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RESEARCH ARTICLE

Carbon and water footprints of irrigated corn and non-irrigated wheat in Northeast Spain

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Abstract Irrigation increases yields and allows several crops to be produced in regions where it would be naturally impossible due to limited rainfall. However, irrigation can cause several negative environmental impacts, and it is important to understand these in depth for the correct application of mitigation measures. The life cycle assessment methodology was applied herein to compare the main irrigated and non-irrigated crops in Northeast Spain (corn and wheat, respectively), identifying those processes with greater contribution to environmental impacts (carbon and water footprint categories) and providing scientifically-sound information to facilitate government decisions. Due to concerns about climate change and water availability, the methods selected for evaluation of environmental impacts were IPCC 2013 GWP (carbon footprint) and water scarcity indicator (water footprint). The area studied, a 7.38-km^2 basin, was monitored for 12 years, including the period before, during, and after the implementation of irrigation. The functional unit, to which all material and energy flows were associated with, was the cultivation of 1 ha, throughout 1 year. The overall carbon footprint for irrigated corn was higher, but when considering the higher productivity achieved with irrigation, the emissions per kilogram of corn decrease and finally favor this irrigated crop. When considering the water footprint, the volumes of irrigation water applied were so high that productivity could not compensate for the negative impacts associated with water use in the case of corn. Nevertheless, consideration of productivities and gross incomes brings the results closer. Fertilizer use (carbon footprint) and irrigation water (water footprint) were the main contributors to the negative impacts detected.

Keywords Environmental impact · Irrigation · Fertilization · Rainfed farming · LCA · Spain

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Introduction

The importance of irrigated agriculture for today's world is unquestionable. Irrigation enables the increase of agricultural production and the variety of crops to be produced in areas where it would be naturally impossible due to limited rainfall. As irrigation may generate several negative environmental impacts, it is important to understand these impacts in depth for the correct application of mitigation measures (Tanji and Kielen 2002; FAO 2003).

With the worldwide expansion of irrigated land, the need to consider the environmental impacts of the transformation of an area (i.e., a natural area, or rainfed farming, into irrigated area) is as important, or even more important, than the consideration of economic impacts. This necessity increases side by side with environmental awareness and the clear limitations of our natural resources.

In this context, the life cycle assessment (LCA) applies comprehensive methods to the assessment of environmental impacts of products and activities, quantifying environmental loads and, at the same time, fulfilling the requirements to become a support tool to design more sustainable products and activities (Baumann and Tillman 2004; ISO 14040 2006; ISO 14044 2006).

Studies have been successfully applying LCA for a better understanding of the environmental impacts of irrigation. Sanjuan et al. (2005) and Aranda et al. (2005) utilized LCA to analyze, respectively, orange and wine production in Spain. Contreras et al. (2009) took irrigation into consideration in their LCA comparison of four different alternatives for the use of by-products and wastes of sugar production in Cuba. Payraudeau and van der Werf (2005) reviewed the main methods of environmental impact assessment for a farming region, including LCA. These authors observed that LCA took into account long-term effects of pollutant emissions and enabled a holistic approach to environmental assessment, clear advantages due to the complexity of agricultural activity.

Hospido et al. (2013) described a procedure to incorporate water source information at the LCA inventory level and evaluate the influence on the environmental impact assessment level. The authors then applied their results in a LCA study of irrigated lettuce production. Mohammadi et al. (2013) applied LCA and data envelopment analysis for 94 soybean farms in Iran to measure efficiency in each farm. The authors observed that irrigation was the second greatest contributor to greenhouse gas emissions and the greatest contributor to total global warming potential reduction, implying that there is a great scope for global warming potential reduction by improving the efficiency of irrigation systems.

In a northeastern Thailand basin, Thanawong et al. (2014) used LCA to investigate three cropping systems based on water management system: wet-season rainfed rice, wet-season irrigated rice, and dry-season irrigated rice. Their results highlighted the low performances of dry-season irrigated systems in both techno-economic and environmental terms.

These studies brought considerable advances in the understanding of the environmental impacts of irrigation through LCA. However, none of these studies used data obtained from a monitored area before, during, and after the implementation of irrigation.

The LCA methodology was applied herein to the comparison of irrigated and non-irrigated agriculture, expressing results in kilogram CO_2-equivalent/ha year and cubic meter of water/ha year. The study area was monitored during 12 years and data were made available for the periods before, during, and after the implementation of irrigation, which helped identify and understand the processes with a greater contribution toward negative environmental impacts. Throughout time, farmers in the zone have been shifting from non-irrigated agriculture to irrigated agriculture. The goal of this study was to estimate and understand the environmental impacts in two specific time periods: study area before its transformation into irrigated area (main crop: non-irrigated wheat) vs. nowadays (main crop: irrigated corn).

Materials and methods

The study area corresponded to the Lerma basin (7.38 km^2), located in Northeast Spain. This basin is part of the Ebro river basin, a major area of irrigated agriculture that has been expanding in recent years with the transformation of sections that were allotted decades ago and still had no irrigation. Lerma basin is one of those recent transformation areas, where structuring and adjustment works started in 2003. The irrigation system network and other infrastructure constructions lasted until 2006, when 31% of the area began to be irrigated. Between 2009 and 2013, it reached 100% of the area intended for this purpose (3.54 km^2). Hydrological, geological, climatic, and agricultural studies have been performed in the study area throughout 12 years by the authors, since before the transformation of the area (Causapé et al. 2004; Abrahao et al. 2011a, b; Merchán et al. 2013; García-Garizábal et al. 2014; Merchán et al. 2015; Abrahao et al. 2015). Data obtained from these studies include, but are not limited to: dynamics of the transition of the Lerma basin into irrigated land, irrigation systems implemented, established crops, irrigation volumes applied, type, and quantities of seeds, fertilizers and pesticides used and standard irrigation system materials.

The LCA methodology was applied to compare the environmental loads produced in the study area without irrigation and with irrigation. LCA consists of the research and assessment of the environmental impacts that a particular process, product, or activity causes. The purpose of LCA is to quantify these impacts, establishing a full spectrum of environmental and social damage and enabling the comparison of competing products and resulting in the selection of the product with the lowest environmental impact (ISO 14040 2006; ISO 14044 2006). More details on LCA can be found in Guinée (2001, 2002).

The functional unit of this study, to which all material and energy flows relate to, is the cultivation of 1 ha, throughout 1 year. Two different crops were assessed, representing the main non-irrigated crop and the main irrigated crop in the area: wheat (without irrigation) and corn (irrigated), with different auxiliary consumptions of materials and energy. The two models (and consequent environmental impacts) could be compared through the functional unit, which finally expressed results in kg CO_2-equivalent/ha year and cubic meter of water/ha year.

There are several methods for the evaluation of environmental impacts in LCA, using different environmental criteria and, therefore, evaluate and consider various environmental aspects. The first characterization method chosen for this study (global warming potential, GWP) utilizes the conversion factors published by the IPCC (Intergovernmental Panel on Climate Change) (IPCC 2013). This method considers the direct global warming potential of gaseous emissions, adding emissions through a common metric (equivalent CO_2)

(PRéconsultants 2014a). CO_2 is chosen as the reference substance, expressing the potential contribution to global warming of the substance for a time horizon of 100 years (GWP 100) so that the quantifying unit is kilogram CO_2-equivalent, also known as carbon footprint. The scope of this indicator is global (PRéconsultants 2014a). The second characterization method chosen was the water scarcity indicator (WSI) based on Hoekstra et al. (2012). The WSI is a water footprint method calculated as the fraction between consumed (referred to as blue water footprint) and available water. The focus was on scarcity of water available in rivers, lakes, reservoirs, and groundwater, known as blue water (Hoekstra et al. 2011; Hoekstra et al. 2012; Hoekstra 2016). The indicator was applied to the consumed water volume and only assessed consumptive water use. Scarcity of direct precipitation (green water) and water required to assimilate pollutants entering water bodies (gray water) were not considered.

SimaPro® 8.2.0.0 was utilized to carry out the LCA, which is a software developed by the company PRé Consultants (PRé Consultants 2014b). SimaPro® includes several inventory databases with thousands of detailed processes. In this study, Agri-footprint (Agri-footprint 2014) and Ecoinvent 3 (Ecoinvent 2013) databases were used.

With the many studies carried out in the Lerma basin, before, during, and after its transformation into irrigated area, it was possible to organize the inventories to compare the situation of the area with and without irrigation. Collaboration with the irrigation district authority and the 55 farmers responsible for the plots included in the study area was very important. For the situation without irrigation (Table 1), wheat was chosen as the reference crop, as it was the main rainfed crop in the basin prior to transformation. Corn was selected to represent the situation of the basin with irrigation, as corn is the main irrigated crop in the area (Table 2). The sprinkler was the main irrigation system implemented. The materials and equipment actually used in the basin were organized in an inventory (Table 3).

In Table 2, the electricity consumed originated from the Spanish national electricity mix.[1] This process starts from 1 kWh of electricity fed into the high voltage transmission (distribution) network, and ends with the transport of 1 kWh of low voltage electricity in the transmission network over cables and aerial lines. This dataset includes electricity inputs produced in Spain as well as imports, transformation to low voltage, the transmission network, direct emissions to air (SF_6 from the insulation gas in the medium voltage level switchgear are allocated to the electricity demand on low voltage), and electricity losses during transmission. All process descriptions follow ecoinvent (2013).

[1] 15% hard coal, 8% hydro, 38% natural gas, 18% nuclear, 6% oil, 10% wind, and 4% biomass (wood chips and biogas). The remaining 1% refers to imports from France and Portugal.

Table 1 Inventory of inputs for wheat (not irrigated) cultivated in Lerma basin (Spain)

Inputs	Quantity (kg/ha year)
Seeds	200
Fertilizer–Urea	303
Fertilizer–NPK 8–15-15	250
Herbicide–2,4-D	0.40

In Table 3, the sprinklers were made of cast brass (35 sprinklers/ha, 430 g each), and the hydrants were made of concrete and cast iron (1 hydrant/10 ha = 1840 kg concrete + 20 kg cast iron). PVC DN 90 and polyethylene DN 32 pipes were obtained by adapting the production of polyethylene DN 200 pipes. A lifetime of 30 years was considered for the material of the irrigation system. For corn and wheat prices, the average values of years 2014 and 2015 in Northeast Spain were used.

Each kilogram of herbicide 2,4-D included 2,4-dichlorophenol and chloroacetic acid, as well as water and 2,4-D emissions to air and water. In the NPK 8-15-15 compound production process, potassium chloride, ammonium nitrate, diammonium phosphate, and crushed rock (as filler) were mixed to form the NPK compound in the required proportions, plus transportation and packaging materials (25 kg container).

Production of urea considered ammonia and carbon dioxide. Transports of the intermediate products were included as well as the transport of the fertilizer product from the factory to the regional storehouse. Production and waste treatment of catalysts, coating and packaging of the final fertilizer products were not included. CO_2 consumption (733 kg CO_2/t of urea) during production of urea was not included, since CO_2 arises as a by-product during the production of ammonia. Infrastructure was also included.

Production of seeds includes the inputs of seeds, mineral fertilizers, and pesticides. The dataset includes all machine operations and corresponding machine infrastructure and sheds. Machine operations are as follows: soil cultivation, sowing, fertilization, weed control, pest and pathogen control,

Table 2 Inventory of inputs for corn (irrigated) cultivated in Lerma basin (Spain)

Inputs	Quantity
Seeds	25 kg/ha year
Liquid fertilizer–N 30	1167 kg/ha year
Fertilizer–NPK 8-15-15	625 kg/ha year
Herbicide–Glyphosate	1.68 kg/ha year
Irrigation water	7500 m^3/ha year
Electricity	247.7 kWh/ha year

Table 3 Inventory for the standard irrigation system material for corn cultivated in Lerma basin (Spain)

Inputs	Quantity
Polyethylene pipe DN32mm	550 m/ha
PVC pipe DN90mm	250 m/ha
Sprinklers	35 units/ha
Hydrants	1 unit/10 ha

and combine harvester, transport from field to regional processing centre and drying of grains. Further, direct field emissions are included. At the processing centre, seeds are treated (pre-cleaning, cleaning, eventually drying, and chemical dressing), stored, and transported to the regional storage centre.

Glyphosate production includes the reception of precursors (acetic anhydride, ammonia, chlorine, formaldehyde, phosphorous chloride, sodium hydroxide, and decarbonized water) at the factory gate. The dataset includes the input materials, energy uses, infrastructure, and emissions. The dataset does not include emulsives or additives.

Results and discussion

Comparison of carbon footprints demonstrated relatively close negative environmental impacts for the two situations ("irrigation" and "without irrigation"). For wheat without irrigation, the resulting emissions were 1340 kg CO_2-equivalent/ha year, whereas for irrigated corn the resulting emissions were 1700 kg CO_2-equivalent/ha year (Figs. 1 and 2). Sankey diagrams are presented in these figures, where the thickness of the connection lines is proportional to the intensity of the environmental impact.

In the case of wheat, fertilization was the main contributor to the carbon footprint, with urea representing approximately 78% of these impacts and compound fertilizers 9%. The total contribution of fertilizers to the impacts generated by wheat production without irrigation in the study basin was 87%. Seeds contributed 13%, demonstrating a significant portion of impacts from an input that normally is not considered in environmental studies. Herbicides contributed only 0.13% to negative impacts. The low value was achieved by the low application rates suggested by the manufacturer and followed by the farmers.

For irrigated corn, fertilizers were also the main contributor to the carbon footprint, with liquid fertilizers accounting for 69% of the negative impacts, and compound fertilizers accounting for 18%. Seeds contributed 3%, while herbicides contributed only 1%. The electricity, considering the Spanish national electricity mix, accounted for 7% of the impacts, which is a relatively high value, as most electricity consumption relates to the use of hydraulic pumps for the area of Lerma basin that requires forced pressure for irrigation.

The last component considered for the assessment of irrigated corn resulted in an unexpected low contribution to the carbon footprint. The component referred to as "irrigation system" (Fig. 2) includes standard materials that constitute the sprinkler irrigation system for corn grown in the Lerma basin. This component accounted for only 1% of the negative impacts, represented by 17 kg CO_2-equivalent/ha year. The assessment encompassed the life cycle of the hydrants, 35 sprinklers and 800 m of pipe for each hectare studied. However, the 30 year lifetime of these materials ensured that the equivalent emissions were distributed (diluted) throughout time, resulting in the low annual values presented herein.

Fertilization was the main factor responsible for the negative impacts detected in both cases (87%). The environmental impacts of the fertilization applied in Lerma basin to local water resources had already been studied by other evaluation methodologies (Abrahao et al. 2011b; Merchán et al. 2013; Abrahao et al. 2013; Merchán et al. 2015). These studies have identified periods of the year and areas of the basin in which the nitrate concentrations in water and the masses of nitrogenous contaminants exported were more pronounced. Impact mitigation in the study area should prioritize the fertilizer application rates, especially urea, in the case of wheat, and liquid fertilizers, in the case of irrigated corn.

Mohammadi et al. (2013), in their study of 94 soybean farms in Iran, also detected that fertilization emitted the highest CO_2-equivalent among the field practices. The authors suggested that the change to other fertilizer sources could be an option to reduce emissions. Thanawong et al. (2014) applied different LCA indicators to rainfed and irrigated rice, and observed that fertilizer application and manufacturing contributed to the majority of total energy use, a large part of ozone depletion, freshwater aquatic ecotoxicity, and a marginal amount to acidification, eutrophication, and global warming potential (GWP100), especially due to the prevailing direct emissions at field level. The authors highlighted that nitrogen fertilizers contributed most to GWP100 through N_2O direct field emissions.

Sanjuan et al. (2005), Ribal et al. (2009) and Pergola et al. (2013) compared agriculture under organic and conventional management, and also reported that in conventional production scenarios the greatest negative impacts were caused largely by fertilizers, while in organic production the primarily responsible emissions were a result of machinery and irrigation energy consumption.

Furthermore, the negative impacts of the two situations assessed in the present study may be perceived in different ways, depending on the emphasis given to the value obtained by the LCA. Comparing the two situations regarding the cultivated area, it was found that irrigated corn represented a carbon footprint 27% higher than wheat without irrigation

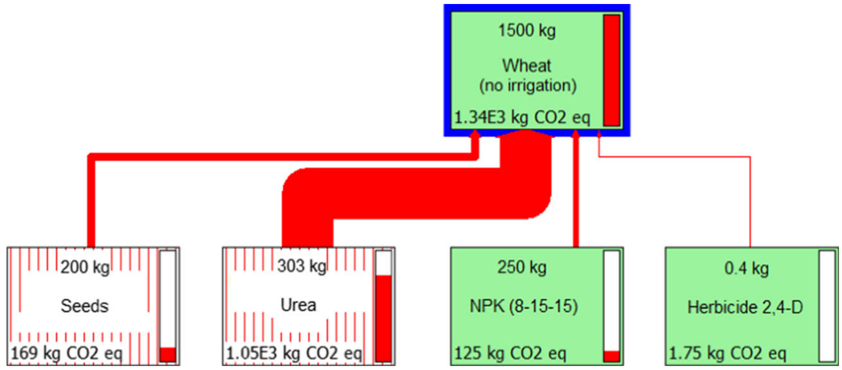

Fig. 1 Flowchart of annual CO_2 equivalent emissions of wheat grown without irrigation on 1 ha in the basin of Lerma (Spain)

(Table 4). However, taking into consideration the average production obtained by each crop and, notably, gross income per hectare, it can be seen that an income almost ten times higher (also Table 4) could be much more attractive to the farmer rather than a modest reduction in carbon footprint. It is important to emphasize that the costs associated with irrigated corn are higher and, obviously, the difference in net incomes will result that extreme. The possibility of higher profits has been attracting more and more farmers to the study area and proximities, with existing farmers also being attracted toward irrigated agriculture (Abrahao et al. 2011a; Merchán et al. 2013). The preferred option by the farmers is usually irrigated corn, which clearly incentivizes the expansion of new irrigated lands in this region of Northeast Spain.

Since Lerma basin is a representative of the new irrigated areas of Northeast Spain, the results can be extrapolated. The results showed that non-irrigated wheat was responsible for 1340 kg CO_2-equivalent/ha year, while irrigated corn was responsible for 1700 kg CO_2-equivalent/ha year. It is important to note that, although absolute corn emissions were higher, when dividing these impacts per production, 0.893 kg CO_2-equivalent/kg of wheat produced was obtained. For irrigated corn, 0.121 kg CO_2-equivalent/kg produced was obtained. Analysis of the flowcharts of the carbon footprint revealed that the highest contributions to environmental impacts were associated with the use of fertilizers, common for both crops studied. Utilization of other fertilizer sources could be an option to reduce emissions; however, an identified barrier for this action could be resistance of farmers to change their traditional/usual practices. The importance of the interrelationship between the results obtained herein and sustainable development in the irrigated and non-irrigated agriculture context is the provision of a new insight of fertilizer usage and irrigation, and how fertilization practices affect the environmental impact of agricultural activities.

Ways to change or improve the observed situation include further investigation of utilization of sludge from effluent treatment stations at industries (biosolid fertilization), or even the use of pig manure, as pig farming is a common practice in the area.

Application of the WSI revealed considerable higher negative environmental impacts associated with irrigated corn (Table 4). These results were partially expected for a blue water footprint, since 7500 m^3/ha year of irrigation water was applied for corn production in the area. As discussed by Hoekstra (2016), the impact differences between the two crops would not be that far if green water was considered. Nevertheless, the WSI still is a fair indicator for blue water use in the study area, evidencing the importance of incentivizing rainfed crops and increasing water use efficiency in water-scarce basins.

When dividing the WSI per production, 0.097 m^3/kg of wheat produced and 0.728 m^3/kg of irrigated corn produced

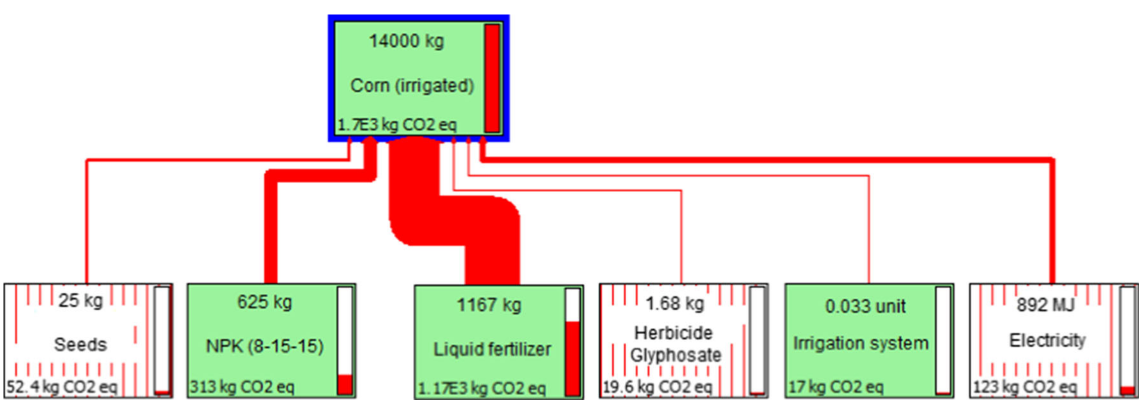

Fig. 2 Flowchart of annual CO_2 equivalent emissions of irrigated corn grown on 1 ha in the basin of Lerma (Spain). Emissions related to the standard irrigation system are included in the flowchart

Table 4 Negative environmental impact estimated by carbon footprint and water scarcity indicator (WSI), production and gross income of the two situations compared in Lerma basin (Spain)

Crop	Carbon footprint (kilogramg CO_2-equivalent/ha year)	WSI (m^3/ha year)	Production (kg/ha year)	Gross income (euros/ha year)
Wheat (not irrigated)	1340	145	1500	271.50
Corn (irrigated)	1700	10,200	14,000	2450.00

were obtained. Consideration of gross incomes brings these values to 0.534 m^3/euro of gross income for wheat and 4.163 m^3/euro of gross income for irrigated corn, which considerably reduces the differences in the water footprint and provides the perspective of how "inexpensive" irrigation water is.

In this way, the results presented herein evidence the importance of water use planning for Northeast Spain. As irrigation is expanding in the area, irrigated corn is being increasingly common and non-irrigated wheat is becoming less common. Incentives to increase irrigation water use efficiency and diversification of the crops could help mitigate the impacts observed.

Conclusions

Due to growing concerns regarding the environmental impacts related to the demands of modern society, life cycle assessment has been increasingly applied to determine the most *environmentally unfriendly* activities and to compare impact reduction strategies in several sectors, including agriculture.

This manuscript applied the LCA methodology to compare carbon and blue water footprints associated with irrigated and non-irrigated agriculture in Northeast Spain. These categories were selected due to concerns about climate change and water use. Environmental information was obtained from live monitoring of a 7.38-km^2 basin throughout 12 years, covering the period before, during, and after implementation of irrigation. Such richness of primary data is a strong contribution of this study. The functional unit was the cultivation of 1 ha, throughout 1 year. Two different crops were cultivated: non-irrigated wheat (including production and transportation chains for seeds, fertilizers, and herbicides) and irrigated corn (including production and transportation chains for seeds, fertilizers, herbicides, irrigation water, and electricity, in addition to the irrigation infrastructure: pipes, hydrants, and sprinklers); results were expressed in kg CO_2-equivalent/ha year and m^3/ha year to enable comparison.

The carbon and water footprints associated with the production of 1 kg of non-irrigated wheat at the Lerma basin were, respectively, 0.893 kg CO_2-equivalent and 0.097 m^3. For the production of 1 kg of irrigated corn, the carbon and water footprints were 0.121 kg CO_2-equivalent and 0.728 m^3, respectively. The overall carbon footprint associated with the material and energy flows for irrigated corn was higher, but when considering the higher productivity achieved with irrigation, the emissions per kilogram of corn decrease and finally favor this irrigated crop. However, when considering the water footprint only, the volumes of irrigation water applied are so high that productivity cannot compensate for the negative impacts associated with water use in the case of corn; non-irrigated wheat presents the lowest negative impacts before and after consideration of productivity. This raises a sustainability concern regarding the expansion of irrigated areas in Northeast Spain.

Nevertheless, from the farmers' perspective, the economic benefits indicate the opposite: when the average production obtained by each crop was considered along with gross income per hectare, an income almost ten times higher was obtained for irrigated corn. This could be much more attractive to the farmer rather than a modest reduction in environmental impacts, in the case of carbon footprinting.

The buy-in of farmers is essential for the success of any global warming mitigation strategy directed to changes in fertilization and water use, however any extra investment will compete with other options that can prove to be more economically attractive, which could be another barrier for cleaner production. Special regulation or standards can play important roles in the reduction of carbon and water footprints in agricultural activities.

Future studies include the application of different environmental impact assessment methods to verify whether the proportions of impacts are maintained when wider perspectives are studied, encompassing damage to the environment and human health, for example.

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