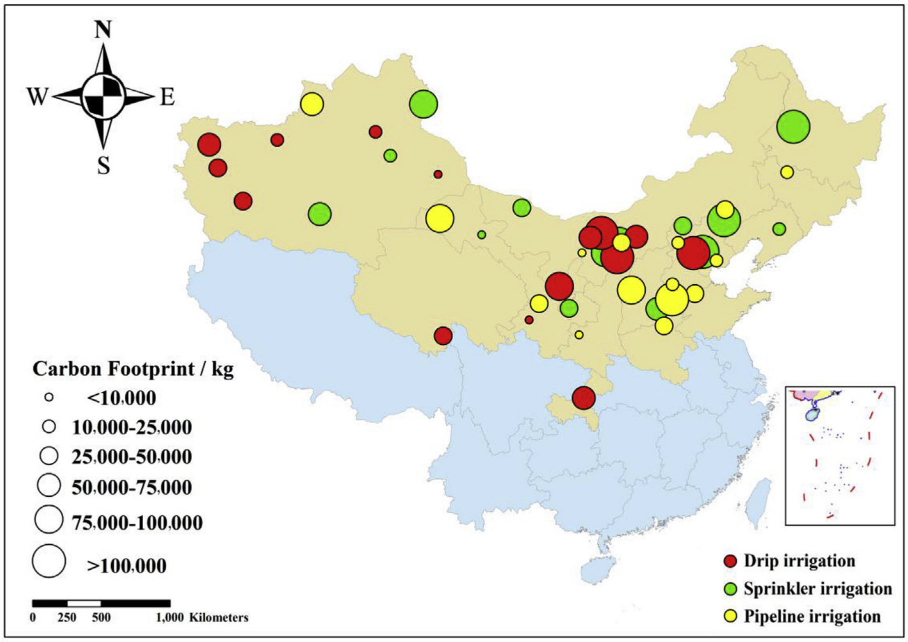

Fig. 3. Carbon footprint distribution of typical irrigation projects.

area of the irrigation project was calculated. The largest value, occurring for sprinkler irrigation, was 1.9 mm yr^{-1}, followed by drip irrigation and pipeline irrigation at 1.6 mm yr^{-1} and 0.6 mm yr^{-1}, respectively. These values do not include the impacts from using the irrigation system for crop production. When crop production is included, agricultural water footprints are much higher. For example, the annual water consumption of tomatoes grown in Spanish greenhouses was calculated as 239 mm yr^{-1} (Hoekstra, 2007). Researchers estimated the global *WF* of crop production at 964.0 Gm^3 yr^{-1} using remote sensing technology, and its *WF* was nearly 143 mm yr^{-1} (Romaguera and Hoekstra, 2010). The water footprints of wheat, maize, and wheat-maize rotations in the North China Plain were calculated as 96.72 mm yr^{-1}, 98.33 mm yr^{-1}, and 252.6 mm yr^{-1} (Gai et al., 2010). The water requirements of grassland and forests are relatively small, accounting for nearly 4900 m^3 hm^{-2}. The water requirements for food crops (e.g. wheat, rice and barley), fruits and vegetables (e.g. tomato, cucumber and watermelon) are much higher, accounting for 6950 m^3 hm^{-2} and 7800 m^3 hm^{-2} respectively (DB33T769-2016; DB14-T1049.1–2015. China). When considering the broader water use requirements for irrigated agriculture, the *WF* of irrigation construction projects only accounted for 0.23%–1.50% (≤5%) of water used for irrigated crop

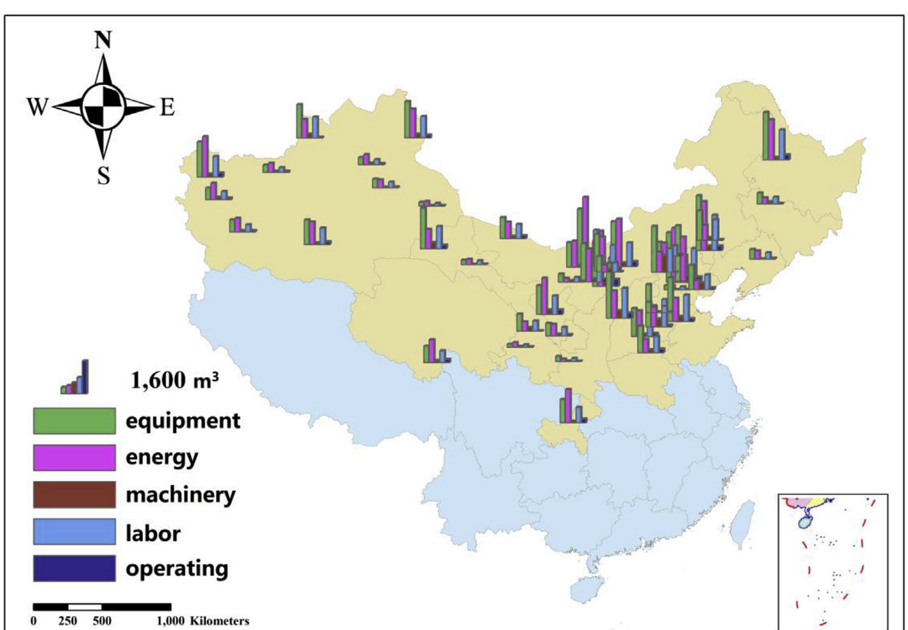

Fig. 4. Distribution of water footprint among different components in a typical irrigation project.

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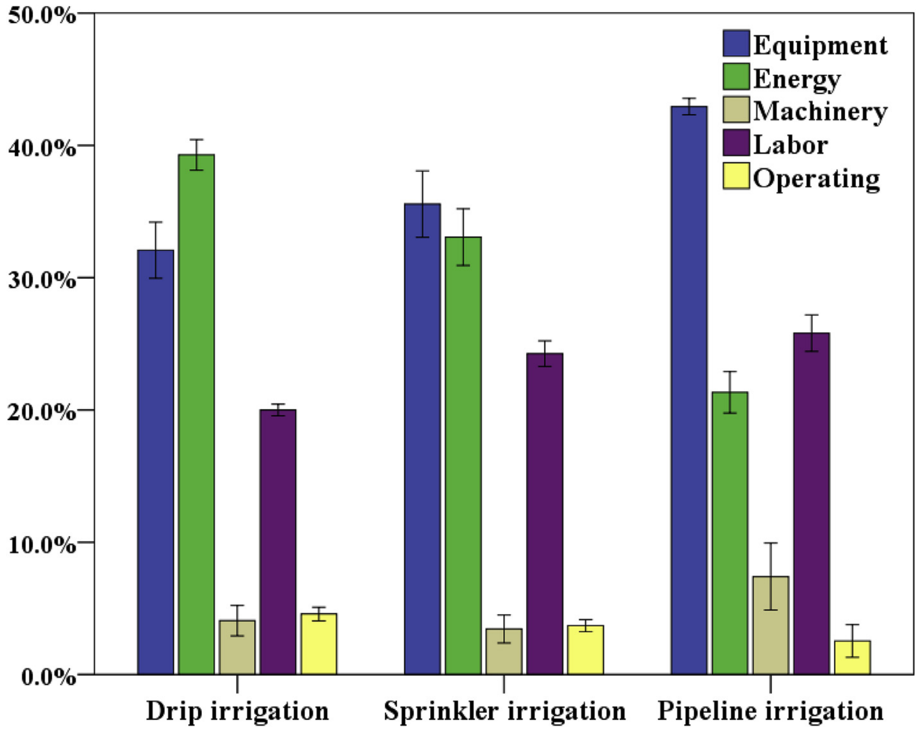

Fig. 5. The proportion of water footprint among different components for three types of irrigation projects.

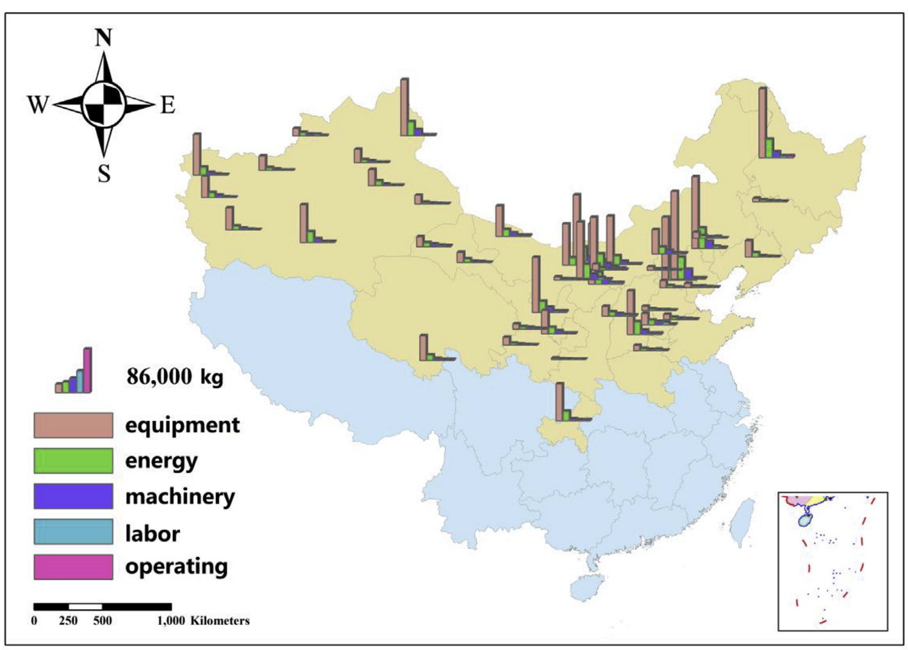

Fig. 6. Distribution of carbon footprint among different components in a typical irrigation project.

production. Following LCA principles (Sambito, 2017), the *WF* of irrigation construction projects can therefore be considered negligible as compared to the footprint assessment for irrigated agriculture as a whole, including water used for crop production. To impact actual crop water use, decisions on the type of irrigation projects to pursue could have a large role in saving water, increasing water use efficiency, and reducing blue water footprint (e.g. surface water and groundwater consumption).

4.2. The relationship between CF and project scale

The *CF* of irrigation projects was closely associated with the project scale, in terms of both the land area and total financial investment (including construction and upgrade). According to Economics of Water Conservancy Project and General Principle of Comprehensive Energy Consumption (Lopez-Roudergue et al., 2011; Rossi et al., 2016), the relationship between *CF* and financial

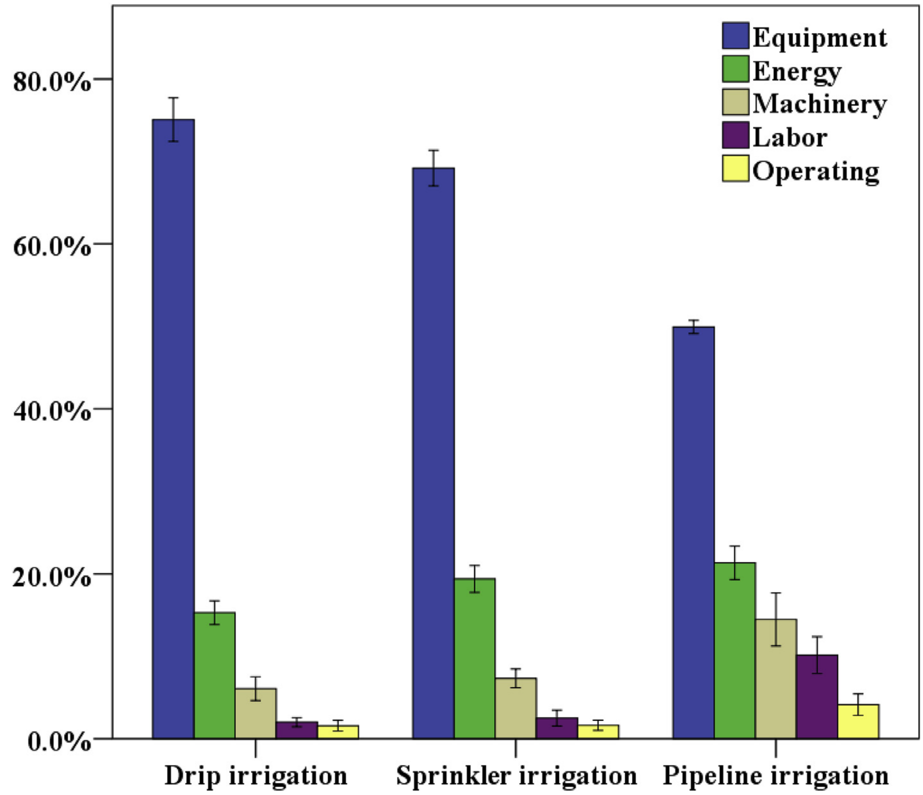

Fig. 7. The proportion of carbon footprint among different components for three types of irrigation projects.

investment was analyzed for irrigation projects in northern China. The results of the regression analysis are listed in Table 2.

The CF_{tot} and financial investment for three types of irrigation projects have a significant positive correlation (Fig. 8). With increases in project investment, the *CF* of the irrigation project also increases. The *CF* per unit investment of sprinkler irrigation was larger than that of drip and pipeline irrigation projects, because the construction and operation of sprinkler irrigation projects consume more materials (e.g., energy, machinery, and labor). However, this assessment of *CF* for irrigation projects was limited, because engineering data was lacking. As a simple alternative, the *CF* for irrigation projects could be estimated based on correlation with financial investment information (Fig. 8), which would enable *CF* assessments in spite of lacking engineering information. The regression model can estimate the *CF* of irrigation projects accurately with errors within ±6%. As compared to the *LCA* of *GHG* emissions developed by Carnegie Mellon University (http://www.eiolca.net), which estimated *CF* based on the Purchase Price Index (*PPI*), Purchasing Power Parity (*PPP*), and construction investment (Contreras-Jimenez et al., 2017; Inoue, 2011; Ziogou et al., 2017), the model developed herein was simpler and more effective in the estimation of *CF* for irrigation projects.

Table 2
Regression analysis of the carbon footprint for irrigation projects.

	Drip irrigation	Sprinkler irrigation	Pipeline irrigation
Investment	0.73*	0.82*	0.52*
Constant	8.73*	7.96*	4.67*
F-Statistic	85.14	549.59	60.599
R Square	0.87	0.98	0.82
N	20	20	20

Notes: Dependent variables are different types of irrigation projects, respectively. * Means $p < 0.05$.

The relationship between the total project area and *CF* per unit area is shown in Fig. 9. The *CF* per area had a substantial negative correlation with overall project area. The *CF* per unit area of sprinkler irrigation was larger than for drip and pipeline irrigation projects. The larger irrigation projects will have smaller *CF* per area. With a condition of equal total control area, the supporting facilities amount for large-scale irrigation projects (such as filter equipment, pipes and transformation equipment) is less than that for small-scale irrigation projects, and it also has less depreciation. So, the larger the control area of a single water source, the lower the input per unit area will be (Deng and Zhai, 2017). Accordingly, in future irrigation construction projects, small-scale irrigation projects should be merged to realize *CF* improvements. Large-scale construction and management of irrigation projects and systems is preferred to reduce overall *CF* (Raz, 2014; Sakurai, 2016).

4.3. Scenario analysis of WF and CF

Scientific irrigation technologies can simultaneously solve the problems of shortage and wastage of water resources (Voron, 1995). Long-term drip irrigation has been recognized as one of the most economical and water-saving irrigation methods for years, and it has a certain impact of increasing yield and income, especially for perennial crops (Kazumba et al., 2010). Thus, differences between traditional irrigation techniques and more modern, water-saving irrigation technologies was analyzed by calculating differences in *WF* and *CF* before and after the conversion to modern irrigation systems. For this analysis, four assumptions were proposed. (a) Given the water yield of a single well, the single-well control area was assumed to be 66.7 hm^2 (GB/T 50625−2010; SL/T153-95, China). (b) The single-wing labyrinth drip irrigation lateral was assumed to operate for one year. The patch-type drip irrigation

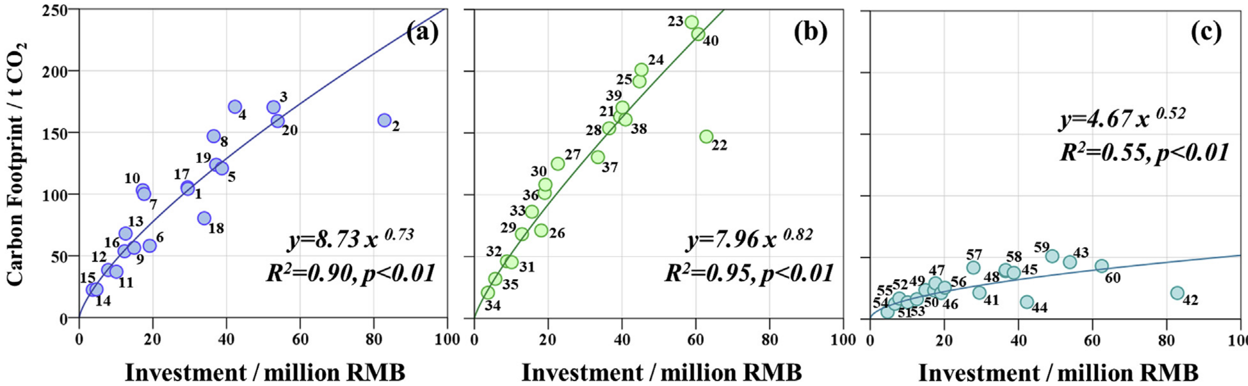

Fig. 8. The relationship between carbon footprint and financial investment for (a) drip irrigation, (b) sprinkler irrigation, and (c) pipeline irrigation.

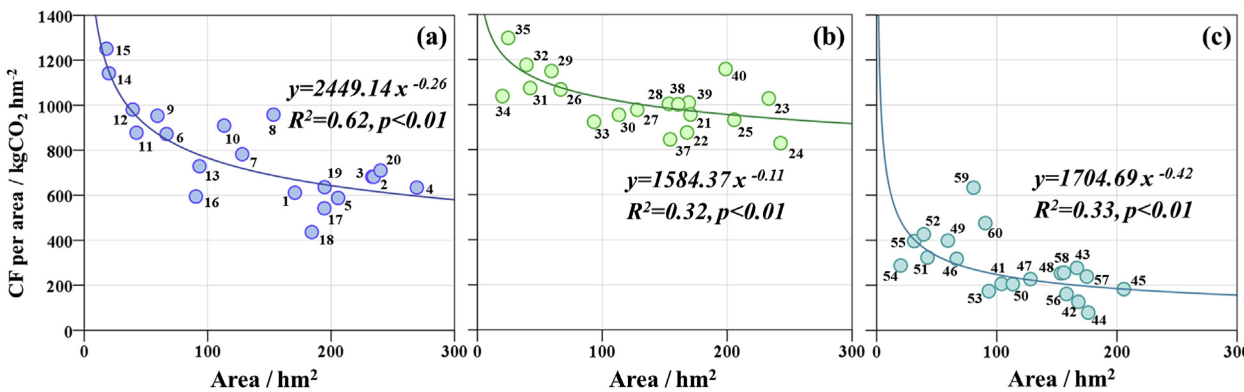

Fig. 9. The correlation between area and carbon footprint per area for (a) drip irrigation, (b) sprinkler irrigation, and (c) pipeline irrigation.

lateral was assumed to operate for three years, and the inner cylinder drip irrigation lateral was assumed to operate for five or seven (SL207-98; GB5084-92; SL13-2004; GB50288-99, China). (c) The scenario analysis was conducted in accordance with different planting periods for different crops. Sunflowers and potatoes represented annual crops, and alfalfa represented 2- to 5-year perennial crops. Wolfberry represented perennial crops with a growth period of more than five years. (d) The data for yield changes were analyzed using literature analysis (Ismail, 2013; Kiani and Mostafazadeh-Fard, 2016) and the empirical ranges and results are listed in Table 3.

The results demonstrated that updating from pipe irrigation to

Table 3
Changes to water and carbon footprints after conversion between irrigation systems.

Before conversion	After conversion	Investment (dollar/hm^2·y)	Yield	Irrigation projects		Agricultural production chain		Crop type	References
				WF (m^3 hm^{-2} y^{-1})	CF (kg hm^{-2} y^{-1})	WF (m^3 hm^{-2} y^{-1})	CF (kg hm^{-2} y^{-1})		
Pipe irrigation	Disposable drip irrigation	+78.4	15%–20%	+279.5	+452.3	−3650.7	+84.6	Annual crops (Sunflower)	(Sinha et al., 2017))
Pipe irrigation	Disposable drip irrigation	+78.4	10%–25%	+279.5	+452.3	−3180.4	+84.6	Annual crops (Potato)	(Ziogou et al., 2017)
Pipe irrigation	Semi-fixed sprinkler irrigation	−120.0	15%–25%	−46.4	−294.9	−1820.6	−356.9		
Pipe irrigation	3-year drip irrigation	+62.7	15%–20%	−104.6	+252.5	−2487.0	+12.8	Perennial crops (2–5 years)	(Kandelous et al., 2012)
Disposable drip irrigation	5-year drip irrigation	−17.5	0	−126.3	−110.9	−2550.8	−20.6	(Alfalfa)	(Wang et al., 2018)
Pipe irrigation	Disposable drip irrigation	+78.4	10%–20%	+279.5	+329.9	−2755.5	+84.6	Perennial crops (>5 years)	(Zhang et al., 2019)
Disposable drip irrigation	3-year drip irrigation	−14.3	0	−104.6	−122.4	−2898.6	+12.8	(Wolfberry)	
Disposable drip irrigation	5-year drip irrigation	−17.5	0	−126.3	−110.9	−3013.1	−20.6		
Disposable drip irrigation	7-year drip irrigation	−20.0	0	−158.4	−80.3	−3115.9	−32.0		

drip or sprinkler irrigation could effectively reduce *WF* (Table 3), but the *CF* and investment decreased at the same time. More advanced irrigation technologies will produce higher yields and crop quality, so economic costs and benefits need to be taken into account before upgrading irrigation projects. If disposable drip irrigation was changed to perennial drip irrigation, the *CF* and *WF* both decreased with varying degrees, depending on the life cycle. Therefore, compared with disposable irrigation equipment, long-term irrigation equipment is more environmentally friendly. In addition, while reducing actual irrigation water in the overall agricultural production chain effectively, the *WF* of water-saving irrigation construction projects increased, accounting for 2.30%–18.75% of the amount of water savings. According to crop type and given the factors of *WF*, *CF*, and yield, an appropriate irrigation method can be selected for minimum environmental impact.

5. Conclusion

The construction of irrigation projects will bring some negative effects on the environment, such as virtual water consumption and greenhouse gas emission. This paper assessed water and carbon footprints of 60 irrigation projects in northern China by the life cycle assessment method. The results showed that the *WF* of irrigation projects ranged from 540 to 8100 $m^3 yr^{-1}$ while the *CF* ranged from 6 to 240 $t\ yr^{-1}$. The order of carbon footprint per unit area is sprinkler irrigation, drip irrigation and pipe irrigation. By assessing *CF* for different construction stages, the following relationship was found: $CF_{equ} > CF_{eu} > CF_{mac} > CF_{lab} > CF_{ope}$. The water footprint of irrigation construction projects is small when compared to water used during the whole process of agricultural production. But compared with the amount of water saved, this portion of water accounts for more than 8% of saved water. In other words, the water-saving effects of water-saving irrigation systems are typically overestimated, because water requirements for irrigation project construction is usually not considered. The *CF* per area of irrigation project showed a negative correlation with total area, while the total *CF* was positively correlated with investment. But there is no obvious distribution rule in space. Through scenario analysis, it suggests that when upgrading irrigation technology, input costs, benefits and water resource status should be considered comprehensively. It provides reference for the design and transformation of low carbon irrigation project.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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