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A Comparative Life Cycle Assessment of Crop Systems Irrigated with the Groundwater and Reclaimed Water in Northern China

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Abstract: Using reclaimed water from treated wastewater as an irrigation source is gaining popularity in arid and semi-arid areas. However, life cycle assessment studies, utilizing experimental data to analyze the environmental and health impacts of crops irrigated with reclaimed water, are lacking. This study presents the first comparative life cycle assessment of corn, soybean and wheat systems irrigated with groundwater and reclaimed water in Northern China. While the life cycle foreground inventory was based on a combination of experimental and modeling datasets, the life cycle background inventory was compiled with commercially available data packages augmented with Chinese electricity mix data. The life cycle impact analyses were based on the characterization factors from state-of-art life cycle impact assessment models. The analyses indicated that the life cycle global warming impacts of the crop systems ranged from 0.37 to 0.64 kg CO2-eq/kg grain, with reclaimed water irrigated soybean and ground water irrigated wheat exhibiting, respectively, the lowest and highest global warming impacts. Irrigation, farming equipment operation, on-field emissions and fertilizer production ranked as top contributors to the life cycle impacts for corn, soybean, and wheat. The comparative analyses of irrigation sources suggested that significant environmental tradeoffs existed. Replacing groundwater with reclaimed water as the irrigation source significantly decreased life cycle global warming, acidification, ozone depletion, smog formation, and respiratory impacts of corn, soybean and wheat systems. However, replacing groundwater with reclaimed water increased the life cycle noncancer impacts of those systems. Coordinating policies within the water–food–health nexus is required, in order to minimize the environmental tradeoffs, while maximizing the benefits of irrigation with reclaimed water.

Keywords: reclaimed water reuse; life cycle assessment; crop production; environmental impacts

1. Introduction

Irrigation plays a critical role in boosting crop yield, ensuring food security and stabilizing the global food market. Globally, 40% of freshwater resources are consumed by agricultural production [1]. The global demand for irrigation water, now roughly 400 billion cubic meters per year, is expected to reach 665 billion cubic meters by 2030, due to increasing population and dietary shifts [1]. As the demand for fresh water intensifies, reclaimed water from municipal wastewater is frequently being seen as a valuable resource for alleviating water scarcity in semi-arid and arid regions. To appropriately utilize reclaimed water for irrigation, it's necessary to understand the environmental health impacts of crop systems irrigated with reclaimed water.

Numerous studies have reported environmental and human health concerns with utilizing reclaimed water for irrigation [2,3]. These studies investigated the accumulation of heavy metals and nutrients [4,5]; the environmental fate of organics in the wastewater irrigated soils [6,7]; the influence of reuse schemes on catchment hydrology [2]; the risk models for helminth infections [8,9]; microbiological contamination risks for aquifers and surface waters [8,10,11]; the transfer efficiencies of chemical contaminants from soil to plants, and the health effects of chronic exposure to chemical contaminants [12–14]. Despite extensive experimental and modeling efforts, the life cycle assessment (LCA) of crop systems irrigated with reclaimed water is still lacking [15–17].

Agricultural LCA is capable of quantifying the comprehensive environmental impacts of agricultural processes and products through their entire life cycles, and of identifying the potential tradeoffs and the most environmentally preferable system options [18–20]. Numerous studies have assessed the life cycle environmental impacts of crop systems [15–17,21,22]. However, the majority of these studies focused on crop systems using traditional irrigation sources such as rain, ground water and surface water. For example, Kumar et al. analyzed the energy consumption and greenhouse gas emissions of Jatropha-derived biodiesel in India using a life cycle approach [22], revealing that irrigation is one of the most influential factors for energy consumption and greenhouse gas emissions (GHGs). Grant et al. quantified life cycle GHGs of corn-chips and found that pumping irrigation water from deep bores resulted in as much as three times the GHGs as did pumping from surface water [21].

Recently, increasing LCA studies have begun to quantify the environmental impacts of crop systems irrigated by reclaimed water [15–17]. However, to the author's best knowledge, only three existing studies utilized experimental data to analyze the life cycle environmental impacts of agricultural systems irrigated with treated wastewater [15–17]. Munoz et al. investigated the life cycle impacts of tobacco in Spain with three different irrigation sources including groundwater, treated municipal wastewater, and desalinated water [17]. Moretti et al. assessed the life cycle environmental impacts of treated municipal wastewater reuse for irrigating fruit orchards in the Mediterranean coastal region [15]. Miller-Robbie et al. investigated the energy consumption, water use, life cycle GHGs, and crop pathogen quality of spinach in an Indian urban farm with three irrigation sources, including treated wastewater, untreated wastewater, and groundwater [16]. To date, life cycle environmental impacts of corn, soybean and wheat irrigated with reclaimed water in China remain unknown.

Irrigated agriculture in Northern China presents several unique characteristics from food security and water resource management perspectives. First, Northern China ranks as a major producer of Chinese corn, soybean and wheat. Ensuring grain production in Northern China is critical for national economic development and social stability [23]. Second, alternative water supplies are urgently needed to meet irrigation demands and to support long term sustainability of agricultural production in Northern China. Approximately 75% of Chinese grains are harvested from irrigated land [24]. The agricultural sector in Northern China consumes 72.67% of the region's total groundwater extraction, consequently causing the decline of the shallow and deep groundwater tables at a corresponding rate of 0.42 meter/year and 1.2 meter/year, respectively [25]. To reduce groundwater withdrawal, the use of reclaimed water for irrigation has increased. Approximately 7.33% of total irrigated farmland area utilizes reclaimed water [26]. A comparative LCA of crops irrigated with groundwater and reclaimed water in Northern China is required to ascertain the environmental consequences of using reclaimed water for irrigation, and to provide scientific guidance for sustainable utilization of reclaimed water.

To fill in this knowledge gap, this study conducted a comparative LCA of crop systems irrigated with reclaimed and ground water sources in Northern China. In order to reflect the regional condition, a combination of experimental measurements and modeling datasets was used to compile the life cycle inventory of corn, soybean, and wheat. To the best of the author's knowledge, this is the first study which assesses the life cycle environmental impacts of reusing treated wastewater as an irrigation source for corn, soybean and wheat systems in Northern China.

2. Methods

Following the International Organization for Standardization (ISO)'s guidelines [27], this study performed a process-based LCA for comparing the life cycle impacts of crop systems with reclaimed water and ground water as irrigation sources. As defined by the ISO 14040 series, LCA is an iterative four-stage process: (1) goal and scope definition identifies the extent of analysis and the system boundaries, (2) life cycle inventory analysis documents material and energy flows which occur within the system boundaries, (3) life cycle impact assessment characterizes and assesses the environmental effects using the data obtained from the inventory, and (4) life cycle interpretation determines the level of confidence in the life cycle inventory and life cycle impact assessment results, and recommends environmentally preferred solutions or improvement strategies. Each step of the LCA study is described below.

2.1. Goal and Scope

The goal of this study was to compare life cycle environmental impacts of crop systems irrigated with groundwater and reclaimed water. The crop system irrigated by groundwater and reclaimed water in the agricultural experimental station at the Tongliao City of Inner Mongolia Province in China was used as a representative case study. Figure 1 depicts the location of the agricultural experimental station. Based on the latest survey, approximately 600 hectares of farmland in Tongliao City are utilizing reclaimed water for irrigation [28,29]. Tongliao City lies in the semi-arid grassland zone of the north temperate zone and has a continental monsoon climate with a mean annual temperature of five degrees Celsius. Tongliao City experiences an annual water deficit of 350 mm due to evaporation exceeding precipitation. The dominate vegetation species in Tongliao include corn, wheat and soybean. Groundwater is the primary irrigation source, accounting for 85% of the total irrigation water in Tongliao City. With the continuous decline of groundwater reserves, at least two million hectares of farmland in Tongliao City are facing water shortage [28,30]. The local and regional stakeholders are actively considering expanding the reclaimed water program in order to solve this irrigation challenge.

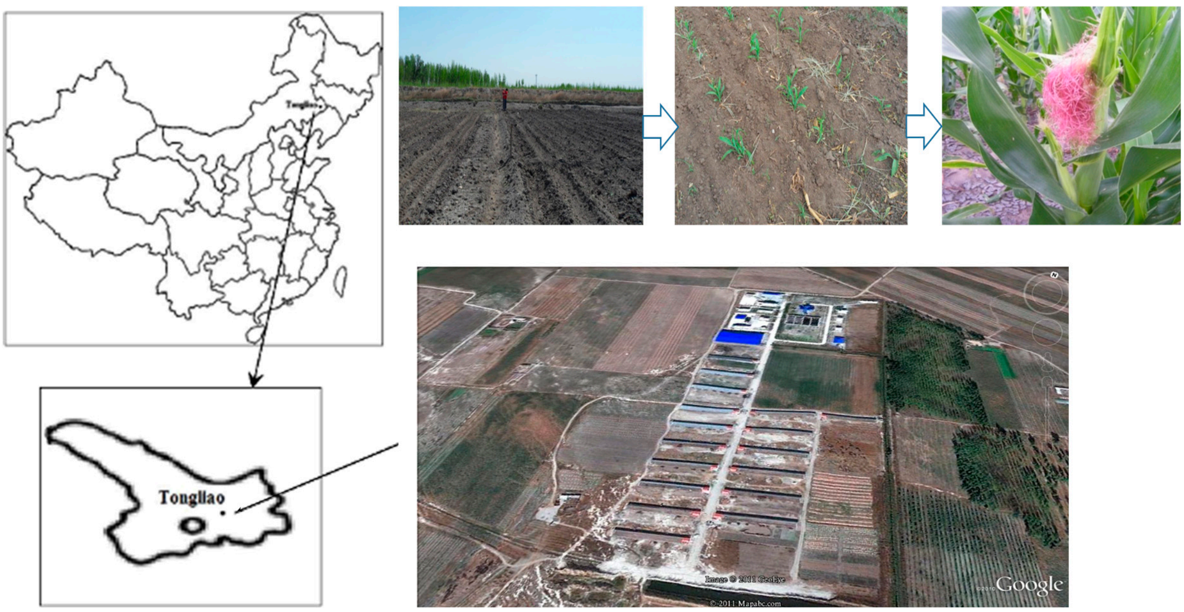


Figure 1. The location of the experimental sites, and the example growth stages of corn.

The agricultural experimentation station in Tongliao grows corn, soybean and wheat, with a total area of 1800 m^2. The soil properties of the experimental station are summarized in Table 1. The numbers reported in Table 1 reflect the average values of six soil samples including three soil samples from the groundwater irrigated plot and three soil samples from groundwater irrigated plot. Two independent irrigation systems corresponding to the groundwater and reclaimed water were installed. While the groundwater for irrigation was obtained from the on-site groundwater well, the reclaimed water was transported via a brick channel from the adjacent wastewater treatment plant and stored in a pond. The wastewater treatment plant employs anaeroic-anoxic-oxic biological processes and chlorine disinfection, prior to the discharge. The water quality of groundwater and reclaimed water is described in Table 2. After discharge, the reclaimed water was pumped from the storage pond to a mixing well, where the nitrogen, phosphorus and potassium fertilizers were added and mixed with the reclaimed water. Similarly, the groundwater was pumped from the groundwater well to another mixing well, where the fertilizers were added. After mixing with fertilizers, the irrigation water was pumped to the corresponding experimental plots via plastic pipes. The total nutrient application rates were the same for the reclaimed wastewater and groundwater irrigated plots. The synthetic fertilizer was the only exogenous nutrient source for ground water irrigated plots. The nutrients for the reclaimed water plots originated from both synthetic fertilizer and reclaimed wastewater.

Table 1. Physical and chemical properties of experimental soil.

Soil Layers cm	Soil Texture, %			pH	Total Nitrogen, g/kg	Total Phosphorus, mg/kg	Total Sulfur, mg/kg	Total Potassium, mg/kg
	Sand	Silt	Clay					
0–23	64	32	4	8.3	81	63.8	113	17.4
23–46	56	20	24	7.7	495	461.5	31	27.7
46–75	72	12	16	9.1	540	420	326	30
75–100	80	8	12	8.9	238	600	138	23.8
100–140	88	8	4	9.1	111	340	54	25.1

Table 2. Water quality of irrigation sources.

Water Quality Indicator	Ground Water	Reclaimed Water
pH	7.2	7.4
Chlorides (mg/L)	104.309	90.528
Volatile phenol (mg/L)	0.002	0.002
Total Nitrogen (mg/L)	1.037	30
Total Phosphorus (mg/L)	0.074	7.243
Dissolved oxygen (mg/L)	2.14	3.57
Dissolved solid (mg/L)	305	420
Suspended solid (mg/L)	8	10
COD_{Mn} (mg/L)	1.07	2.82
Total Hg (mg/L)	0.00001	0.00001
Total As (mg/L)	0.0012	0.0026
Total Cu (mg/L)	0.001	0.005
Total Zn (mg/L)	0.05	0.05
Total Cr (mg/L)	0.03	0.03
Total Pb (mg/L)	0.01	0.03
Total Cd (mg/L)	0.001	0.002

The scope of this cradle-to-farm LCA considered both on-field and supply chain activities for growing corn, soybean and wheat. Shown in Figure 2, the on-field activities were comprised of farming equipment operation for planting seeds, tillage, applying agrochemicals, harvesting; irrigation with groundwater or treated wastewater; and agrochemical transportation. Moreover, supply-chain activities consisted of agrochemical production and their upstream material, energy and infrastructure needs. The atmospheric, aqueous, and soil emissions of both on-field and supply-chain activities were calculated. The wastewater treatment plant was not included in the system boundary, because 1) this study primarily focused on crop systems, and 2) the wastewater treatment plant was operated, no matter if its discharge was used for irrigation [17].

The functional unit aims to provide a reference level for comparison. We used 1 kg of grain as the functional unit to compare environmental impacts of crop systems in this study. Mass-based functional units have also been used in previous agriculture LCA studies [31]. All energy consumption, material use, and associated emissions were allocated 100% to the grains, since the grains are the only final product.

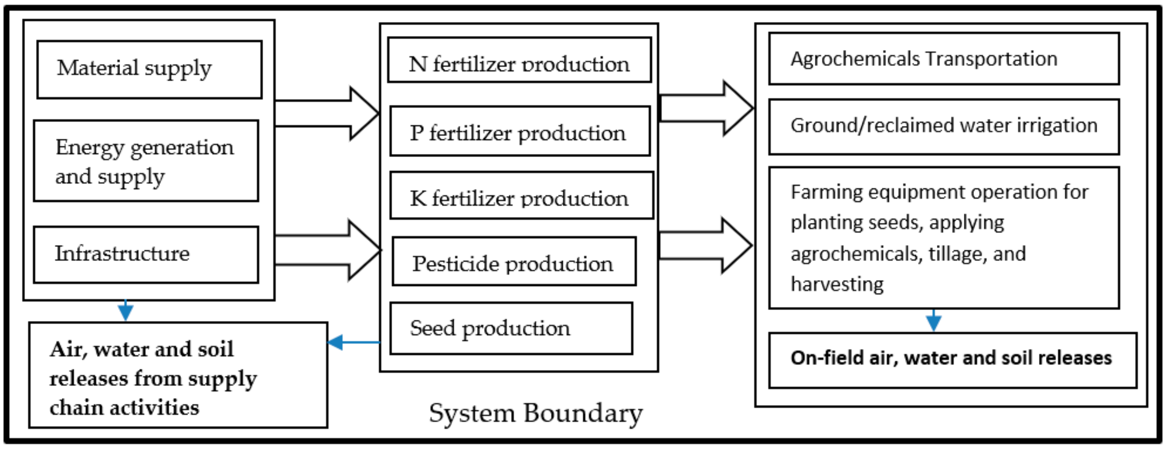


Figure 2. System boundary for life cycle assessments of crop production systems. The system boundary includes environmental releases from both on-field and supply chain activities.

The combination of experimental measurements and modeling approaches was used to compile the on-field environmental emission inventory. The agrochemical application rates and irrigation volumes for corn, soybean and wheat reflected the actual field experimentation values. Table 3 reports nutrient application rates and irrigation volumes for corn, soybean and wheat systems. The electricity consumption of pumping groundwater and reclaimed water was recorded at the experimental station. The electricity consumption for pumping ground water and reclaimed water was approximately 0.015 kwh/m^3 and 0.004 kwh/m^3, respectively. The heavy metal releases to the soil compartment were measured in the lab. The testing procedures and results of heavy metal releases were reported in existing publications [28–30]. The GHGs from soil were determined using the emission factor approach developed by the Intergovernmental Panel on Climate Change (IPCC) [32]. The agrochemicals were transported via a truck for approximately 30 km. The GHGs and criteria pollutants for transporting agrochemicals from the regional retail store to the experimental site was calculated by greenhouse gases, regulated emissions and energy use in transportation (GREET) model [33]. The GREET model was developed by the US Department of Energy, and widely used for estimating air pollutants of energy and transportation processes. The GREET.net tool (2016 version) was used in this study. The on-field nutrient emissions, including NO_3^- and PO_4^{3-} to the water compartment, were estimated by the previously developed emission factor model, which was tailored for calculating on-field aqueous nutrient emissions from corn, soybean and wheat [34]. The pesticide releases were calculated based on PestLCI model [35]. PestLCI model is a modular model capable of estimating the pesticide releases to air, surface water and groundwater compartments, based on pesticides' physiochemical properties, weather, soil and crop information. The physiochemical properties of paraquat, rotenone, and chlorpyrifos were obtained from the hazardous substance data bank [36]. The weather information was obtained from the China Meteorological Data Service Center [37]. The soil information is provided in Table 1. In addition, approximately 28 liters of diesel/hectare was used by a tractor for tillage, agrochemical application and harvesting activities. The air pollutants associated with tractor usage were estimated by utilizing the NONROAD model, which was developed by the US Environmental Protection Agency to estimate GHGs and criteria air pollutants from agricultural equipment usage [38].

Table 3. The nitrogen, phosphorus and potassium fertilizer application rates for corn, soybean and wheat production.

Fertilizer Application Rate	Corn	Soybean	Wheat
Nitrogen application rate (kg/hectare)	156	32	168
Phosphorus application rate (kg/hectare)	67	52	57
Potassium application rate (kg/hectare)	89	89	129
Irrigation Volume (m^3/hectare)	8896	15,320	6177

To compile life cycle inventory from supply-chain activities, the ecoinvent v3.0 database was used [39,40]. For example, agrochemical production processes in ecoinvent v3.0 were used. It is worth noting that we have modified the electricity mix embedded in fertilizers and pesticides manufacturing processes in the ecoinvent database to represent the local condition. According to a recent report, authored by the Energy Information Administration [41], the average China electricity mix consists of 71% of coal, 19% of petroleum, 6% of hydropower, 3% of natural gas and 1% of others. Table 4 summarized the data sources for the life cycle inventory.

Table 4. Data sources for the life cycle inventory.

Parameters or Process	Data Sources	References
Corn, soybean, and wheat yields	Field experimentation data	[28,30,42]
Nitrogen, Phosphorous and Potassium fertilizer application amounts	Field experimentation data	[28,30,42]
Pesticide and herbicide application amounts	Field experimentation data	[28,30,42]
Electricity usage for pumping water	Field experimentation data	[28,30,42]
Fuel use for operating farming equipment	Field experimentation data	[28,30,42]
On-field GHGs from soil	Calculated based on IPCC emission factor	[32]
On-field NO_3^- and PO_4^{3-} to water compartment	Calculated based on an emission factor based nutrient release model	[34]
On-field heavy metal to soil compartment	Lab experimentation data	[28,30,42]
On-field GHGs and criteria air pollutants generated from farming equipment operation	Calculated based on GREET model	[33]
On-field GHGs and criteria air pollutants generated from farming equipment operation	Calculated based on NONROAD model	[38]
On-field pesticides to air and water compartments	Calculated based on PestLCI model	[35]
Agrochemical production	Ecoinvent v3.0 database modified with Chinese electricity mix	[40,41]

2.2. Life Cycle Impact Analysis

While a life cycle impact the analysis tool tailored specifically for China does not exist, this study followed Hauschild and colleagues' recommendations on the best available characterization models to compute the life cycle impacts of the studied crop systems [43]. The mid-point characterization factors, primarily obtained from IPCC [32], USEtox [44], and ReCiPe models [45], were used in this study (Table 5). The global warming characterization factors corresponding to the heating effect of GHGs for the time frame of 100 years, supplied by IPCC, were utilized to quantify the life cycle global warming potentials of crop systems. The USEtox v2.0 model provided the characterization factors for ecotoxicity, human health cancer and human health noncancer impact categories. The characterization factors of ReCiPe model were used to calculate acidification, eutrophication and photochemical formation potential. The characterization factors for ozone depletion were derived from the assessment conducted by the World Meteorological Organization. The ozone depletion characterization factors were also consistent with the characterization factors suggested by the US Environmental Protection Agency [46]. The particulate matter and associated respiratory health impacts were identified based on characterization factors computed by Humbert and colleagues [47]. Table 4 summarizes the tools for calculating the life cycle impacts and their resulting units. The comparative life cycle impact results are presented in Sections 3.1–3.3.

Table 5. Life cycle impact assessment models used in this study.

Impact Category	Methodology	Unit	References
Acidification	ReCiPe	kg SO_2-eq/kg	[45]
Ecotoxicity	USEtox 2.0	comparative toxic units (CTU)	[44]
Eutrophication	ReCiPe	kg N-eq/kg	[45]
Global warming	IPCC	kg CO_2-eq/kg	[32]
Human health criteria	Humber et al., 2011	kg $PM_{2.5}$-eq/kg	[47]
Human health toxicity–cancer	USEtox 2.0	CTU	[44]
Human health toxicity–non-cancer	USEtox 2.0	CTU	[44]
Ozone depletion	WMO method	kg CFC11-eq	[46]
Photochemical formation	ReCiPe	kg O_3-eq/kg	[45]

2.3. Life Cycle Impact Interpretation

Sensitivity analyses were performed to determine the influences of key input parameters on the LCA results, by utilizing the "one at a time perturbation" technique [48]. This approach determines the responses of model outputs by sequentially varying single model input, while keeping the rest of inputs fixed. The assessed inputs include nitrogen concentrations of reclaimed water, volumes of irrigation water, and nitrogen fertilizer application rates for corn, soybean and wheat, respectively. The sensitivity results are summarized in Section 3.4. A comparison between this study and other LCAs using experimental data is presented in Section 4.1. The representativeness of life cycle inventory and life cycle impact assessment in this study for Northern China's crop systems is discussed in Section 4.2. In addition, policy implications for using reclaimed water as an irrigation source in Northern China is discussed in Section 4.3.

3. Results

3.1. Magnitudes of Corn, Soybean and Wheat's Life Cycle Impacts

The life cycle impacts of corn, soybean and wheat irrigated with groundwater and reclaimed water are summarized in Table 6. The life cycle global warming impacts of crop production ranged from 0.37 to 0.64 kg CO_2-eq/kg grain, with reclaimed water irrigated soybean and ground water irrigated wheat exhibiting the lowest and highest global warming potentials, correspondingly. Compared with the existing LCAs on rain and groundwater fed corn, the life cycle global warming impact of corn estimated by this study was 10% higher than the average of reported values, mainly due to the inclusion of energy intensive irrigation processes and relatively lower yield rates [33,49–51]. The life cycle eutrophication potential was estimated to fall in the range of 0.0084 to 0.013 kg N-eq/kg grain in this study. Previous studies showed that the life cycle eutrophication impact of rain-fed corn spanned from 0.01 to 0.2 kg N-eq/kg corn [19,20]. Our estimates of life cycle eutrophication impacts of corn resided in the lower end of the reported range, primarily because of lower fertilizer application rates.

Table 6. Life cycle impacts of corn, soybean and wheat systems irrigated by groundwater and reclaimed water.

Impact Category	Unit	Corn		Soybean		Wheat	
		GW	RW	GW	RW	GW	RW
Global warming	kg CO_2-eq/kg	0.44	0.37	0.39	0.37	0.64	0.56
Acidification	kg SO_2-eq/kg	0.0035	0.0029	0.0029	0.0028	0.0068	0.0066
Cancer	CTU/kg	7.3×10^{-9}	7.6×10^{-9}	5.3×10^{-9}	5.4×10^{-9}	1.7×10^{-9}	1.8×10^{-9}
Non-cancer	CTU/kg	2.3×10^{-8}	2.3×10^{-8}	1.7×10^{-8}	1.6×10^{-8}	1.2×10^{-7}	1.1×10^{-7}
Respiratory effects	Kg $PM_{2.5}$-eq/kg	2.1×10^{-4}	1.9×10^{-4}	1.7×10^{-4}	1.6×10^{-4}	4.5×10^{-4}	3.7×10^{-4}
Eutrophication	kg N-eq/kg	0.0084	0.0083	0.013	0.012	0.013	0.013
Ozone depletion	kg CFC11-eq/kg	4.3×10^{-8}	4.4×10^{-8}	1.7×10^{-8}	1.8×10^{-8}	5.2×10^{-8}	5.2×10^{-8}
Ecotoxicity	CTU/kg	3.3	2.8	0.88	0.85	4.33	4.26
Photochemcial formation	kg O_3-eq/kg	0.026	0.025	0.022	0.021	0.053	0.051

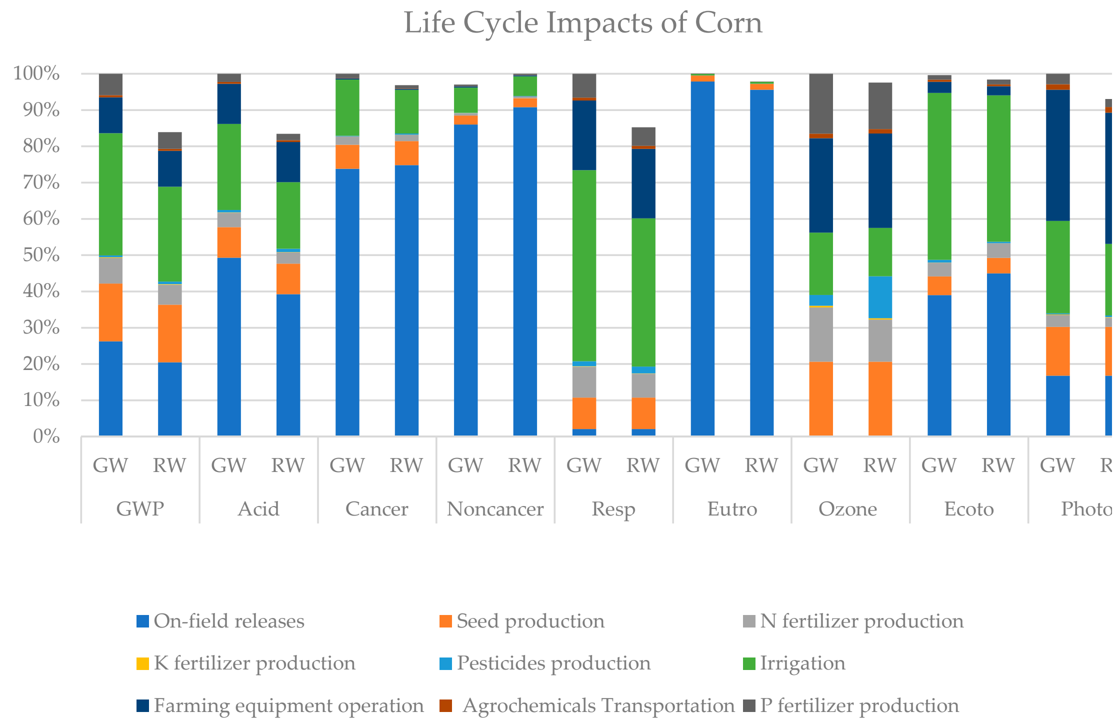
Note: The abbreviations of GW and RW represent the irrigated crops with groundwater and reclaimed water, respectively.

The comparison among the crop types suggested that the life cycle impacts of corn and wheat were higher than the life cycle impacts of soybean. Among the three crops, wheat presented the highest life cycle global warming, acidification, respiratory effects, eutrophication, ozone depletion, ecotoxicity and photochemical oxidation impacts. The combination of relatively high agrochemical and modest yield led to the highest environmental impacts of wheat, in the unit of per kg grain. In contrast, corn resulted in higher life cycle cancer and noncancer impacts than soybean and wheat, which is mainly caused by corn's relatively higher inputs of pesticides than soybean and wheat.

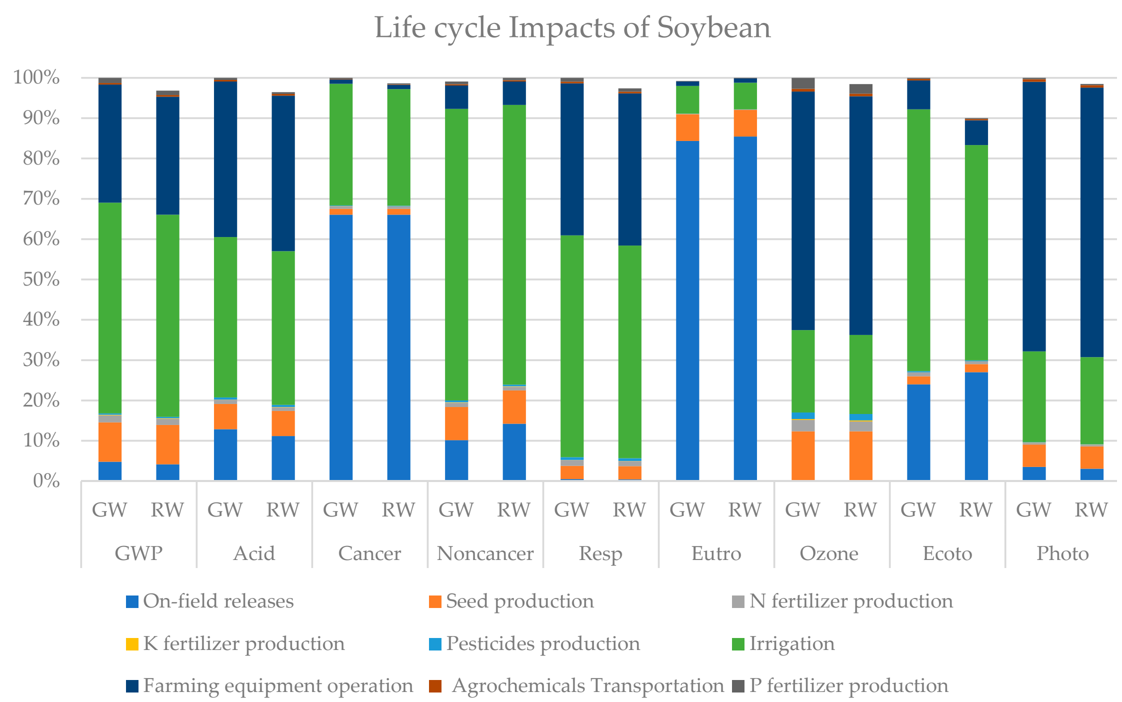
3.2. Stage Contributions of Corn, Soybean and Wheat's Life Cycle Impacts

As seen in Figure 3, the contributions of life cycle stages varied across impact categories and crop types. For corn, the irrigation stage ranked as the top contributor to the life cycle global warming (approximately 30%) and respiratory health (approximately 40%) impacts, primarily due to the electricity-intensive water pumping and transport. On-field emissions dominated the life cycle eutrophication, cancer and noncancer impacts. For example, on-field nitrogen and phosphorus emissions resulted in approximately 90% of total life cycle eutrophication impact. On-field pesticides and heavy metal emissions resulted in over 70% of life cycle cancer and noncancer impacts, due to their high characterization factors. In addition, due to particulate matter, NO_x, and SO_x emissions from diesel combustion, farming equipment operation played a key role in life cycle ozone depletion and photochemical formation impacts for corn.

Similarly, irrigation, farming equipment operation, and on-field emissions were major contributors to the life cycle impacts of soybean systems. The combination of their shares exceeded 75% of life cycle global warming, acidification, cancer, noncancer, respiratory, eutrophication, ozone depletion, ecotoxicity and photochemical formation impacts. In particular, irrigation resulted in over half of life cycle global warming, noncancer, respiration and ecotoxicity impacts, due to its energy-intensive feature. On-field emissions led to approximately 85% of life cycle eutrophication impact for soybean farming. Furthermore, farming equipment operation generated GHGs and criteria air pollutants, consequently causing significant contributions to life cycle global warming, acidification, respiratory health, and photochemical formation impacts. In addition, seed production and fertilizer manufacturing were responsible for less than 15% of life cycle impacts of soybean systems.

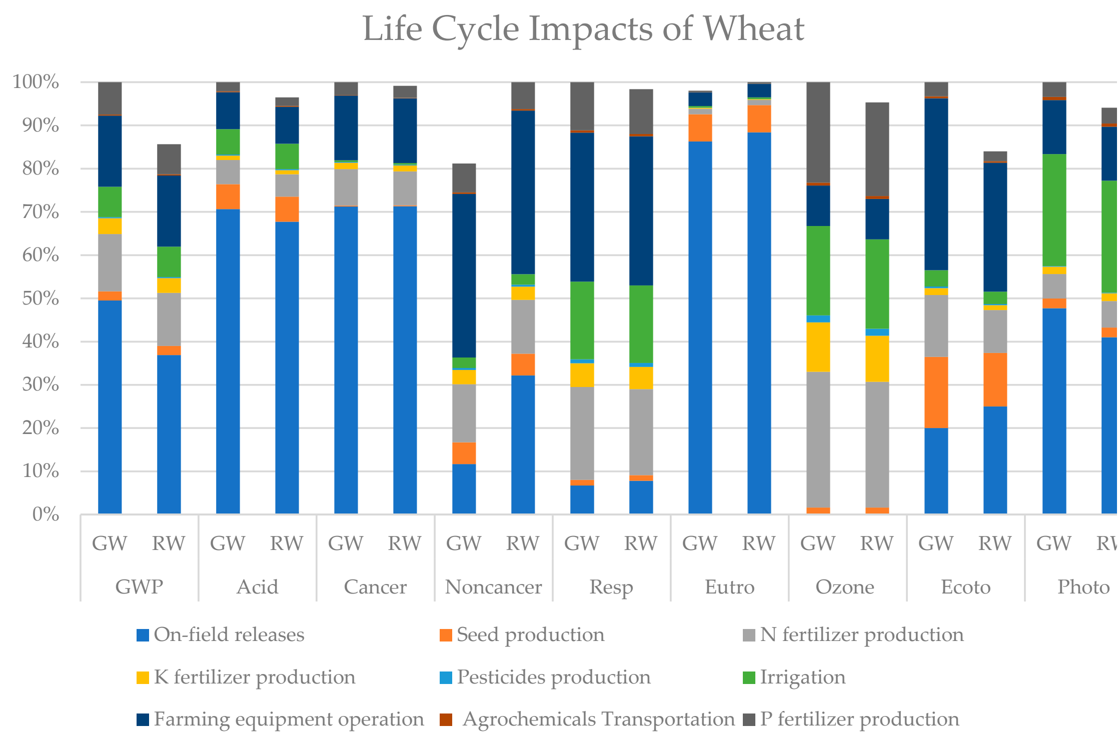


(**a**) Life cycle impacts of corn



(**b**) Life cycle impacts of soybean

Figure 3. *Cont.*



(**c**) Life cycle impacts of wheat

Figure 3. The life cycle environmental impacts of corn, soybean, and wheat irrigated with groundwater and reclaimed water. The abbreviations of GW and RW represent the irrigated crops with groundwater and reclaimed water, respectively. The impact results are exhibited in the following categories including global warming (GWP), acidification (Acid), carcinogenic (Cancer), non-carcinogenic (Noncancer), respiratory (Resp), eutrophication (Eutro), ozone depletion (Ozone), ecotoxicity (Ecoto), and photochemical formation (Photo) impacts. The life cycle impact values were normalized to the largest impact value of its corresponding impact category. For example, life cycle GWPs of corn were normalized to the life cycle GWP of GW-irrigated corn.

For life cycle global warming impact of wheat, the primary contributors included on-field emissions, fertilizer production and farming equipment operation. While on-field N_2O, CH_4, and CO_2 emissions directly resulted in a global warming impact, supply chain activities such as fertilizer production and farming equipment operation required energy and emitted these GHGs as well. Moreover, on-field emissions also caused life cycle acidification, cancer, and eutrophication impacts, due to a wide spectrum of environmental releases such as NH_3 (corresponding to acidification), pesticides and heavy metals (both corresponding to cancer), and nitrate and phosphate (both corresponding to eutrophication). Additionally, farm equipment operation, irrigation and fertilizer production ranked as the largest contributors to the respiratory health and ozone depletion impacts, due to criteria air pollutants from both on-field and supply chain activities.

3.3. Comparing Life Cycle Impacts of Groundwater and Reclaimed Water as Irrigation Sources

As shown in Figure 3, replacing groundwater with the reclaimed water as the irrigation source reduced life cycle global warming, acidification, cancer, respiratory, ozone depletion, ecotoxicity and smog formation impacts of corn, soybean and wheat systems. The reduction of these environmental impacts was mainly due to the two factors. First, utilizing reclaimed water reduced the requirements of synthetic nitrogen and phosphorus fertilizer, and avoided energy and environmental releases associated with producing and delivering synthetic fertilizers. Second, reclaimed water utilization eliminated the electricity consumption, which would otherwise be required for extracting and pumping groundwater. Moreover, no significant difference of nutrient releases were observed between ground water and reclaimed water irrigation scenarios, since the same nutrient application rates were used for both irrigation scenarios. In addition, replacing groundwater with reclaimed water resulted in increases of life cycle noncancer impacts for three crops. For corn and soybean, the life cycle noncancer impacts of reclaimed water irrigation were 2% higher than of groundwater irrigation. For wheat, the reclaimed water scenario presented an approximately 20% higher life cycle noncancer impact than did the ground water scenario. Although using reclaimed water reduced the life cycle energy consumption and mitigated the life cycle noncancer impacts associated with energy production and consumption, the elevation of heavy metals in reclaimed water resulted in higher noncancer impacts for crops irrigated with reclaimed water. Due to the combinational effects of decrease in energy usage and increase in heavy metal concentration, the reclaimed water scenario showed higher life cycle noncancer impacts than ground water scenario.

3.4. Sensitivity of Life Cycle Global Warming and Eutrophication Impacts

The top influential factors for life cycle global warming impacts of crop systems were nitrogen fertilizer application rate and irrigation volume (Figure 4). Nitrogen fertilizer application rate ranked as the most influential factor for life cycle global warming impacts of corn and wheat. Varying synthetic nitrogen application by 5% resulted in a change of life cycle global warming impact of corn by approximately 15%. Similarly, varying synthetic nitrogen application by 5% led to a change of life cycle global warming impact of wheat by approximately 17%. Following nitrogen fertilizer application rate, irrigation volume was the second most influential factor for life cycle global warming impacts of corn and wheat. An increase of irrigated volume by 5% caused the increases of life cycle global warming impacts of corn and wheat by 12% and 13%, respectively. Irrigation volume was the most influential factor for life cycle global warming potential of soybean. When irrigation volume varied by 5%, the life cycle global warming potential of soybean changed by 28%. Consistently, the life cycle global warming impacts of corn, wheat and soybean irrigated with reclaimed water were least sensitive to the nitrogen content of reclaimed water. Varying nitrogen content of reclaimed water by 5% led to changes of life cycle global warming impacts by less than 9%.

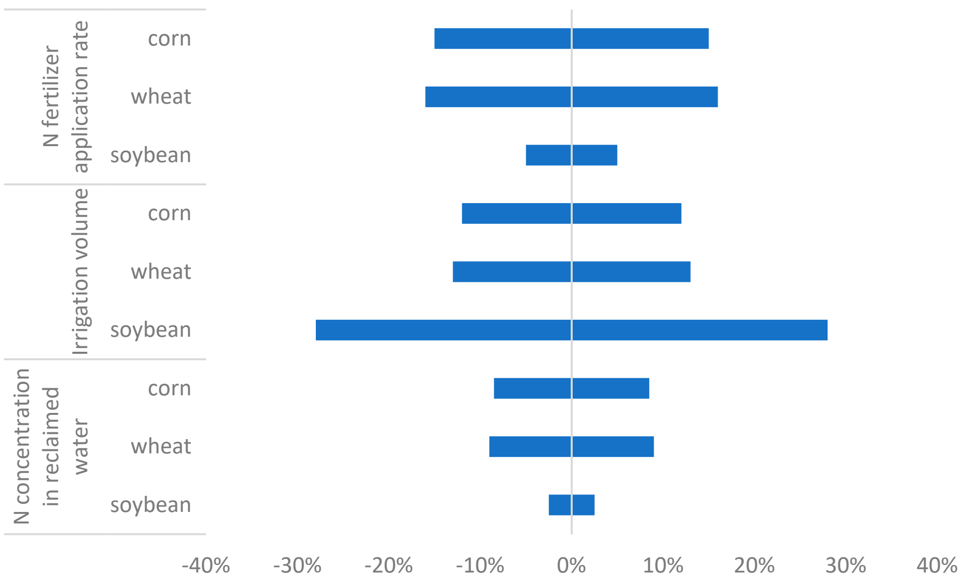


Figure 4. The sensitivity analysis of input parameters for global warming impacts of crops. The input parameters including nitrogen (N) fertilizer application rate, irrigation volume and nitrogen concentration of the reclaimed water varied by +/−5%.

Life cycle eutrophication impacts were most sensitive to the change in application rates of synthetic nitrogen fertilizer (Figure 5). Varying synthetic fertilizer application rates by 5% resulted in changes of life cycle eutrophication impacts by 22%, 20% and 5% for corn, soybean and wheat, respectively. The synthetic fertilizer usage affected life cycle eutrophication impact by changing nutrient releases during both supply chain and on-farm releases. In addition, the influences of synthetic fertilizer application rate on life cycle eutrophication impacts of corn were larger in magnitude than life cycle eutrophication impacts of soybean and wheat. This magnitude difference was due to the disparity in nitrate emission factors of crops. The nitrate emission factor (a ratio between nitrogen release and nitrogen application rate) of corn was higher than the nitrate emission factors of soybean and wheat [34,52]. Therefore, life cycle eutrophication impact of corn was more sensitive to nitrogen application rate than the life cycle eutrophication impact of soybean and wheat.

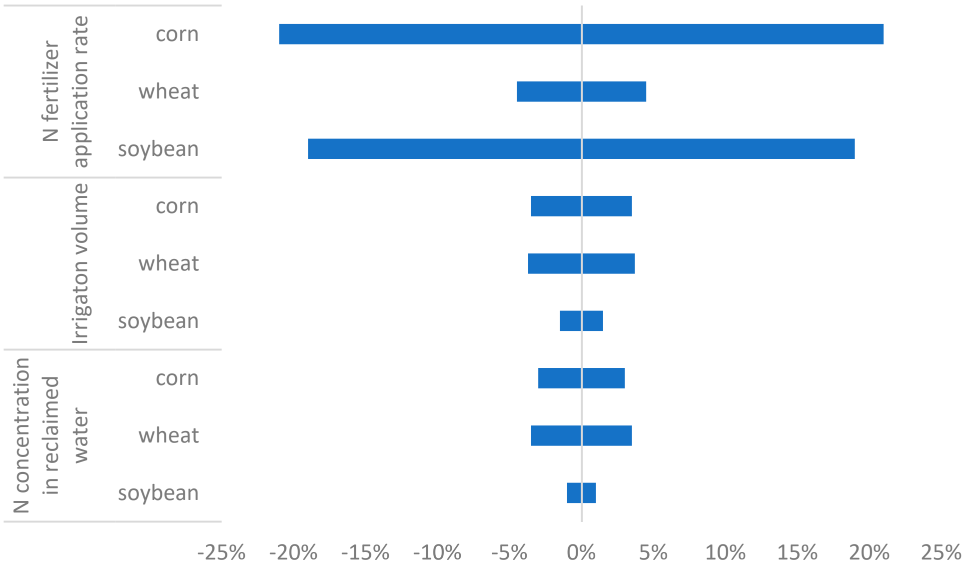


Figure 5. The sensitivity analysis of input parameters for eutrophication impacts of crops. The input parameters including nitrogen (N) fertilizer application rate, irrigation volume and nitrogen content in wastewater varied by +/−5%.

4. Discussion

4.1. Comparison with the Existing Agricultural LCA Studies Using Experimental Datasets

The syntheses of three existing studies and this study indicated that the irrigated crop systems resulted in diverse environmental impacts ranging from energy consumption and global warming to water and soil quality impacts [15–17]. The top contributors varied across different environmental impact categories, which suggested that different strategies should be adopted for effectively remediating the corresponding environmental impacts. For example, energy use of irrigation played an important role in life cycle global warming impacts of corn and soybean. Accordingly, reducing energy use of irrigation should be prioritized for reducing life cycle global warming impact of corn and soybean. In contrast, on-farm nutrient releases ranked as a dominating contributor to the life cycle eutrophication impact of crops. Strategies such as utilization of low-impact fertilizers and buffer strips should be recommended for mitigating life cycle eutrophication impacts of crops. Moreover, environmental tradeoffs existed among irrigation sources. Using reclaimed water to replace traditional irrigation sources decreased life cycle energy use and global warming impacts, while increasing soil salinization, terrestrial ecotoxicity and noncancer human health impacts. This tradeoff highlights the need for mitigating soil salinization, terrestrial ecotoxicity and noncancer human health impacts, when treated wastewater is reused for irrigation.

Significant differences existed among these studies in the scopes of system boundary, methods for calculating life cycle inventory, and assessed environmental impact categories. The system boundary differed in the inclusion of wastewater treatment processes, on-field emissions, crop types and geographical context. Munoz et al. [17] and this study excluded wastewater treatment processes from the system boundary, since municipal wastewater is treated to meet the discharge standard regardless of reuse as an irrigation source. In contrast, Moretti et al. [15] and Miller-Robbie et al. [16] included wastewater treatment processes in the system boundary. Also, the assessed crop types and geographical contexts varied significantly. Munoz et al. [17] focused on tobacco in Spain. Moretti et al. studied fruit orchards in Southern Italy. Miller-Robbie et al. [16] assessed spinach in India. In contrast, this study is the only study focusing on corn, soybean and wheat in Northern China. Moreover, distinct models were utilized for compiling life cycle inventory. Munoz et al. [17] utilized a mass balance approach to estimate aqueous nitrogen releases. Moretti et al. [15] employed the SALCA-Phosphorus model to calculate aqueous phosphorus releases. This study applied an emission factor approach to calculate both nitrogen and phosphorus releases to the water compartment. Different approaches were used for calculating GHGs as well. Miller-Robbie et al. [16] utilized the DAYCENT model for GHGs from soil processes. Instead, this study utilized IPCC equations for soil emissions. Moretti et al. [15] didn't include GHGs from soil processes. Among the existing studies, this is the only study including heavy metal releases in life cycle inventory. In addition, the choices of life cycle impact categories were inconsistent [15,17]. Munoz et al. [17] included global warming, acidification, eutrophication, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, primary energy use, soil organic carbon change and salinization. Moretti et al. [15] focused on climate change, human toxicity, acidification, freshwater and marine eutrophication, freshwater ecotoxicity, and water scarcity. This study utilized global warming, acidification, human noncancer, human cancer, respiratory, eutrophication, ozone depletion, ecotoxicity and photochemical formation. These fundamental differences suggested a future need for developing standardized guidance on life cycle inventory and impact assessment for wastewater reuse for agricultural irrigation.

4.2. Models and Datasets for Representing Northern China's Crop Systems

This study contributed to establishing the life cycle inventory of Chinese agricultural production. The life cycle environmental releases of agricultural systems are often region-specific. Developing regional life cycle inventory is necessary for accurately accounting for regional environmental releases and designing appropriate mitigation strategies. Despite significant improvement and expansion of life cycle inventory, the life cycle inventory of reclaimed water irrigated agriculture in China is lacking [53]. To acquire the region-specific inventory data to reflect farming activities and related environmental releases in China, both experimental and modeling datasets were compiled to represent life cycle inventory from crop systems in Northern China in this study. Additionally, for estimating upstream emissions and releases for energy production, ecoinvent database, modified with the Chinese electricity mix, was used to represent the regional condition. This study mainly regionalized on-field emissions and supply chain releases from electricity production. We recommend future studies to incorporate additional regional inventory such as environmental releases of agrochemical production in Northern China, when these datasets become available.

This study provided a comparative assessment on life cycle environmental impacts of crops with two different irrigation sources in Northern China. This study was built upon the recommended and publicly available life cycle impact assessment tools [43]. Midpoint characterization factors, rather than endpoint factors, were chosen, because endpoint characterization factors were more uncertain and require further development. The choice of impact tools does not influence the results of global warming impacts, because other mid-point impact assessment tools have consistent characterization factors for global warming impacts [43,45]. Switching to other mid-point life cycle impact assessment tools may change the absolute values of acidification, smog formation, eutrophication, human cancer, human non-cancer and human criteria impacts. However, the relative ranking of ground water and reclaimed water across these impact categories will not change. This study serves the purpose of comparing the life cycle environmental impacts of reclaimed and ground water for irrigation, rather than quantifying absolute environmental health risks associated with irrigation.

4.3. Policy Implications for Using Reclaimed Water as an Irrigation Source

Both opportunities and barriers exist for using reclaimed water for irrigation in China. Rapid establishment and development of wastewater infrastructure in China will produce reliable wastewater discharge, which could be potentially used to augment water supply for irrigation. A recent study has estimated that reclaimed water from wastewater treatment plants would potentially increase the national water supply by up to 56% in China, based on assumptions that 80% of urban municipal water is collected and treated by wastewater infrastructure after use and 70% of treated wastewater is reclaimed for reuse [26]. This estimate likely lies at the conservative end, given that the 13th Five-year National Urban Sewage Treatment and Recycling Facilities Construction Plan mandated that 90% of wastewater would be treated by municipalities by year 2020 [54]. Meanwhile, a range of state and national policies were implemented to promote the use of reclaimed water for irrigation. For example, the Ministry of Construction and Standardization Administration has issued a series of regulations and standards for supporting the development of wastewater reclamation and reuse [26]. However, these policies didn't take into account the LCA findings and, thus, may result in environmental problem shifting.

This LCA study provides novel perspectives on coordinating policies within the realm of the water–food–health nexus, particularly for avoiding environmental problem shifting and maximizing benefits of wastewater irrigation. First, environmental tradeoffs exist between groundwater and reclaimed water as irrigation sources. Replacing groundwater with the reclaimed water as the irrigation source reduced global warming, acidification, cancer, respiratory, ozone depletion, ecotoxicity and smog formation, while increasing life cycle noncancer impacts of crops. In addition to promoting wastewater reuse, future policies should consider targeting the reduction of life cycle noncancer impacts caused by wastewater irrigation. For example, more stringent water quality standards, regarding the heavy metal content of irrigation water, are recommended for mitigating the human health noncancer impact of crops irrigated with reclaimed water. Moreover, policy incentives on reducing both supply chain and on-field impacts are needed. The current irrigation policies primarily focus on meeting water quantity and quality requirements for the agricultural sector. The LCA study demonstrated that the upstream GHGs of electricity supply for irrigation are significant contributors to life cycle global warming impact of crops. Policy incentives on utilizing cleaner electricity sources for pumping irrigation water can promote the reduction of life cycle global warming impact of irrigated crops. Additionally, due to intricate connections among the water–food–health sectors, cross-sector policies are needed to maximize the benefits of wastewater reuse. Particularly, integrated water resource management and multi-sector planning are needed for successfully implementing reclaimed water for agricultural irrigation in the future.

5. Conclusions

This study presented the first comparative LCA study of crop systems irrigated with groundwater and reclaimed water in Northern China. The stage contribution analyses indicated that top contributing stages varied for different crops. While irrigation, farming equipment operation, and on-field emissions ranked as the top three contributors to the life cycle impacts of corn and soybean, the on-field emissions, fertilizer production and farming equipment operation ranked as the leading contributors to the life cycle impacts of wheat. Moreover, environmental tradeoffs existed between groundwater and reclaimed water as irrigation sources. Utilizing reclaimed water as an alternative irrigation source would reduce the majority of the environmental impacts of crop production (such as life cycle global warming, acidification, cancer, respiratory, ozone depletion, ecotoxicity and smog formation impact). However, care should be taken to mitigate the noncancer health impacts. In addition, this study supports policy coordination within the realm of the water–food–health nexus, in order to avoid health and environmental problem shifting and to maximize the benefits of wastewater irrigation.

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References

1. Eshel, G.; Martin, P.A. Diet, energy, and global warming. *Earth Interact.* **2006**, *10*, 1–17. [CrossRef]
2. Hamilton, A.J.; Stagnitii, F.; Xiong, X.; Kreidl, S.L.; Benke, K.K.; Maher, P. Wastewater Irrigation: The State of Play. *Vadose Zone J.* **2007**, *6*, 823–840. [CrossRef]
3. Pereira, L.S.; Oweis, T.; Zairi, A. Irrigation Management under Water Scarcity. *Agric. Water Manag.* **2002**, *57*, 175–206. [CrossRef]
4. Liu, Y.Y.; Haynes, R.J. Longterm irrigation with dairy factory wastewater influences soil quality. *World Acad. Sci. Eng. Technol.* **2010**, *4*, 524.
5. Chen, S.F.; Wu, W.L.; Hu, K.L.; Li, W. The effects of land use change and irrigation water resource on nitrate contamination in shallow groundwater at county scale. *Ecol. Complex.* **2010**, *7*, 131–138. [CrossRef]
6. Diacono, M.; Montemurro, F. Long-term effects of organic amendments on soil fertility. A review. *Agron. Sustain. Dev.* **2009**, *30*, 401–422. [CrossRef]
7. Mañas, P.; Castro, E.; de las Heras, J. Irrigation with treated wastewater: Effects on soil, lettuce (*Lactuca sativa* L.) crop and dynamics of microorganisms. *J. Environ. Sci. Health Part A Toxic Hazard. Subst. Environ. Eng.* **2009**, *44*, 1261–1273. [CrossRef]
8. Cifuentes, E. The epidemoiology of enteric infections in agricultural communities exposed to wastewater irrigation: Perspectivies for risk control. *Int. J. Environ. Health Res.* **1998**, *8*, 203–213. [CrossRef]
9. Gross, A.; Azulai, N.; Oron, G.; Ronen, Z.; Arnold, M.; Nejidat, A. Environmental impact and health risks associated with greywater irrigation: A case study. *Water Sci. Technol.* **2005**, *52*, 161–169. [CrossRef]
10. Rattan, R.K.; Datta, S.P.; Chhonkar, P.K.; Suribabu, K.; Singh, A.K. Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater—A case study. *Agric. Ecosyst. Environ.* **2005**, *109*, 310–322. [CrossRef]
11. Steele, M.; Odumeru, J. Irrigation water as source of foodborne pathogens on fruit and vegetables. *J. Food Prot.* **2004**, *67*, 2839–2849. [CrossRef]
12. Asano, T.; Cotruvo, J.A. Groundwater recharge with reclaimed municipal wastewater: Health and regulatory considerations. *Water Res.* **2004**, *38*, 1941–1951. [CrossRef]
13. Hutchins, S.R.; Tomson, M.B.; Bedient, P.S.; Ward, C.H.; Wilson, J.T. Fate of trace organics during land application of municipal wastewater. *Crit. Rev. Environ. Control* **2009**, *15*, 355–416. [CrossRef]
14. Rusan, M.J.M.; Hinnawi, S.; Rousan, L. Long term effect of wastewater irrigation of forage crops on soil and plant quality parameters. *Desalination* **2007**, *215*, 143–152. [CrossRef]
15. Moretti, M.; van Passel, S.; Camposeo, S.; Pedrerod, F.; Dogot, T.; Lebailly, P.; Vivaldi, G.A. Modelling environmental impacts of treated municipalwastewater reuse for tree crops irrigation in the Mediterranean coastal region. *Sci. Total Environ.* **2016**, *660*, 1513–1521. [CrossRef]
16. Miller-Robbie, L.; Ramaswami, A.; Amerasinghe, P. Wastewater treatment and reuse in urban agriculture: exploring the food, energy, water, and health nexus in Hyderabad, India. *Environ. Res. Lett.* **2017**, *12*, 075005. [CrossRef]
17. Munoz, I.; Gomez, M.; Fernandez-Alba, A.R. Life cycle assessment of biomass production in a Miditerranean greenhouse using different water sources: Groundwater, treated wastewter and desalinated seawater. *Agric. Syst.* **2010**, *103*, 1–9. [CrossRef]
18. Ghasemp, A.; Ahmadi, E. Assessment of environment impacts of egg production chain using life cycle assessment. *J. Environ. Manag.* **2016**, *183*, 980–987. [CrossRef]
19. Xue, X.; Landis, A.E. Eutrophication potential of food consumption patterns. *Environ. Sci. Technol.* **2010**, *44*, 6450–6456. [CrossRef]
20. Schoen, M.E.; Xue, X.; Hawkins, T.R.; Ashbolt, N.J. Comparative human health risk analysis of coastal community water and waste service options. *Environ. Sci. Technol.* **2014**, *44*, 6450–6456. [CrossRef]

21. Grant, T.; Beer, T. Life Cycle Assessment of Greenhouse Gas Emissions from Irrigated Maize and Their Significant in the Value Chain. *Aust. J. Exp. Agric.* **2006**, *48*, 375–381. [CrossRef]
22. Kumar, S.; Singh, J.; Nanoti, S.M.; Garq, M.O. A comprehensive life cycle assessment of jatropha biodiesel production in India. *Bioresour. Technol.* **2012**, *110*, 723–729. [CrossRef]
23. Xua, H.; Tian, Z.; He, X.; Wang, J.; Sun, L.; Fischerd, G.; Fan, D.; Zhong, H.; Wu, W.; Pope, E.; et al. Future increases in irrigation water requirement challenge the water-food nexus in the northeast farming region of China. *Agric. Water Manag.* **2019**, *213*, 594–604. [CrossRef]
24. Harwood, R.R.; Cassman, K. The nature of agriculture systems:food security and environmental balance. *Food Policy* **1995**, *20*, 439–454.
25. Hu, X.; Shi, L.; Zeng, J.; Yang, J.; Zha, Y.; Yao, Y.; Cao, G. Estimation of actual irrigation amount and its impact on groundwater depletion: A case study in the Hebei Plain, China. *J. Hydrol.* **2016**, *543*, 433–449. [CrossRef]
26. Lyu, S.; Chen, W.; Zhang, W.; Fan, Y.; Jiao, W. Wastewater reclamation and reuse in China: Opportunities and challenges. *J. Environ. Sci.* **2016**, *39*, 86–96. [CrossRef] [PubMed]
27. ISO 14044:2006. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; International Organization for Standardization: Geneva, Switzerland, 2006; Available online: https://www.iso.org/standard/38498.html (accessed on 13 May 2019).
28. Bo, L.; Yao, H.; Yang, J. Present condition of sewage disposal Tongliao and Feasibility of wastewater irrigation. *Environ. Sci. Manag.* **2011**, *3*, 1–5. (In Chinese)
29. Yu, X.; Zhao, J.; Yao, H.; Yuan, X.; Yao, X. Vertical Migration of Heavy Metals in Soil Under Sweage Irrigation. In Proceedings of the International Conference on Electric Technology and Civil Engineering, Lushan, China, 22–24 April 2011; pp. 7075–7078.
30. Yao, H.; Xue, X.; Zhang, S.; Yuan, X.; Li, T.; Kelin, H. Evaluation of spatial and vertical variability of nitrogen and phosphorus in sewage-irrigated soil in Tongliao, China. *Trans. Tianjin Univ.* **2013**, *19*, 241–247. [CrossRef]
31. Mourad, A.L.; Coltro, L.; Oliveira, P.A.P.L.V.; Kletecke, R.M.; Baddini, J.P.O.A. A simple methodology for elaborating the life cycle inventory of agricultural products. *Int. J. Life Cycle Assess.* **2007**, *12*, 408–413. [CrossRef]
32. IPCC. *IPCC Guidelines for National Greenhouse Gas Inventories*; Institute for Global Environmental Strategies: Hayama, Japan, 2006.
33. Argonne National Laboratory. *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model*; Argonne National Laboratory: Argonne, IL, USA, 2006.
34. Xue, X.; Pany, Y.; Landis, A.E. Evaluating agricultural managment practices to improve the environmental footprint of corn-derived ethanol. *Renew. Energy* **2014**, *66*, 454–460.
35. Dijkman, T.J.; Birkved, M.; Hauschild, M.Z. PestLCI 2.0: A second generation model for estimating emissions of pesticides from arable land in LCA. *Int. J. Life Cycle Assess.* **2012**, *17*, 973–986. [CrossRef]
36. Toxnet Toxicology Data Network. Available online: http://toxnet.nlm.nih.gov/ (accessed on 13 May 2019).
37. China Meteorological Data Service Center Meteorological data. Available online: https://data.cma.cn/en (accessed on 13 May 2019).
38. US Environmental Protection Agency NONROAD Model (Nonroad Engines, Equipment, and Vehicles). Available online: https://www.epa.gov/moves/nonroad-model-nonroad-engines-equipment-and-vehicles (accessed on 5 May 2018).
39. Pre Consultants SimaPro LCA software. Available online: http://www.pre.nl/simapro/ (accessed on 15 June 2018).
40. Ecoinvent Center Ecoinvent Database Website. Available online: http://www.ecoinvent.ch/ (accessed on 13 May 2019).
41. Energy Information Administration Country Analysis Briefs. Available online: http://www.eia.gov/cabs/china/Full.html (accessed on 5 May 2018).
42. Yang, Y.H.; Fang, J.Y.; Guo, D.L.; Ji, C.J.; Ma, W.H. Vertical patterns of soil carbon, nitrogen can carbon: nitrogen stoichimetry in Tibetan grasslands. *Biogeosci. Disscuss.* **2010**, *7*, 1–24. [CrossRef]
43. Hauschild, M.Z.; Goedkoop, M.; Guiee, J.; Heijungs, R.; Huijbregts, M.; Jolliet, O. Identifying best existing practice for characterizaton modeling in life cycle impact assessment. *Int. J. Life Cycle Assess.* **2013**, *18*, 683–697. [CrossRef]
44. Rosenbaum, R.K.; Bachmann, T.M.; Gold, L.S.; Huijbregts, M.A.; Jolliet, O.; Ronnie, J. USEtox—The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int. J. Life Cycle Assess.* **2008**, *13*, 532–546. [CrossRef]

45. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: a harmonized life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
46. Bare, J.C.; Norris, G.A.; Pennington, D.W.; Makone, T. TRACI-the tool for the reduction and assessment of chemical and other environmental impacts. *J. Ind. Ecol.* **2003**, *6*, 49–78. [CrossRef]
47. Humbert, S.; Marshall, J.D.; Shaked, S.; Spadaro, J.; Nishioka, Y.; Preiss, P. Intake fraction for particulate matter: Recommendation for life cycle assessment. *Environ. Sci. Technol.* **2011**, *45*, 4808–4816. [CrossRef]
48. Xue, X.; Hawkins, T.; Schoen, M.; Garland, J.; Ashbolt, N. Comparing the life cycle energy consumption, global warming and eutrophication potentials of several water and waste service options. *Water* **2016**, *8*, 154. [CrossRef]
49. Huo, H.; Wang, M.; Bloyd, C.; Putsche, V. *Life Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels*; Argonne National Laboratory, US Department of Energy: Argonne, IL, USA, 2008.
50. Kim, S.; Dale, B.E. Regional variations in greenhouse gas emissions of biobased products in the United States—Corn-based ethanol and soybean oil. *Int. J. Life Cycle Assess.* **2009**, *14*, 540–546. [CrossRef]
51. Sheehan, J.; Camobreco, V.; Duffield, J.; Graboski, M.; Shapouri, H. *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*; National Renewable Energy Laboratory, US Department of Energy: Golden, CO, USA, 1998.
52. Landis, A.E.; Miller, S.A.; Theis, T.L. Life cycle of the corn-soybean agroecosystem for biobased production. *Environ. Sci. Technol.* **2007**, *41*, 4. [CrossRef]
53. Liang, L.; Rattan, L.; Ridoutt, B.G.; Du, Z.; Wang, D.; Wng, L.; Wu, W.; Zhao, G. Life Cycle Assessment of China's agroecosystems. *Ecol. Indic.* **2018**, *88*, 341–350. [CrossRef]
54. National Development and Reform Commission The 13th Five-Year Plan For Economic And Social Development Of The People's Republic Of China. Available online: http://en.ndrc.gov.cn/newsrelease/201612/P020161207645765233498.pdf (accessed on 13 May 2019).