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Combining cleaner production and life cycle assessment for reducing the environmental impacts of irrigated carrot production in Brazilian semi-arid region

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ABSTRACT

Agriculture is the activity that contributes most to the emission of greenhouse gases, water quality degradation, soil loss and nutrient runoff worldwide. These harmful environmental impacts are issues in irrigated agriculture in the Brazilian semi-arid region. The rational use of natural resources and the efficiency of agricultural systems can reduce the environmental impacts and are essential for a more sustainable agriculture. However, a limited amount of data concerning the environmental impacts of horticultural practices is available. To date, no evaluation of a carrot crop life cycle in Brazil could be found in the literature. The purpose of this paper is to present a methodological approach combining Life Cycle Assessment (LCA) and Cleaner Production (CP) principles in the environmental and economic evaluation of irrigated carrot farming. Life Cycle Impact Assessment was carried using the International Reference Life Cycle Data System (ILCD, 2011) method, including data uncertainty. We evaluated the base scenario based on management practices widely adopted in the studied area, and the recommended scenario based on adoption of CP selected opportunities using agronomic recommendations for the carrot production system. By these means, the environmental impacts can be reduced between 15 and 70% in the evaluated categories from the base to the recommended scenario. Most environmental impacts were related to fertilizer production and field emissions. The global warming effect related to the emission of 0.12 kg CO_2 eq/kg product from the base scenario can be reduced to 0.07 kg CO_2 eq/kg product in the recommended scenario. This represents a lower value than most global warming rates for carrots found in literature. The costs of inputs were reduced by 49% from in the recommended scenario. Most costs of inputs were related to fertilizers and seed purchasing. The combined use of the two methods proved feasible as LCA identifies the main hotspots of the analyzed system, while CP support practices that reduce costs and the use of inputs such as water, energy, fertilizers, seeds and pesticides. CP provided a higher level of compliance with the technical requirements for the studied system and proved to be more economically and environmentally efficient than 'end of pipe' practices. The complementary use of CP and LCA provided better support for a more sustainable irrigated carrot production in the semiarid region of Brazil.

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List of acronyms

AC	Acidification
AFOLU	Agriculture, forestry and other land use
ANEEL	Brazilian electricity regulatory agency
BS	Base scenario
CONAMA	Environmental national council
CP	Cleaner production
ESRI	Environmental systems research institute
ET-f	Freshwater ecotoxicity
EU-f	Freshwater eutrophication
EU-m	Marine eutrophication
EU-t	Terrestrial eutrophication
FAO	Food and agriculture organization of the united nations
Fig	Figure
GSD	Geometric standard deviation
GW	Global warming
HT-c	Human toxicity, cancer effects
HT-n	Human toxicity, non-cancer effects
IBGE	Brazilian institute of geography and statistics
IH	Water index
ILCD	International reference life cycle data system
INEMA	Institute of environment and water resources
IPCC	International panel on climate change
IR-e	Ionizing radiation to ecosystem
IR-h	Ionizing radiation to humans
ISO	International organization for standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LU	Land use
MAPA	Ministry of agriculture, livestock and supply
N	Nitrogen
NPK	Nitrogen, phosphorus, potassium
OD	Ozone depletion
pH	Potential of hydrogen
PM	Particulate matter
PO	Photochemical ozone formation
RD	Mineral, fossil and renewable resource depletion
RS	Recommended scenario
UNEP	United nations environment programme
UNIDO	United nations industrial development organization
USA	United states of america
WD	Water resource depletion

Units

Eq	equivalent
G	gram
Ha	hectare
Hp	horse-power
Kg	kilogram
Km	kilometer
kWh	kilowatt-hour
L	liter
M	meter
Mg	milligram
MJ	mega joules
Mm	millimeter
T	tonne
Tg	teragram
USD	United States dollar

1. Introduction

The Food and Agriculture Organization (FAO, 2014) estimated that greenhouse gas emissions from agriculture, forestry, other land use (AFOLU), energy use in agriculture and fisheries have doubled in the last fifty years. This increase was mainly due to the expansion of agriculture in developing countries and it could additionally rise by 30% by 2050 if no efforts are made to counter it (FAO, 2014).

In 2010, AFOLU emissions accounted for 24% of global greenhouse gases (IPCC, 2014) and have continuously increased, even though deforestation is declining, mainly due to the application of synthetic fertilizers. Nitrous oxide from this source, is among the largest agricultural greenhouse gas contributions (Smith et al., 2008).

Food crops worldwide use 95% of irrigated land, consume 92% of water for irrigation and 70% of the nitrogen and phosphorus applied to agricultural land, which in turn are excessively deposited in the soil (West et al., 2014).

In 2010, global emissions of reactive nitrogen totaled 189 Tg, of which 161 Tg came from industries and agriculture (Oita et al., 2016). They calculated the nitrogen demand per capita and found that it ranges from 7 to 100 kg N per year. China, India, USA and Brazil accounted for 46% of global emissions of reactive nitrogen.

Agriculture also contributes to the degradation of water quality and water scarcity (Carpenter et al., 1998), by the use of pesticides that are harmful to local and regional biodiversity, water, soil and human health. According to Lima Junior et al. (2014), irrigation increases the yield and improves the quality of carrots, however, either a deficit or an excess of water and inadequate management affect their development. Improper management of the production system increases the cost of electricity and contaminates the water with fertilizers and pesticides. According to Figueirêdo et al. (2016), the modification of fertilization and pest management is the best way to improve the environmental performance of agricultural production.

The Irecê region, Bahia State, Brazil, is a semi-arid region where agriculture is the main economic activity. The study location is a karst[1] region with large groundwater reserves (Leal and Silva, 2004). The availability of surface water is low, but its fertile soils, flat land, and underground water resources favor intensive irrigated agriculture. The groundwater in this region is brackish and its continued use causes soil salinization (Nossa, 2011), nevertheless irrigated carrot cultivation in Irecê has been carried out on a large scale since 1990. Monitoring of groundwater conducted by Maia et al. (2010) in 1969 and 2003 showed a continuous lowering of the aquifer level in the Irecê region due to the intense exploitation of water for irrigation.

Worldwide carrot consumption is approximately 4.29 kg per person per year, making them one of the most economically valuable root vegetables (Freitas et al., 2009). Carrot production in Brazil is concentrated in the States of Minas Gerais, São Paulo, Paraná and Bahia (Freitas et al., 2009). According to the Brazilian Institute of Geography and Statistics (IBGE, 2006), the Irecê region produced

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[1] Karst is the term used to describe a type of natural landscape characterized by the chemical dissolution of rocks that lead to the appearance of caves and extensive groundwater systems in rocks such as limestone, marble, and gypsum. Approximately 20–25% of the global population depends on a large extent or entirely of groundwater obtained from Karst regions (Ford and Williams, 1989).

85% of the carrots in the Bahia State which represents 54% in the Northeast region of Brazil and 14% in Brazil. In this region, 5000 families cultivate irrigated carrots within an area of 6000 ha with a maximum throughput of 60 tons per hectare and production capacity of up to three annual cycles (Pinheiro et al., 2010).

Cleaner Production (CP) and Life Cycle Assessment (LCA) methods were adopted in this study to assess carrot cultivation. According to the United Nations Industrial Development Organization (UNIDO, 2002), CP method, which means the continuous application of an integrated environmental strategy to processes, products, and services, aims to promote production efficiency, environmental management and human development.

According to the International Organization for Standardization (ISO), a product life cycle is a compilation and evaluation of inputs, outputs and the potential environmental impacts of an activity (ISO 14044, 2006). LCA is used to evaluate environmental effects associated with any product or activity, from the raw materials extraction to the point of return of the waste (Vigon et al., 1993). It constitutes a starting point for the development of Environmental Product Declaration (Ingrao et al., 2015). In addition, LCA serves as a tool to support local policies for sustainable production and consumption patterns (Cellura et al., 2012). However, Rahim and Raman (2015) warn that an LCA study only identifies environmental impact, not mitigation strategies.

Some LCA studies in horticulture can be found in the literature, however, few are related to carrot production. The LCA food Denmark (2006) database presents only emissions of nitrogen and phosphorus compounds. However, this database does not represent the Brazilian context. Silva and Forbes (2016) examined sustainability in the horticulture industry in New Zealand and identified costs and time as the main barriers to implementing sustainable practices. Soode et al. (2015) argue that one way to combat climate change is to reduce the impacts of isolated products. However, the carbon footprint studies of German horticultural products are limited in coverage and do not include the entire supply chain. These authors identified that products from open field crops perform better than foreign crops transported by plane or greenhouse crops, regardless of the producing country. Perrin et al. (2014) suggest a way to characterize the crop in space and time, as well as to include the complete inventory to assess impacts such as eutrophication, toxicity, and water deprivation in LCA of vegetable products. Cellura et al. (2012) applied LCA to tomatoes, cherry tomatoes, peppers, melons, and zucchinis in Italy and identified that the overuse of fertilizers and pesticides increases environmental impacts such as eutrophication, acidification, and water consumption. They found that the adoption of best practices in vegetable production reduced environmental impacts significantly.

Among the studies found in the literature for carrot cultivation, Raghu (2014) and Röös and Karlsson (2013) only evaluated global warming. Stoessel et al. (2012) also evaluated the water footprint. On the other hand, carrot crop inventories available in life cycle databases such as Agribalyse® (Koch and Salou, 2015), Agri-footprint (2015) and World Food (Nemecek et al., 2015) are more complete LCA approaches and enable the evaluation of several impact categories. Stoessel et al. (2012) used LCA to evaluate the carbon and water footprints of 34 food products, including carrots, and suggest the inclusion of other environmental categories to avoid problem shifting. Raghu (2014) assessed the life cycle of carrots in Finland for different production systems: local organic, local conventionally grown and those imported from Italy.

To date, we have not found any carrot LCA study in Brazil, therefore this is an opportunity to present this research. This study stands out in relation to literature for its completeness and use of primary local data, which enables the evaluation of several impact categories. Furthermore, we did not identify any papers in the literature that combine CP and LCA approaches to evaluate agricultural products. Therefore, the purpose of this paper is to present a methodological approach combining CP and LCA to study agricultural products with the carrot case study in Brazilian semi-arid region, using primary data from the field.

2. Material and methods

The study area is located at coordinates 11° 28′ 32.5” S and 41° 51′ 55.1” W (Fig. 1) in the municipality of the Lapão, microregion of Irecê, Bahia State, northeastern Brazil.

The predominant biome in this study area is the *caatinga*.[2] The climate is described as BSh[3] according to the Köppen classification (Kottek et al., 2006): semi-arid, sub-humid dry in the winter and very hot and rainy in summer, with average annual temperatures of 23–24 °C. According to Nossa (2011), the annual precipitation varies from 500-700 mm with a mean of 653 mm and the soil is classified as Cambisol.

2.1. Combining CP and LCA

In this study, our methodological approach combined CP and LCA principles in the assessment of irrigated carrot. Two production scenarios were evaluated. The first was based on practices adopted in the study area in the data collection period (base scenario - BS). The second was based on CP selected opportunities to implement on carrot crop for the study area (recommended scenario - RS). CP was adopted to make the environmental diagnosis of carrot production and to identify the opportunities for environmental improvement of the process. Although CP considers technical, economic and environmental evaluation, the environmental impact was further assessed by an LCA method. As a result, we identified LCA to be a robust method of improving CP decision making. LCA was used to evaluate the environmental impact of selected CP opportunities among the measures identified. In Fig. 2 the steps followed in this study, combining CP and LCA are presented. For a better understanding, the steps in each method are described separately. The CPmethod was used as recommended by UNIDO (2002), followed by the LCA according to ISO 14044 (2006).

2.1.1. Pre-assessment

Initially, a visit was made to get to know the background of the farm and the process flow, to understand the carrot production process, agricultural management operations, the layout of the facilities and other farm activities. Through technical visits, in which the researchers met the owner of the farm and the workers, the whole crop cycle was studied, from soil preparation to harvest, in order to better understand all the stages of production (Fig. 3).

2.1.2. Assessment

At this phase, a preliminary diagnosis was completed and the environmental inventory was made including the balance of inputs, water and energy. The opportunities of CP practices to be addressed, based on measures of control of waste at the source were identified. These field data were collected from May to July 2014 and August to September 2015.

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[2] *Caatinga* is an exclusive Brazilian biome and the largest one in the northeast of the country. The term “caatinga” means white forest, characterized by small trees of thin stems and shrubs that lose their leaves seasonally (FAO, 2015).

[3] According to the World Map of Köppen-Geiger, the climate classification is based on the Main climate (B = arid), Precipitation (S = steppe) and Temperature (h = very arid) (Kottek et al., 2006).

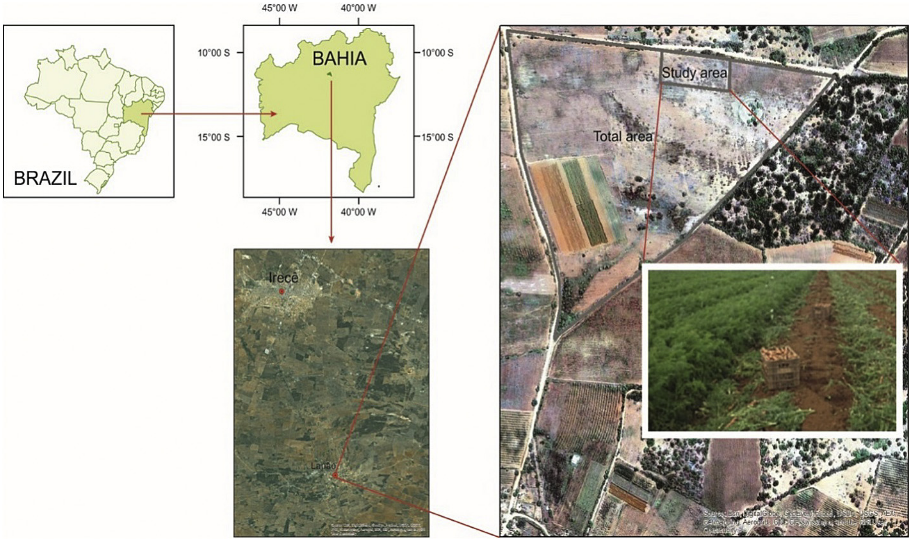
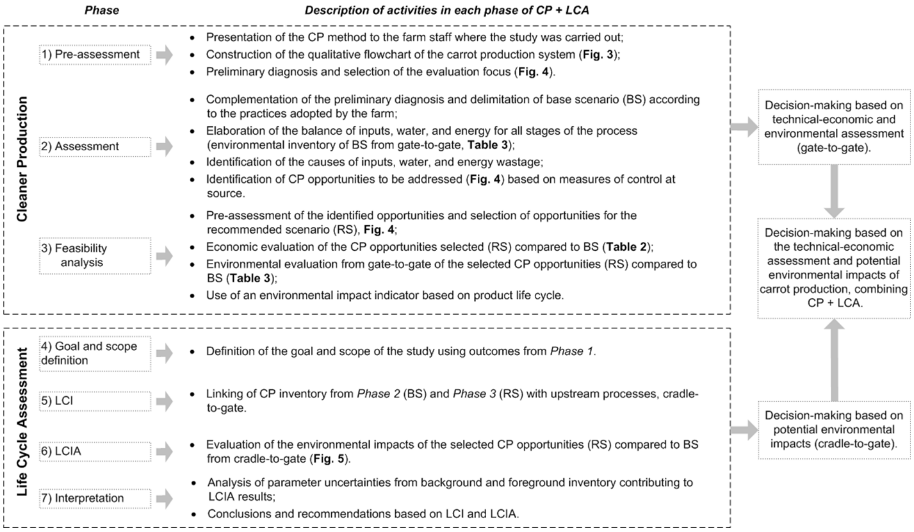


Fig. 1. Study area located in Lapão, Bahia State, Brazil. Source: Environmental Systems Research Institute (ESRI, 2016).



1) Pre-assessment
- Presentation of the CP method to the farm staff where the study was carried out;
- Construction of the qualitative flowchart of the carrot production system (**Fig. 3**);
- Preliminary diagnosis and selection of the evaluation focus (**Fig. 4**).

2) Assessment
- Complementation of the preliminary diagnosis and delimitation of base scenario (BS) according to the practices adopted by the farm;
- Elaboration of the balance of inputs, water, and energy for all stages of the process (environmental inventory of BS from gate-to-gate, **Table 3**);
- Identification of the causes of inputs, water, and energy wastage;
- Identification of CP opportunities to be addressed (**Fig. 4**) based on measures of control at source.

3) Feasibility analysis
- Pre-assessment of the identified opportunities and selection of opportunities for the recommended scenario (RS), **Fig. 4**;
- Economic evaluation of the CP opportunities selected (RS) compared to BS (**Table 2**);
- Environmental evaluation from gate-to-gate of the selected CP opportunities (RS) compared to BS (**Table 3**);
- Use of an environmental impact indicator based on product life cycle.

4) Goal and scope definition
- Definition of the goal and scope of the study using outcomes from *Phase 1*.

5) LCI
- Linking of CP inventory from *Phase 2* (BS) and *Phase 3* (RS) with upstream processes, cradle-to-gate.

6) LCIA
- Evaluation of the environmental impacts of the selected CP opportunities (RS) compared to BS from cradle-to-gate (**Fig. 5**).

7) Interpretation
- Analysis of parameter uncertainties from background and foreground inventory contributing to LCIA results;
- Conclusions and recommendations based on LCI and LCIA.

Decision-making based on technical-economic and environmental assessment (gate-to-gate).

Decision-making based on the technical-economic assessment and potential environmental impacts of carrot production, combining CP + LCA.

Decision-making based on potential environmental impacts (cradle-to-gate).

Fig. 2. Methodological approach combining CP and LCA.

The information on diesel consumption of the agricultural tractor was obtained from the workers on the farm. Fertilizer information was also obtained from the workers and was based on sample collection in the field which underwent soil macronutrient laboratory analysis. For the recommended scenario, recommendation of agronomic practices were considered. Seed information was also obtained from workers for the base scenario and CP selected opportunities, using agronomic recommendations, for the recommended scenario. After the germination of the seeds, still some small plants are eliminated manually to standardize the planting forming a more uniform stand of plants. These discarded plants are collected in the field to feed animals. Electricity consumption of the irrigation system was obtained from an electricity meter and, for the recommended scenario, it was estimated based on the pump power and operation time.

The water index for the town of Irecê was calculated according to the method of Thornthwaite and Mather (1955) (Table A.1). This index reflects the water balance. Water is a limiting factor for agricultural production and the water index relates the availability of water to the soil through precipitation and irrigation with appropriate practices. The irrigation water consumption data were obtained from the owner of the farm, who provided technical information about the water well. The water demand for irrigation in the recommended scenario was estimated based on agronomic coefficients, Irecê's regional data and carrot cultivation technical data (Table A.1). The water consumption was quantified for irrigation and pesticide dilution.

The information concerning the actual use of pesticides was obtained from the workers. Recommendations were based on CP selected opportunities using Ministry of Agriculture, Livestock and Supply advices. However, only the *Afalon* herbicide and the *Amistar Top* fungicide used for growing carrots are registered in the Ministry of Agriculture, Livestock and Supply (MAPA, 2016). The unregistered pesticides were considered to be the same amount in both scenarios. The pesticide compositions were based on the technical specification (Table A.2). Nitrogen, phosphorus, heavy metals and pesticide emissions into the air, water, and soil compartments were calculated based on the regional soil, plant and

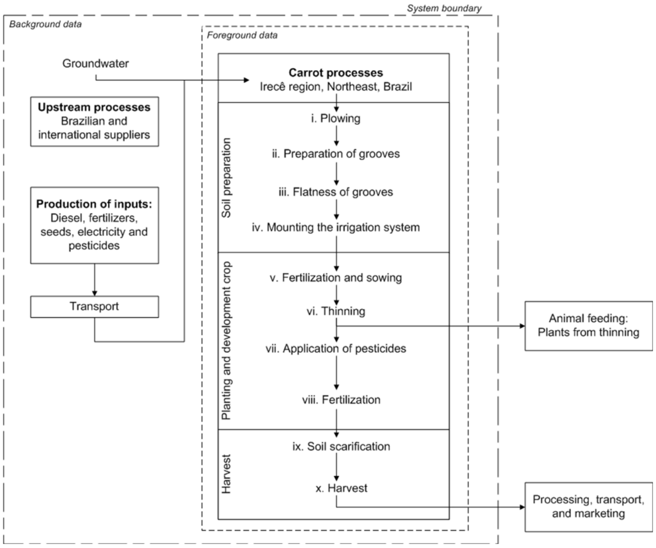


Fig. 3. Flowchart of carrot production.

climate data according to the method of Nemecek and Schnetzer (2012) for estimating direct emissions of Life Cycle Inventory (LCI) of agricultural production systems (Table A.3).

Harvesting and product information were obtained from local workers and agronomists. The leaves which are removed from the roots of the carrot during the harvest are collected to feed cattle and sheep. Losses of this biomass were not considered in the product system because they represents less than 1% of the total mass. Consequently, the total inputs and outputs of the product system were attributed to the main product (harvested carrots). The phases of post-harvest, transport, and marketing were not included in this study.

Prices of inputs such as diesel, fertilizers, seeds and pesticides were collected from local suppliers. There is one water pump connected to an electricity meter that provided data for electricity consumption. The amount and price of electricity was based on the bill payed to the electricity supplier. Water extraction and pollutant emissions are not priced in the Irecê region, therefore they were not included in the cost analysis.

The pre-assessment and assessment phases of CP for the carrot crop were used to identify areas for improvement and recommend more efficient management practices. Understanding the cost and physical balances enabled the identification of opportunities for environmental and economic improvement strategies.

2.1.3. *Feasibility analysis*

At this phase, the feasibility of implementing the identified CP opportunities was analyzed. CP opportunities were selected based on the following criteria defined in preliminary assessment: implementation based on changes in operational practices and immediate return time without the initial need for financial investment. The selected CP opportunities were evaluated technically based on the agronomic recommendations for the carrot. The CP selected opportunities were assessed through cost and environmental aspects and compared with the base scenario.

The farm evaluated in this study is a family farm that does not have permanent employees and does not have administrative expenses and taxes in relation to the object of the study. Therefore, costs with, taxes, labor and administration were not discounted from gross revenue. Gross revenue was estimated based on a harvest of 111,000 kg, marketed in 20 kg bags. The price considered for each bag was 3.50 USD. Technical assistance is provided by input suppliers and public agencies, therefore, these costs were disregarded. Net revenue is gross revenue minus input costs. The economic benefits and input costs were demonstrated. A more detailed cost analysis of the selected opportunities (reduction in excessive use of fertilizers, seeds, irrigation and pesticides) was performed. The recommended scenario payback was estimated by dividing the cost of the investment by the annual savings that can be obtained with the recommended practices. Price and costs are given in USD using the quotation of 3.42 *Reais* per dollar in June 2nd 2016. The detailed cost data can be found in Table A.4.

In addition, the environmental analysis of CP selected opportunities, including non-priced flows such as water extraction and pollution emissions, was carried out for the recommended scenario using LCA.

2.1.4. *Scope*

The LCA study was conducted based on ISO 14044 (2006) and the ILCD (EC-JRC, 2010) guidelines. The analysis was from cradle-to-gate of the farm and the reference flow of the study was 1 kg of harvested carrots.

The production system (Fig. 3) considered plowing, fertilizing, sowing, irrigation, application of pesticides and harvesting, for both scenarios. The farm has 26 ha and the study area covered one ha, with a productivity of 111,000 kg (ha year)$^{-1}$, including three cycles of 90–120 days each. Both scenarios were considered having a continuous production with the same yields.

The carrot production stages presented in Fig. 3 start with the displacement of a 62 hp compact tractor and agricultural equipment to a distance of 0.87 km from the field. Over the three annual crops, the machinery is displaced at least 42 times. Plowing is performed with a three discs plow coupled to the tractor (i) and preparation of the grooves is made with a trencher coupled with three discs (ii). Leveling is done with a mechanical rotary hoe that fragments and homogenizes the soil into smaller clods (iii). Then the irrigation system is assembled (iv). The main line of water distribution and micro perforated hoses are distributed manually. The well that supplies the water has a depth of 80 m and is 200 m away. Fertilizers are applied manually in the field (v). During the sowing (v), a planter coupled to the tractor is used. Then the field is irrigated. The carrot seeds are placed directly in the crop area rather than by transplanting seedlings. After the germination phase, excess plants are removed manually (vi) to ensure uniform spacing between plants. In the control step of pests and diseases (vii), pesticides are applied manually by a worker using a backpack pump sprayer. During the development of the carrot, two more fertilizations are made with potassium chloride (viii). In the pre-collection step (ix), the tractor is used to break up the soil to facilitate manual harvesting (x). The harvested product is transported to a packing house, where it is washed, sorted, packed into bags of 20 kg and transported to the resale or final consumer center. However, these processes were not considered in this study.

2.1.5. *Inventory*

The LCA inventory was based on the mass and energy balance of the farm from gate-to-gate, as presented in Section 3.2.2. The datasets for the production and transportation of raw materials were obtained from the global LCI database ecoinvent® (Wernet et al., 2016), using the allocation default version 3.1 (Moreno-Ruiz et al., 2014) with electricity data from the Brazilian energy matrix.

The carbon captured by plants was not considered in this study because it was assumed that the net carbon balance is neutral in a short cycle crop (Downie et al., 2014). Change in land use was also not considered because the area has previously been used for irrigated agricultural production. It was considered that the production of root growth stimulant, infrastructure (e.g. irrigation

Table 1
Comparison of the main aspects of CP and LCA methods.

Aspects	CP	LCA	CP and LCA
Process qualitative diagnose	●	○	●
Process quantitative diagnose	●	●	●
Waste estimation	●	○	●
Improvement scenarios and mitigation strategies	●	○	●
Cost analysis	●	○	●
Environmental impact analysis	○	●	●
Environmental and economic benefits	●	○	●
Product function	○	●	●
Gate-to-gate coverage	●	●	●
Cradle-to-gate coverage	○	●	●
Emissions of substances into the environment	○	●	●
Environmental impacts associated with the production of inputs, transport and waste treatment	○	●	●
Environmental certifications and more sophisticated models for information systematization	○	●	●

hose, pump machine, and tractor) and packages represented less than 1% of the environmental impacts, so these processes were not included. Some plants lost in thinning as well as those lost during harvesting are used to feed animals, therefore the cut-off criteria was applied (Fig. 3). The transport of material inputs considered global average distances of ecoinvent® market datasets (Moreno-Ruiz et al., 2013).

2.1.6. *Life cycle impact assessment*

The potential environmental impact assessment method used in this study was the ILCD 2011 (EC-JRC, 2012) version 1.07. The GW, global warming, category was used to compare the results with those of the literature. Simapro® 8 was used for calculating the assessment of the LCIA.

2.1.7. *Interpretation*

The interpretation of LCA results used the following approaches: contribution analysis, comparative analysis, uncertainty and discernibility analysis. The contribution analysis identifies the share of a certain process or life cycle stage in a certain impact category. The comparative analysis presents the LCA results for different product alternatives. The discernibility analysis combines the comparative analysis and the uncertainty analysis (Heijungs and Kleijn, 2001).

For the assessment of uncertainty, the Monte Carlo method was used considering a confidence interval of 95%, 10000 runs and lognormal distributions for the inputs and outputs. The squared geometric standard deviation of the foreground inventory was calculated according to the uncertainty estimates of Goedkoop et al. (2016), based on basic uncertainty and pedigree matrix (Weidema and Wesnaes, 1996). In addition, the uncertainty factors contained in the background data from ecoinvent® v3.1 inventory database for inputs and transport production chains were also considered.

3. Results and discussion

Cleaner Production and Life Cycle Assessment methods are useful to identify green supply chains of production and consumption. The combination of CP and LCA adopted in this study showed that the farmer can reduce the impacts of his agricultural production, by applying better operational practices. A simultaneous application of CP and LCA supports decision making, based on technical, economic and environmental assessment, based on internationally recognized methodological principles that can be associated with environmental labeling. By means of an Environmental Product Declaration producers can communicate the environmental performance of their supply chains to consumers. This allows them to choose more environmental friendly products.

In the environmental assessment here used, CP focuses on the production aspects, while LCA allows broader considerations that include upstream processes of the production chain.

The CP main focus is the continuous improvement of the process through opportunities to reduce waste generation allowing economic gains which can provide immediate returns. LCA focuses on the environmental diagnosis of products and permits a sensitivity analysis that seek for more eco-efficient scenarios. For this reason it has been used to support Environmental Product Declarations and strategic planning. Practices suggested using a CP approach can be enriched by more rigorous methods of evaluation of environmental impacts. As this work presents, LCA supports CP with a broader identification and quantification of the environmental effects of raw material consumption and pollutants emission. Thus, the combination of the two provides a broader and better-informed assessment. A combined application of CP and LCA methods is summarized in Table 1.

CP is a practical method and involves an organization's human resources through a so called eco-team that, after developing an environmental diagnosis, identifies opportunities with technical and economic feasibility to reduce potential environmental impacts. As a result, CP is more effective than the LCA in terms of pointing out specific solutions for environmentally related problems of the organization. These solutions may involve the Triple Bottom Line framework - economic, social and environmental sustainability. Other life cycle methods such as Life Cycle Costing and Social Life Cycle Assessment have been used, together with the LCA, to make up the Life Cycle Sustainability Assessment. However, despite CP having a more limited scope compared to life cycle methods, its advantage is the practicality of implementation in the company, the elaboration of improvement scenarios and the generation of benefits prioritizing viable opportunities.

Moreover, CP and LCA combined promote process and product sustainability. A sustainable and resilient society is expected to have an effective control of environmental impacts to avoid over-exploitation of resources and excess of pollution.

3.1. *Preliminary evaluation of CP opportunities*

The results of the study indicated the overuse of inputs in the base scenario due to low production efficiency, which could be improved through technological and behavioral changes on the part of the farmer. The existing production practices do not support an acceptable environmental performance.

According to United Nations Environment Programme (UNEP),[4] in the preliminary evaluation, one defines the criteria for selecting CP opportunities: implementation based on changes in operational practices and immediate return time without the initial need for financial investment. Application of CP in the studied farm identified opportunities for cost and environmental optimization that were proposed for the recommended scenario. These, mainly focused on pollution prevention practices and techniques (Fig. 4).

Next, a brief description of the identified CP opportunities is made, grouped according to the first column of Fig. 4. Further details on the economic feasibility and environmental impacts are described in the following section, only the selected opportunities, highlighted in Fig. 4.

3.1.1. *Tractor*

The study showed that the tractor and other machines used in

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[4] Document entitled Understanding Cleaner Production, undated. Available at: <http://www.unep.fr/scp/cp/understanding/industries.htm> (accessed 26.05.2017).

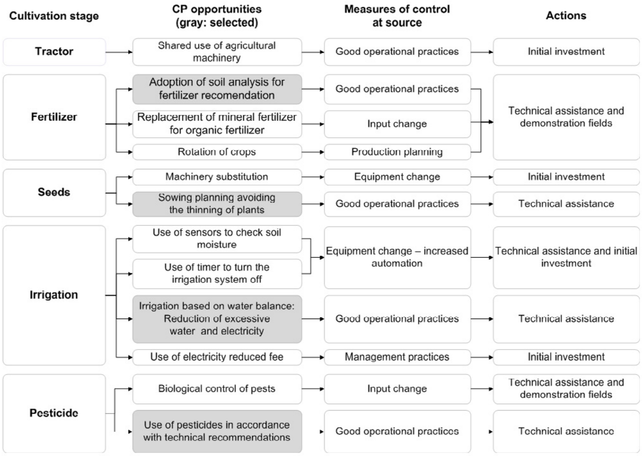

Fig. 4. Summary of cleaner production opportunities identified and selected for carrot cultivation. Note: Measures of control at source according to LaGrega et al. (1994).

the cultivation of carrots are mostly idle. The shared use of machinery, through associations and cooperatives, is an opportunity with economic and environmental benefits. However, it was not prioritized because it requires an initial investment.

3.1.2. *Fertilizer*

From the chemical soil analysis shown in Table A.5, it was found that the farm's soil has an almost alkaline pH, a high phosphorus content, lacking the presence of exchangeable aluminum and a low percentage of organic matter. The calcareous soils of the Irecê region presented by Nossa (2011) showed similar characteristics to those in this study. Based on the soil analysis, we observed excessive fertilizer use in BS and recommended smaller amounts for RS with fewer environmental impacts. RS can avoid a loss of 49% of the fertilizer used in BS.

Recommendations included: Soil quality analysis in each of the production cycles, production planning, incorporation of organic matter into the soil with crop rotation using legumes and animal manure application. Application of these recommendations lead to the improvement of the soil quality and a significant reduction of environmental impacts. On the farm where the study was carried out, cattle and sheep are raised that produce manure that could be treated for use after a more detailed analysis. Food plants such as corn, beans, and vegetables are grown in the farm and could serve for a crop rotation. However, the owner of the farm does not understand these practices to be effective. These two opportunities were not selected because they require demonstration in the field, which was not the object of this study. On the other hand, the use of fertilizers based on soil analysis and other agronomic recommendation can be implemented with immediate return.

NPK commercial formulations have rapid release and absorption in the ionic form. The application of ammonia-based fertilizers acidifies the soil over the long-term. For Malavolta (1981), energy expenditure to produce these major nutrients is high. During each growing cycle lasting 90–120 days, there is much loss of nitrogen fertilizer that has quick release and overloading of phosphorus with a slow release.

The excessive use of nitrogen, phosphorus, and potassium found in this study and the use of C_3-S_1 and C_4-S_1[5] groundwater increases the risk of soil salinization (Nossa, 2011). These results are in line with Jordan and Weller (1996) and Vitousek et al. (1997), who claim that the amount of nitrogen in the global biogeochemical cycle doubled through reactive nitrogen fixation due to the use of industrial fertilizers, burning of fossil fuels and increased use of legumes in agriculture. For Carpenter et al. (1998) and Caraco and Cole (1999), the most serious implications of these disturbances are climate change, eutrophication, acidification of aquatic and forest ecosystems, groundwater pollution and imbalances in the status of nutrients in the soil.

3.1.3. *Seeds*

Adopting a precision planter is a control measure that would reduce costs and wastes. However, changing this equipment requires a high initial investment and therefore was not here adopted. Moreover, changing the planter would not reduce diesel consumption because the tractor to which the planter is coupled would be the same. The production of 1 kg of carrots using irrigation will reduce the amount of seeds from 0.22 g, in the BS to 0.07 g in the RS. Sowing using the appropriate seed dosage, according to the technical recommendations, would reduce seed waste by an estimated 69% in this case study.

3.1.4. *Irrigation*

The water index in the region is −25.84, with an average annual rainfall of 653 mm, which represents 57% of potential evapotranspiration of 1147 mm per year. A water deficit is observed in every month of the year in the area of study. Because the Irecê region has low rainfall with an uneven distribution, water is a valuable resource. The exploitation of groundwater in the region requires control measures for resource preservation. The inventory shows a loss of 32% of the water used for irrigation in BS compared to the RS, mainly due to the lack of knowledge of the water demand of the soil, lack of enforcement of water use, and the low cost of electricity for the producer. The reduction in water consumption for the RS system requires operational practices such as reduced daily irrigation periods, analysis of the quality of the water used for irrigation, use of a tensiometer to monitor soil moisture, and the use of a timer device to turn off the irrigation system. In the long term, the farmer and the community should preserve local water sources using such practices. However, these measures require equipment change and initial investment. Only the water balance in the soil was estimated as an opportunity to irrigate only the amount of water required. In future work, it is recommended to compare irrigation systems for carrot cultivation, where other opportunities for reducing water consumption may be identified.

Electricity has varying tariffs, according to the Brazilian Electricity Regulatory Agency (ANEEL, 2017) depending on the time of day it is used. The "green tariff" is aimed consumer units with irrigation and guarantees discounts of 60–90% on rural electricity tariff at times between 21:30 and 06:00. Membership of the "green tariff" requires an investment of 1100 USD for system deployment and no additional operating costs. The payback of this opportunity is not long, but we did not select it because it requires initial investment, albeit low.

The high consumption of irrigation water along with fertilizer and the use of pesticides is a problem that requires changes to the BS. Besides the natural factors of soil salinization, observed by Akramkhanov et al. (2011), land irrigation affects groundwater quality (Bouaziz et al., 2011). Nossa (2011) obtained average values of 77.90 mg L^{-1} and 0.17 mg L^{-1} for nitrite and nitrate in groundwater, respectively; these values are above the maximum allowable values for human consumption according to Decree 518/2004 of the Ministry of Health and Resolution 396/2008 of the Environmental National Council (CONAMA).

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[5] According to Richards (1954), these water are classified as follows: C_3S_1 - high salinity and low sodium concentration; C_4S_1 - very high salinity and low sodium concentration. Both of them are not recommended for irrigation because they cause soil salinization.

Table 2
Summary of the economic feasibility and environmental evaluation of recommended CP opportunities (RS).

CP selected opportunities	Unit	Environmental benefit	Economic benefit (USD) (ha year)$^{-1}$	Estimated investment costs (USD) (ha year)$^{-1}$	Payback period (year)
Adoption of soil analysis for fertilizer estimation	kg (ha year)$^{-1}$	1828.85	942.18	0	Immediate
Sowing planning avoiding the thinning of plants	kg (ha year)$^{-1}$	16.65	973.69	0	Immediate
Irrigation based on water balance					
Reduction in excessive water	m^3 (ha year)$^{-1}$	6080.06	–	0	Immediate
Reduction in excessive electricity	kWh (ha year)$^{-1}$	1228.77	122.87	0	Immediate
Use of pesticides following the technical recommendations	kg (ha year)$^{-1}$	2.40	88.42	0	Immediate
Total			2127.17	0	

Table 3
Gate-to-gate inventory of 1 kg of carrot production.

Flows	Unit	Base scenario (BS)	Recommended scenario (RS)	Squared geometric standard deviation (GSD^2)	Source
Input					
Heat, diesel	MJ	1.16E-01	1.16E-01	1.05	Collected
Nitrogen fertilizer, as N	kg	3.29E-03	2.26E-03	1.05	Collected
Phosphate fertilizer, as P_2O_5	kg	1.09E-02	3.32E-03	1.05	Collected
Potassium fertilizer, as K_2O	kg	5.15E-03	3.29E-03	1.05	Collected
Inert filler of fertilizer	kg	1.46E-02	8.57E-03	1.05	Collected
Carrot seed	kg	2.18E-04	6.76E-05	1.05	Collected
Electricity, low voltage, Brazilian grid	kWh	3.44E-02	2.34E-02	1.50	Collected
Water, in ground	t	1.70E-01	1.16E-01	1.05	Collected
Pesticide, mancozeb	kg	3.46E-05	3.46E-05	1.05	Collected
Pesticide, benzimidazole compound	kg	3.42E-06	2.07E-06	1.05	Collected
Pesticide, unspecified	kg	4.06E-05	3.36E-05	1.05	Collected
Occupation, annual crop, irrigated, intensive	m^2.year	9.01E-02	9.01E-02	1.20	Collected
Output					
Ammonia, air	kg	1.58E-04	1.10E-04	1.21	Calculated
Dinitrogen monoxide, air	kg	1.16E-04	7.14E-05	1.42	Calculated
Nitrogen oxides, air	kg	2.45E-05	1.50E-05	1.42	Calculated
Water, air	t	3.41E-02	2.31E-02	1.24	Calculated
Phosphorus, river	kg	8.59E-05	8.26E-05	1.52	Calculated
Cadmium, river	kg	2.57E-08	2.56E-08	1.80	Calculated
Chromium, river	kg	2.01E-06	2.01E-06	1.80	Calculated
Lead, river	kg	2.07E-06	2.04E-06	1.80	Calculated
Mercury, river	kg	6.40E-09	6.30E-09	1.80	Calculated
Nitrate, ground water	kg	2.38E-02	1.29E-02	1.51	Calculated
Phosphorus, ground water	kg	6.31E-07	6.31E-07	1.52	Calculated
Water, ground water	t	1.36E-01	9.25E-02	1.05	Calculated
Cadmium, ground water	kg	4.50E-10	4.49E-10	1.80	Calculated
Chromium, ground water	kg	1.91E-07	1.91E-07	1.80	Calculated
Lead, ground water	kg	5.37E-09	5.29E-09	1.80	Calculated
Mercury, ground water	kg	1.16E-11	1.14E-11	1.80	Calculated
Arsenic, soil	kg	2.30E-06	7.72E-07	1.52	Calculated
Cadmium, soil	kg	4.57E-06	1.52E-06	1.52	Calculated
Chromium, soil	kg	4.37E-05	1.32E-05	1.52	Calculated
Lead, soil	kg	2.09E-05	5.72E-06	1.52	Calculated
Mercury, soil	kg	5.05E-08	1.26E-08	1.52	Calculated
Azoxystrobin, soil	kg	5.41E-06	3.24E-06	1.51	Calculated
Difenoconazole, soil	kg	3.42E-06	2.07E-06	1.51	Calculated
Lambda-cyhalothrin, soil	kg	2.70E-06	7.21E-07	1.51	Calculated
Linuron, soil	kg	2.43E-05	1.95E-05	1.51	Calculated
Mancozeb, soil	kg	3.46E-05	3.46E-05	1.51	Calculated
Metalaxyl-M, soil	kg	2.16E-06	2.16E-06	1.51	Calculated
Methomyl, soil	kg	4.32E-06	4.32E-06	1.51	Calculated
Thiamethoxam, soil	kg	9.91E-07	9.91E-07	1.51	Calculated

3.1.5. Pesticide use

The control of the main pests of carrot such as *Agrotis ipsilon*, *Spodoptera frugiperda*, *Diabrotica speciosa*, *Epicauta atomaria*, *Aphis gossypii*, *Cavariella aegopodii*, and *Myzus persicae* requires adequate irrigation management, adequate soil preparation, and use of good quality seeds with integrated pest control (Guimarães et al., 2012). Damage caused by nematodes are minimized by crop rotation and cleaning of the equipment used in the cultivation (Reifschneider, 1984). The adoption of biological control reduces the consumption of pesticides, reduces soil and water pollution, avoids the contamination farm workers and consumers, reduces the loss of biodiversity, and minimizes the mutation and resistance to pests and diseases. We observed that the producers were not interested in applying the technical recommendations and questioned the effectiveness of biological control of pests and diseases and organic fertilization. The adoption of biological control requires demonstration in the field. The opportunity to reduce the use of pesticides was selected based on the manufacturers' technical recommendations. The adoption of RS would avoid an 11% loss of pesticides in BS. In addition, the number of pesticides applied to carrot crop could be reduced if MAPA (2016) had a broader coverage of pesticide recommendations.

3.2. Economic evaluation and environmental impact

3.2.1. Financial viability

The economic benefit (Table 2) estimated in this study was 2127.17 USD (ha year)$^{-1}$, which represents a 49% reduction in the cost of inputs (BS), not including the water wastage because it comes from the well and is not purchased. Seeds represent the largest source of economic benefit for RS compared to BS, estimated at 973.69 USD (ha year)$^{-1}$ or 45.77% of the total benefits. Fertilizers represent 942.17 USD (ha year)$^{-1}$ or 44.29% of total benefits, while electricity represents 122.87 USD (ha year)$^{-1}$ or 5.78% and pesticides represent 88.42 USD (ha year)$^{-1}$ or 4.16%.

The use of fewer seeds in the RS led to a 22% reduction in total carrot costs of inputs compared to the BS system. The water used for irrigation comes from groundwater without cost, so the difference between BS and RS due to operating practices only impacts the cost of electricity. *Afalon* herbicide and *Amistar Top* fungicide had recommendations for smaller amounts in the cultivation of carrots and the costs were consequently lowered while the costs of unregistered pesticides for carrot cultivation were kept the same. The gross revenue from the sale of the product was 19,441.23 USD (ha year)$^{-1}$ for BS or RS. Selected CP (RS) options do not differ from BS in employee costs, fees, and administration.

The smaller use of fertilizers in the RS reduced total carrot costs of inputs by 21% compared to BS. Phosphorus is the most wasted nutrient at 841.90 kg (ha year)$^{-1}$, followed by potassium 206.22 kg (ha year)$^{-1}$ and nitrogen 114.40 kg (ha year)$^{-1}$.

3.2.2. Inventory

Table 3 shows the raw data of the mass inventory and energy use up to the harvest of carrots in the field for BS and RS production systems. The data are primary and were collected at the farm in the Irecê region where the study was conducted. The BS and RS production systems used the same tractor operations and consumed the same amount of diesel.

During each production cycle, three fertilizations were applied to the study area as follows: NPK[6] 10-50-00 for the foundation, NPK 20-00-20 for the first cover and NPK 00-00-60 for the second cover. The BS production system used 1828.85 kg (ha year)$^{-1}$ more fertilizer per hectare year than RS.

In the BS production system, thinning was done after germination to remove the excess carrot plants. The use of a precision planter in RS eliminated the need for thinning. The planter is coupled to the tractor and displaces only the amount of seeds required for the crop. The use of electricity is associated with the consumption of water for irrigation. The BS production system loses 1228 kWh (ha year)$^{-1}$ of electricity from water pumping compared to RS. The BS production system loses 6080 m^3 (ha year)$^{-1}$ due to the lack of knowledge of soil water demand compared to RS. The BS production system uses 0.93 kg (ha year)$^{-1}$ more active ingredients in pesticides than RS. Note that in the MAPA (2016), only azoxystrobin, difenoconazole, and linuron are registered for growing carrots.

The emissions from the BS production system were higher than the RS due to larger amounts of fertilizers and pesticides applied in the field. On the other hand, chromium emissions to the river and to groundwater (both derived from mineral fertilizers) and lambda-cyhalothrin, mancozeb, metalaxyl-M, methomyl, and thiamethoxam emissions to the soil (derived from active ingredients of pesticides) were kept the same. The BS production system had the same manual RS harvesting process and the productivity was the same for BS and RS.

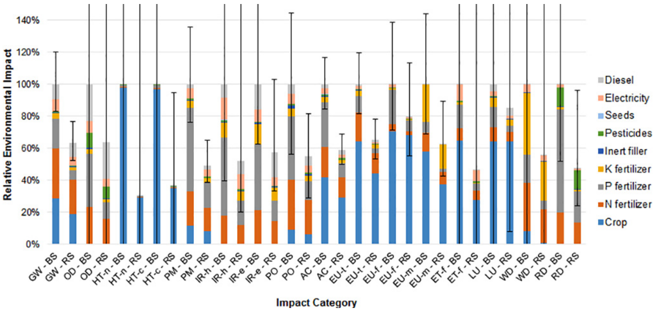

Fig. 5. Comparison of the environmental impact contributions of BS and RS carrot production including background and foreground parameter uncertainties, cradle-to-gate. Acronyms: global warming (GW), ozone depletion (OD), human toxicity, non-cancer effects (HT-n), human toxicity, cancer effects (HT-c), particulate matter (PM), ionizing radiation to humans (IR-h), ionizing radiation to ecosystem (IR-e), photochemical ozone formation (PO), acidification (AC), terrestrial eutrophication (EU-t), freshwater eutrophication (EU-f), marine eutrophication (EU-m), freshwater ecotoxicity (ET-f), land use (LU), water resource depletion (WD), mineral, fossil and renewable resource depletion (RD).

3.2.3. Life cycle impact assessment

Fig. 5 shows the environmental impacts of BS and RS production system. The BS production system is more striking than the RS in all the environmental categories evaluated (Fig. 5). The data of Fig. 5 show that there was a significant difference between BS and RS for the following categories: global warming (GW), particulate matter (PM), acidification (AC) and terrestrial eutrophication (EU-t). In relation to the other categories, there was no significant difference between BS and RS (Fig. A.1). Therefore, RS presented greater environmental benefits compared to BS, and better environmental performance based on the potential environmental impacts analyzed. Field emissions stood out in the categories non-cancer effects (HT-n), cancer effects (HT-c), terrestrial eutrophication (EU-t), freshwater eutrophication (EU-f), marine eutrophication (EU-m), freshwater ecotoxicity (EF-t) and land use (LU). The production of fertilizers stood at global warming, ozone depletion (OD), particulate matter, ionizing radiation to humans (IR-h), ionizing radiation to ecosystem (IR-e), photochemical ozone formation (PO), acidification, water resource depletion (WD) and mineral, fossil and renewable resource depletion (RD) categories. The low impact observed for the carrot production in water resource depletion, in field is attributed to increased water infiltration and thus less evaporation. Other production inputs such as pesticides, seeds, electricity and tractor diesel had little representativeness in the assessed impact categories of BS and RS.

The black bars show the uncertainty with 95% confidence interval and the absolute results are presented in Tables A.6 and A.7. The parameter uncertainty of LCI database increases the total uncertainty of the LCIA results significantly (Fig. A.2), then the upper limit of OD, HT-n, HT-c, IR-h, IR-e, ET-f, LU, WD, RD categories are not completely visible in Fig. 5. If no uncertainty of upstream processes from LCI database were considered, the discernibility of environmental impacts of BS would be even higher than RS (Fig. A.3).

Table 4 presents carrot GW available in literature. This category was chosen because it is a global impact category. Out of twenty impacts on GW of carrots presented in Table 4, the organic carrot cultivated in Finland had the lowest impact. In the production of Finnish organic carrots, cattle manure and leguminous plants serve

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[6] Mixing or fertilizer formula is expressed in percentage of nitrogen, phosphorus, and potassium, representing, respectively, the minimum guaranteed formulas total nitrogen (expressed as N), soluble phosphorus (expressed as P_2O_5) and soluble potassium (expressed as K_2O).

Table 4
Comparison of carrot global warming impact from cradle-to-gate of the farm.

Source	kg CO_2 eq/kg product	Country
LCA food Denmark (2006)		
Conventional	0.058	Denmark
Organic	0.110	Denmark
Ecoinvent® 3.2 (Stoessel et al., 2012)		
Carrot 335	0.348	Global
Paris	0.067	Global
Röös and Karlsson (2013)		
Conventional[a]	0.110	Sweden
Conventional[a]	0.230	Sweden from Netherlands
Conventional[a]	0.310	Sweden from Italy
Raghu (2014)		
Organic[a,b]	0.004	Finland
Conventional[a,b]	0.142	Finland
Conventional, imported[a,b]	0.280	Finland from Italy
Agri-footprint (2015)		
Conventional	0.091	Netherlands
Conventional	0.068	Belgium
Agribalyse® (Koch and Salou, 2015)		
Conventional	0.067	France
Organic	0.060	France
World Food (Nemecek et al., 2015)		
Conventional	0.171	China
Conventional	0.155	Israel
Conventional	0.092	Netherlands
Conventional	0.186	Rest of World
This study		
Conventional	0.121	Brazil (BS)
Conventional with CP	0.076	Brazil (RS)

[a] These product life cycles covered from cradle-to-gate of the market.
[b] These product life cycles included packaging.
Source: IPCC (2007) 100 years method.

as a source of nitrogen, which generates silage as a co-product and contributes to the storage of carbon in the soil. If no carbon sequestration were considered, the Finnish organic carrot would have more impact than the conventional one. According to Raghu (2014), the Danish organic carrot had a larger impact than conventional carrot cultivation as there is no product avoided or carbon sequestration. The Brazilian carrot produced in the Irecê region improved the global warming impact from twelfth (BS) to seventh (RS) lowest impact. This means that other actions should be implemented in order to keep lowering the GW of Brazilian carrot.

In the absence of carrot LCA studies in Brazil, we compared the results with other Brazilian agriculture products from the semi-arid region. In the BS system, water is consumed at a rate of 170 L (kg year)$^{-1}$. This is close to the 198 L of water to produce and export 1 kg of melon in the Brazilian semi-arid region (Figueirêdo et al., 2014). The adoption of the control measures suggested for water leads to a reduction in electricity consumption, resulting in environmental and economic gains for the farmer. For other crops such as peanuts, 90% of the impact on water resource depletion occurs in the field (Ridoutt and Pfister, 2010), unlike in the case of BS and RS.

The global warming of BS and RS (Figs. A1, A2 and A.3) were 0.12 and 0.07 kg CO_2-eq kg^{-1} of the product, respectively. As in Figueirêdo et al. (2016), the best way to improve the environmental performance of irrigated carrot production in the Brazilian semi-arid region is to adjust the BS by modifying the fertilization. The production and use of fertilizers and pesticides are responsible for the largest impacts of BS. As noted by Figueirêdo et al. (2016), further improvements in green manuring and efficiency of fertilization contribute to minimizing nutrient loss.

4. Conclusions

The study showed that application of CP strategies can give significant contribution to the reduction of environmental impacts in carrot production in the conditions observed in Irecê region, karstic area in northeastern semi-arid Brazil. Reduction in the environmental categories considered in this LCA work was between 15% and 70%. It was estimated that the recommended scenario is capable of reducing greenhouse gas emissions from 0.12 kg to 0.07 kg CO_2 eq/kg of carrot produced with the implementation of simple CP options, at low or no cost, with only operational changes. However, other CP measures that present environmental and economic gains need to be better analyzed as they involve medium and long term investments. The CP selected opportunities could lead to a 49% reduction in the total cost of inputs and the costs of implementing these measures could be recovered in only one production cycle. It can be considered that further opportunities, involving higher investment costs, may give significant contributions to achieve better economic and environmental results.

The carrot is a perishable product with high price volatility therefore the proposed solutions should ensure an improvement in productivity. The study results demonstrate the low economic and environmental efficiency of the production of carrots, as practiced today in studied farm, resulting in economic losses and a strong pressure on natural resources. However, CP and LCA tools can help the environmental management and cost reduction in agricultural production and support a bio-economy aimed at accelerating the transition towards equitable, sustainable, post fossil-carbon societies. For future work, we recommend the use of regionalized background data, as well as impact assessment models to reduce uncertainty in the results of environmental impact and facilitate decision making.

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Appendix A

Table A.1
Estimated water consumption for irrigation.

The water demand required by the RS production system was based on technical factors and indications for simplified management of carrot irrigation. Temperature data and Irecê precipitation from the Institute of Environment and Water Resources (INEMA, 2014) were used to calculate the reference evapotranspiration (*ETo* [mm/month]) using the Blaney-Criddle method (Eq. (1).

$$ETo = ((0.46 * T) + 8.13) * P \tag{1}$$

where *T* is the average temperature and *P* is the mean daily percentage of annual daytime hours.

The calculation of crop evapotranspiration (*ETc* [mm/month]) used the *ETo* and the crop coefficient (*Kc*) (Eq. (2)) (Marouelli et al., 2007), each cultivation stage (Table A.1.1).

$$ETc = ETo * Kc \tag{2}$$

The real amount of water (*LRN* [mm]) needed for irrigation was calculated using Eq. (3). The irrigation interval (*IR* [days]) was calculated based on *Kc*, soil texture and depth of the roots (Marouelli et al., 2001; 2007).

(*continued on next page*)

Table A.1 (*continued*)

$$LRN = ETc*IR \tag{3}$$

A 65% efficiency (*Ei*) was adopted for the calculation of the total water required for irrigation blade (*LTN* [mm]) (Eq. (4)) (Marouelli et al., 2007). The requested leaching fraction (*LR*) depends on the electrical conductivity of water (Marouelli et al., 2007). Unaware of the electrical conductivity of the water used LR was disregarded.

$$LTN = 100*LRN/(Ei*(1 - LR)) \tag{4}$$

Irrigation time (*Ti* [i]) was calculated based on *LTN* and water application intensity (*Ia* [mm/h]) (Eq. (5)). The *Ia* was calculated based on the flow of issuers and their spacing. The calculation of Ti considered the duration of each growth phase of the carrot, Table A.1.2.

$$Ti = 60*LTN/Ia \tag{5}$$

The water index (*IH*) for the town of Irecê was calculated according to the method of Thornthwaite and Mather (1955) where *EXC* is the water surplus, *DEF* is the water deficit and *ETP* is the potential evapotranspiration. (Eq. (6)).

$$IH = \frac{100*EXC - 60*DEF}{ETP} \tag{6}$$

Table A.1.1
Crop coefficient (Kc) for the different development stages of carrots, cultivated under sprinkler irrigation system.

Stage	Kc	Length of each stage (days)
Initial	0.95–1.05	25–35
Vegetative	0.95–1.05	20–25
Root thickening	1.05–1.15	25–35
Finalization	0.95–1.10	15–25

Table A.1.2
Total irrigation time registered and total irrigation time required by season, according to Embrapa (2014).

Operation	Irrigation time by season (h)					
	Current practice base scenario			Embrapa's Recommendation		
	1st	2nd	3rd	1st	2nd	3rd
Pre-sowing irrigation	5	5	5	0.44–0.48	0.39–0.43	0.40–0.44
Irrigation – germination	30	30	30	0.88–0.97	0.78–0.86	0.80–0.88
Irrigation – growth	160	160	160	15.73–17.23	14.03–15.37	7.50–17.60
Irrigation – finalization	120	120	120	9.42–10.91	11.55–10.70	10.68–12.37

Source: Marouelli et al. (2007, 1996).

Table A.2
Pesticides used in the carrot crop, brand and active ingredient.

Pesticides	Unit or concentration	Purpose	BS	RS
Ridomil Gold MZ (Acililalaninato/Dithiocarbamate Group)[a]	kg	Fungicide	6.00	6.00
Mancozeb	640 g kg^{-1}		3.84	3.84
Metalaxyl-M	40 g kg^{-1}		0.24	0.24
Amistar Top (Estrobilurina-Triazol Group)[b]	L	Fungicide	3.00	1.80
Azoxystrobin	200 g L^{-1}		0.60	0.36
Difenoconazole	125 g L^{-1}		0.38	0.23
Afalon (Urea Group)[c]	L	Herbicide	6.00	4.80
Linuron	450 g L^{-1}		2.70	2.16
Karate Zeon 50 CS (Pyrethroid Group)[d]	L	Insecticide	3.00	3.00
Lambda-cyhalothrin	100 g L^{-1}		0.30	0.30
Engeo Pleno (Neonicotinoid and Pyrethroid)[e]	L	Insecticide	0.75	0.75
Thiamethoxam	141 g L^{-1}		0.11	0.11
Lambda-cyhalothrin	106 g L^{-1}		0.08	0.08
Lannate BR (Oximebmethyl carbamate)[f]	L	Insecticide	2.25	2.25
Methomyl	215 g L^{-1}		0.48	0.48

[a] http://www3.syngenta.com/country/pt/pt/produtos/Documents/rotulo/rotulo-ridomil-gold-mz-pepite.pdf (accessed 19.05.16).
[b] http://www3.syngenta.com/country/br/pt/produtosemarcas/controle-de-pragas-urbanas-e-de-jardim/produtos/Pages/AmistarTop.aspx (accessed 19.05.16).
[c] http://www.adapar.pr.gov.br/arquivos/File/defis/DFI/Bulas/Herbicidas/afalonsc__1.pdf (accessed 19.05.16).
[d] http://www3.syngenta.com/country/pt/pt/produtos/Proteccao_de_culturas/Insecticidas/Pages/KarateZeon.aspx (accessed 19.05.16).
[e] http://www.servicos.syngenta.com.br/PRODUTOS/ProductDetails.aspx?idProduct=2286 (accessed 19.05.16).
[f] http://www.dupont.com.br/content/dam/assets/products-and-services/crop-protection/assets/pt_BR/LannateBR_Bula.pdf (accessed 19.05.16).

Table A.3
Emissions from agriculture are based on Nemecek and Schnetzer (2012) report.

Emissions	Base scenario (BS)	Recommended scenario (RS)
Ammonia (NH_3) - Air		
We used AGRAMMON model with the global geographic scope of application.		
In our case study there was no application of organic fertilizer in the field (i.e. compost, manure, etc.). The NH_3 emissions from applied mineral fertilizers are calculated by constant emission factors for each group of fertilizer based on Table 2.6 of Nemecek and Schnetzer (2012),		
$N = A*E$		
where:		
N = emission NH_3-N [kg N (ha year)$^{-1}$]	17.56	12.17
A = amount of nitrogen mineral fertilizer [kg N (ha year)$^{-1}$]	365.05	250.65
E = emission factor of 4% to multinutrient fertilizers (NPK fertilizers).	4.00%	4.00%
Nitrate (NO_3) - Ground Water		
We used SQCB-NO_3 model,		
$N = 21.37+[P/(c*L)]*[(0.0037*S)+(0.0000601*N_{org})-(0.00362*U))]$		
where:		
N = leached NO_3 - N [kg N (ha year)$^{-1}$]	2637.42	1437.10
P = precipitation + irrigation [mm year]	2542.40	1935.94
c = clay content [%]	16.92	16.92
L = rooting depth [m]	0.35	0.35
S = nitrogen supply through fertilizers [kg N ha^{-1}]	365.05	250.65
N_{org} = nitrogen in organic matter [kg N ha^{-1}]	4816.67	4816.67
U = nitrogen uptake by crop [kg N ha^{-1}]	80.00	80.00
and N_{org} is calculated by the formula,		
$N_{org} = [(C_{org}/100)*V*Db]/(rC/N*rN_{org})$		
where:		
C_{org} = carbon content [%]	0.87	0.87
V = soil volume [m^3 ha^{-1}]	5000.00	5000.00
Db = bulk density [kg (m^3)$^{-1}$]	1300.00	1300.00
rC/N = C/N ratio [dimensionless]	10.00	10.00
rN_{org} = ratio of N_{org} to N_{tot} (total soil nitrogen) [dimensionless]	0.85	0.85
Phosphate (PO_4^{3-}) - Ground Water		
P leaching to the ground water was estimated as an average leaching, corrected by P-fertilization,		
$Pgw = Pgwl*Fgw$		
where:		
Pgw = quantity of P leached to ground water [kg (ha year)$^{-1}$]	0.07	0.07
Pgwl = average quantity of P leached to ground water for a land use category [kg (ha year)$^{-1}$]	0.07	0.07
Fgw = correction factor for fertilization by slurry (dimensionless)	1.00	1.00
Nitrous Oxides (N_2O) − Air		
Calculations of N_2O emissions are based on the IPCC method. Direct emissions of N_2O and indirect or induced emissions are included. In the case of indirect N_2O emission, nitrogen is first emitted as NH_3 or NO_3^- and subsequently converted to N_2O,		
$N_2O = 44/28*(0.01(Ntot + Ncr)+0.01*14/17*NH_3+0.0075*14/62*NO_3^-)$		
where:		
N_2O = emission of N_2O [kg N_2O ha^{-1}]	12.93	7.92
N_{tot} = total nitrogen in mineral and organic fertilizers [kg N ha^{-1}]	365.05	250.65
N_{cr} = nitrogen contained in the crop residues [kg N ha^{-1}]	0.00	0.00
NH_3 = losses of nitrogen in the form of ammonia [kg NH_3 ha^{-1}]	17.56	12.17
NO_3^- = losses of nitrogen in the form of nitrate [kg NO_3^- ha^{-1}].	2637.43	1437.10
Nitrogen oxides (NOx) - Air		
During denitrification processes in soils, nitrous oxide (NOx) may also be produced. These emissions were estimated from the emissions of N_2O,		
$NOx = 0.21*N_2O$		
where:		
NOx = emission of NOx [kg NOx ha^{-1}]	2.71	1.66
N_2O = emission of N_2O [kg N_2O ha^{-1}]	12.93	7.92
Nutrient Inputs in Agricultural Soils	–	–
This data is presented in the manuscript method and result sections.		
Release of Fossil CO_2 after Urea Applications	–	–
The N source of the fertilizer is ammonium nitrate, so this is not applicable.		
Heavy Metals to Agricultural Soil, Surface Water and Ground Water		
The heavy metal emissions were calculated by SALCA-heavy metal for Cadmium (Cd), Chromium (Cr), Lead (Pb) and Mercury (Hg). Heavy metal emissions into ground and surface water (in case of drainage) are calculated with constant leaching rates as,		
$Mleach_i = mleach_i*A_i$		
$Mleach_i$ = agricultural related heavy metal i emission [mg (ha year)$^{-1}$]	Cd = 49.93; Cr = 21,184.84; Pb = 595.63 and Hg = 1.29	Cd = 49.80; Cr = 21,154.94; Pb = 587.18 and Hg = 1.27
$mleach_i$ = average amount of heavy metal emission [mg (ha.year)$^{-1}$]	Cd = 50.00; Cr = 21,200.00; Pb = 600.00 and Hg = 1.30	Cd = 50.00; Cr = 21,200.00; Pb = 600.00 and Hg = 1.30
$A_i = Magro_i/(Magro_i + Mdeposition_i)$		

(continued on next page)

Table A.3 (*continued*)

Emissions	Base scenario (BS)	Recommended scenario (RS)
where:		
A_i = allocation factor for the share of agricultural inputs in the total inputs for heavy metal i	Cd = 1.00; Cr = 1.00; Pb = 0.99 and Hg = 0.99	Cd = 1.00; Cr = 1.00; Pb = 0.98 and Hg = 0.98
$Magro_i$[a] = total input of heavy metal from fertilizers of agricultural production [mg (ha year)$^{-1}$]	Cd = 510,000.00; Cr = 5,100,000.00; Pb = 2,550,000.00 and Hg = 6307.50	Cd = 171,347.00; Cr = 1,713,470.00; Pb = 856,735.00 and Hg = 2081.87
$Mdeposition_i$ = total input of heavy metal from atmospheric deposition [mg (ha year)$^{-1}$]	Cd = 700.00; Cr = 3650.00; Pb = 18,700.00 and Hg = 50.00	Cd = 700.00; Cr = 3650.00; Pb = 18,700.00 and Hg = 50.00
Heavy metal emissions through erosion (surface water) are calculated as follows,		
$Merosion_i = ctot_i{*}B{*}a{*}ferosion{*}A_i$		
where:		
$Merosion_i$ = agricultural related heavy metal emissions through erosion [mg (ha year)$^{-1}$]	Cd = 2851.19; Cr = 223,040.37; Pb = 229,884.18 and Hg = 710.47	Cd = 2843.48; Cr = 222,725.55; Pb = 226,623.48 and Hg = 699.30
$ctot_i$ = total heavy metal content in the soil [mg kg^{-1}]	Cd = 0.00; Cr = 0.03; Pb = 0.02 and Hg = 0.00	Cd = 0.00; Cr = 0.03; Pb = 0.02 and Hg = 0.00
B = amount of soil erosion [kg (ha year)$^{-1}$]	Cd = 25,000.00; Cr = 25,000.00; Pb = 25,000.00 and Hg = 25,000.00	Cd = 25,000.00; Cr = 25,000.00; Pb = 25,000.00 and Hg = 25,000.00
a = accumulation factor 1.86 [dimensionless]	Cd = 1.86; Cr = 1.86; Pb = 1.86 and Hg = 1.86	Cd = 1.86; Cr = 1.86; Pb = 1.86 and Hg = 1.86
ferosion = erosion factor 0.2 [dimensionless]	Cd = 0.20; Cr = 0.20; Pb = 0.20 and Hg = 0.20	Cd = 0.20; Cr = 0.20; Pb = 0.20 and Hg = 0.20
A_i = allocation factor (calculated for heavy metals to ground water) [dimensionless]	Cd = 1.00; Cr = 1.00; Pb = 0.99 and Hg = 0.99	Cd = 1.00; Cr = 1.00; Pb = 0.98 and Hg = 0.98
The balance of all inputs into the soil (fertilizers, pesticides, seed and deposition) and outputs from the soil (exported biomass, leaching and erosion), multiplied by the allocation factor is calculated as an emission to agricultural soil ($Msoil_i$ [mg (ha year)$^{-1}$]).	Cd = 507,102.76; Cr = 4,855,948.90; Pb = 2,321,197.53 and Hg = 5601.30	Cd = 168,465.39; Cr = 1,470,107.37; Pb = 643,377.21 and Hg = 1397.69
$Msoil_i = (\Sigma\ inputs_i - \Sigma\ outputs_i){*}A_i$		
Arsenic (As) emissions were considered going to the soil by the lack of a specific estimation model [mg (ha year) $^{-1}$].	225,000.00	85,673.50
Pesticides to Agricultural Soil	–	–
All pesticides applied for crop production were assumed to end up as emissions to the soil.		
Carbon dioxide (CO_2) - from the Air	–	–
The CO_2 from the atmosphere used for photosynthesis was not considered, as it is assumed to be released in a short period of time with no actual carbon sequestration.		
Land Use	–	–
It was considered “occupation, an annual crop, irrigated, intensive” in the study. The land transformation was not considered as there is not enough information about the previous uses of the land.		

[a] For each fertilizer analyzed, the concentration of heavy metals reported by the manufacturer *Heringer* was considered document sent to the authors).

Table A.4
Cost of inputs in BS and RS carrot production systems.

Priced inputs	Amount			Cost (USD)		
	BS	RS	Environmental benefit	BS	RS	Annual savings
CP selected opportunities						
Reduction in excessive fertilizer	3765.00	1936.15	1828.85	1752.45	810.28	942.18
Fertilizer NPK 10-50-00 (kg)	2415.00	736.80	1678.20	1279.95	390.50	889.45
Fertilizer NPK 20-00-20 (kg)	600.00	884.85	−284.85	210.00	309.70	−99.70
Fertilizer NPK 00-00-60 (kg)	750.00	314.50	435.50	262.50	110.08	152.43
Reduction in excessive seeds	24.15	7.50	16.65	1412.29	438.60	973.69
Carrot seed (kg)	24.15	7.50	16.65	1412.29	438.60	973.69
Irrigation based on water balance						
Reduction in excessive water	18,900.00	12,835.44	6080.06	–	–	–
Ground water (m^3)	18,900.00	12,835.44	6080.06	–	–	–
Reduction in excessive electricity	3822.75	2594.03	1228.72	382.28	259.40	122.87
Electricity, low voltage (kWh)	3822.75	2594.03	1228.72	382.28	259.40	122.87
Reduction in excessive pesticides	21.00	18.60	2.40	551.98	463.56	88.42
Herbicide *Afalon* (L)	6.00	4.80	1.20	122.82	98.26	24.56
Fungicide *Ridomil Gold MZ* (kg)	6.00	6.00	–	171.90	171.90	
Fungicide *Amistar Top* (L)	3.00	1.80	1.20	159.66	95.80	63.86
Insecticide *Karate Zeon 50 CS* (L)	3.00	3.00	–	50.01	50.01	–
Insecticide *Lannate BR* (L)	2.25	2.25	–	16.45	16.45	–
Insecticide *Engeo Pleno* (L)	0.75	0.75	–	31.14	31.14	–
Remaining inputs	286.14	286.14	–	228.91	228.91	–
Diesel (L)						
Total				4327.91	1973.88	2354.03

Table A.5
Chemical soil analysis results of the study area.

Local	Water pH	P mg/dm^3	K mg/dm^3	Ca cmol$_c$/dm^3	Mg cmol$_c$/dm^3	Ca + Mg cmol$_c$/dm^3	Al cmol$_c$/dm^3	Na cmol$_c$/dm^3	M_O g/kg
Study area	6.5	8.0	172.0	12.0	2.2	14.1	0.0	0.0	17.0

Table A.6
Life cycle impact results of base scenario (BS), cradle-to-gate.

Impact category	Unit	Total	Confidence interval (95%)		Contribution per process								
			2.5%	97.5%	Crop	N fertilizer	P fertilizer	K fertilizer	Inert filler	Pesticides	Seeds	Electricity	Tractor
GW	kg CO_2 eq	1.19E−01	1.01E-01	1.45E-01	3.47E−02	3.79E−02	2.26E−02	3.95E−03	5.77E−04	6.85E−04	5.49E−05	9.53E−03	1.11E−02
OD	kg CFC-11 eq	8.73E−09	−2.27E−09	2.16E-08	0.00E+00	2.06E−09	2.86E−09	2.67E−10	9.58E−11	8.04E−10	7.06E−12	6.31E−10	2.01E−09
HT-n	CTUh	1.36E−06	-1.36E-05	1.68E-05	1.33E−06	6.92E−09	1.50E−08	1.30E−09	1.48E−10	9.63E−10	3.20E−10	2.72E−09	4.14E−10
HT-c	CTUh	1.40E−07	4.53E-09	2.80E-07	1.36E−07	9.81E−10	2.76E−09	1.63E−10	2.55E−11	3.40E−11	3.41E−12	3.57E−10	8.57E−11
PM	kg $PM_{2.5}$ eq	9.17E−05	7.01E-05	1.25E-04	1.07E−05	1.95E−05	4.81E−05	3.78E−06	4.60E−07	1.05E−06	4.46E−08	5.62E−06	2.45E−06
IR-h	kBq U_{235} eq	9.16E−03	3.62E-03	2.98E-02	0.00E+00	1.65E−03	4.46E−03	8.45E−04	5.85E−05	1.00E−04	4.07E−06	1.26E−03	7.82E−04
IR-e	CTUe	3.24E−08	2.03E-08	5.49E-08	0.00E+00	7.01E−09	1.32E−08	4.13E−09	2.74E−10	2.70E−10	1.83E−11	2.54E−09	5.01E−09
PO	kg NMVOC eq	2.63E−04	1.48E-04	3.81E-04	2.44E−05	8.26E−05	1.03E−04	1.30E−05	4.76E−06	3.06E−06	3.17E−07	1.69E−05	1.52E−05
AC	molc H^+ eq	1.18E−03	9.98E-04	1.38E-03	4.96E−04	2.20E−04	3.31E−04	3.74E−05	5.70E−06	1.40E−05	9.05E−07	4.07E−05	3.17E−05
EU-t	molc N eq	3.49E−03	2.85E-03	4.17E-03	2.24E−03	6.43E−04	3.62E−04	1.14E−04	1.72E−05	8.70E−06	3.60E−06	6.55E−05	4.09E−05
EU-f	kg P eq	1.22E−04	8.71E-05	1.69E-04	8.66E−05	5.07E−06	2.64E−05	1.10E−06	7.66E−08	3.24E−07	1.07E−08	2.44E−06	2.97E−07
EU-m	kg N eq	9.26E−03	6.38E-03	1.33E-02	5.39E−03	1.08E−03	6.24E−04	2.15E−03	1.79E−06	2.11E−06	3.64E−07	8.38E−06	4.29E−06
ET-f	CTUe	3.22E+00	-2.02E+01	2.73E+01	2.09E+00	2.57E−01	4.69E−01	3.78E−02	4.62E−03	2.59E−02	2.57E−03	3.26E−01	1.02E−02
LU	kg C deficit	5.59E−01	-1.46E-01	1.27E+00	3.60E−01	4.88E−02	7.10E−02	3.23E−02	3.46E−03	9.23E−04	4.64E−04	1.63E−02	2.57E−02
WD	m^3 water eq	3.53E−04	-1.84E-02	1.95E-02	2.85E−05	1.08E−04	6.06E−05	1.36E−04	2.87E−06	−8.86E−08	−2.04E−08	1.67E−05	2.54E−07
RD	kg Sb eq	1.04E−05	5.38E-06	2.04E-05	0.00E+00	2.08E−06	6.68E−06	1.68E−07	3.25E−08	1.23E−06	5.13E−09	1.70E−07	3.19E−08

Table A.7
Life cycle impact results of recommended scenario (RS), cradle-to-gate.

Impact category	Unit	Total	Confidence interval (95%)		Contribution per process								
			2.5%	97.5%	Crop	N fertilizer	P fertilizer	K fertilizer	Inert filler	Pesticides	Seeds	Electricity	Tractor
GW	kg CO_2 eq	7.69E-02	6.35E-02	9.27E-02	2.31E−02	2.60E−02	6.88E−03	2.53E−03	3.38E−04	5.76E-04	1.71E−05	6.47E-03	1.11E−02
OD	kg CFC-11 eq	5.58E-09	-1.56E-09	1.37E-08	0.00E+00	1.41E−09	8.71E−10	1.71E−10	5.61E−11	6.39E−10	2.19E−12	4.28E-10	2.01E−09
HT-n	CTUh	4.14E-07	-9.06E-06	9.86E-06	4.00E-07	4.75E−09	4.58E−09	8.29E−10	8.68E−11	9.30E−10	9.93E−11	1.84E-09	4.14E−10
HT-c	CTUh	5.13E-08	-3.01E-08	1.33E-07	4.93E−08	6.74E−10	8.39E−10	1.04E−10	1.49E−11	2.89E−11	1.06E−12	2.43E-10	8.57E−11
PM	kg $PM_{2.5}$ eq	4.53E-05	3.56E-05	5.96E-05	7.43E-06	1.34E−05	1.46E−05	2.42E−06	2.69E−07	9.10E-07	1.39E−08	3.81E-06	2.45E−06
IR-h	kBq U_{235} eq	4.79E-03	1.84E-03	1.44E-02	0.00E+00	1.14E−03	1.36E−03	5.40E−04	3.42E−05	8.56E−05	1.26E−06	8.53E-04	7.82E−04
IR-e	CTUe	1.86E-08	1.08E-08	3.34E-08	0.00E+00	4.82E−09	4.01E−09	2.64E-09	1.60E−10	2.31E−10	5.67E−12	1.72E-09	5.01E−09
PO	kg NMVOC eq	1.45E-04	7.63E-05	2.15E-04	1.62E−05	5.67E−05	3.13E−05	8.28E−06	2.78E−06	2.59E−06	9.83E−08	1.14E-05	1.52E−05
AC	molc H^+ eq	6.94E-04	5.90E-04	8.11E-04	3.43E−04	1.51E−04	1.01E−04	2.39E−05	3.33E−06	1.22E−05	2.81E−07	2.76E-05	3.17E−05
EU-t	molc N eq	2.28E-03	1.87E-03	2.73E-03	1.55E-03	4.41E−04	1.10E−04	7.28E−05	1.01E−05	7.34E-06	1.12E-06	4.44E-05	4.09E−05
EU-f	kg P eq	9.78E-05	6.74E-05	1.39E-04	8.33E-05	3.48E−06	8.04E−06	7.03E−07	4.48E−08	2.72E−07	3.32E−09	1.66E-06	2.97E−07
EU-m	kg N eq	5.77E−03	3.95E-03	8.30E-03	3.46E−03	7.40E−04	1.90E−04	1.38E−03	1.05E−06	1.77E−06	1.13E−07	5.69E-06	4.29E−06
ET-f	CTUe	1.50E+00	-1.32E+01	1.62E+01	9.00E-01	1.77E−01	1.43E−01	2.42E−02	2.70E−03	2.45E−02	7.99E−04	2.21E-01	1.02E−02
LU	kg C deficit	4.76E-01	4.51E-02	9.15E-01	3.60E−01	3.35E−02	2.16E−02	2.07E−02	2.02E−03	7.98E-04	1.44E−04	1.10E-02	2.57E−02
WD	m^3 water eq	1.96E-04	-7.50E-03	8.05E-03	3.46E−06	7.42E−05	1.84E−05	8.69E−05	1.68E−06	4.56E-08	−6.33E−09	1.13E-05	2.54E−07
RD	kg Sb eq	4.96E-06	2.49E-06	1.00E-05	0.00E+00	1.43E−06	2.03E−06	1.07E−07	1.90E−08	1.22E−06	1.59E−09	1.16E-07	3.19E−08

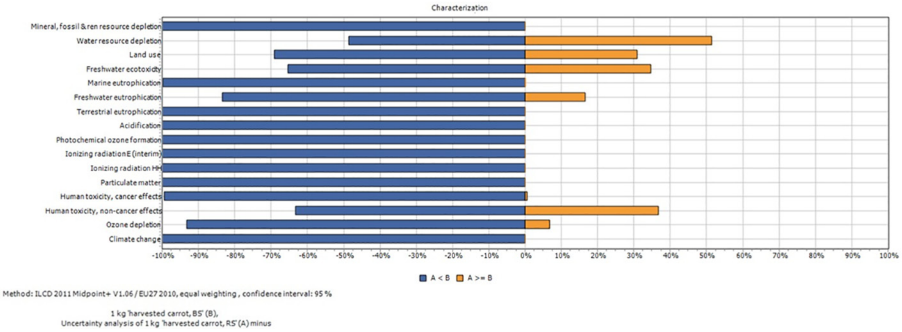

Fig. A.1. Comparative life cycle impact results of base scenario (BS) and recommended scenario (RS) including background and foreground parameter uncertainties, cradle-to-gate.

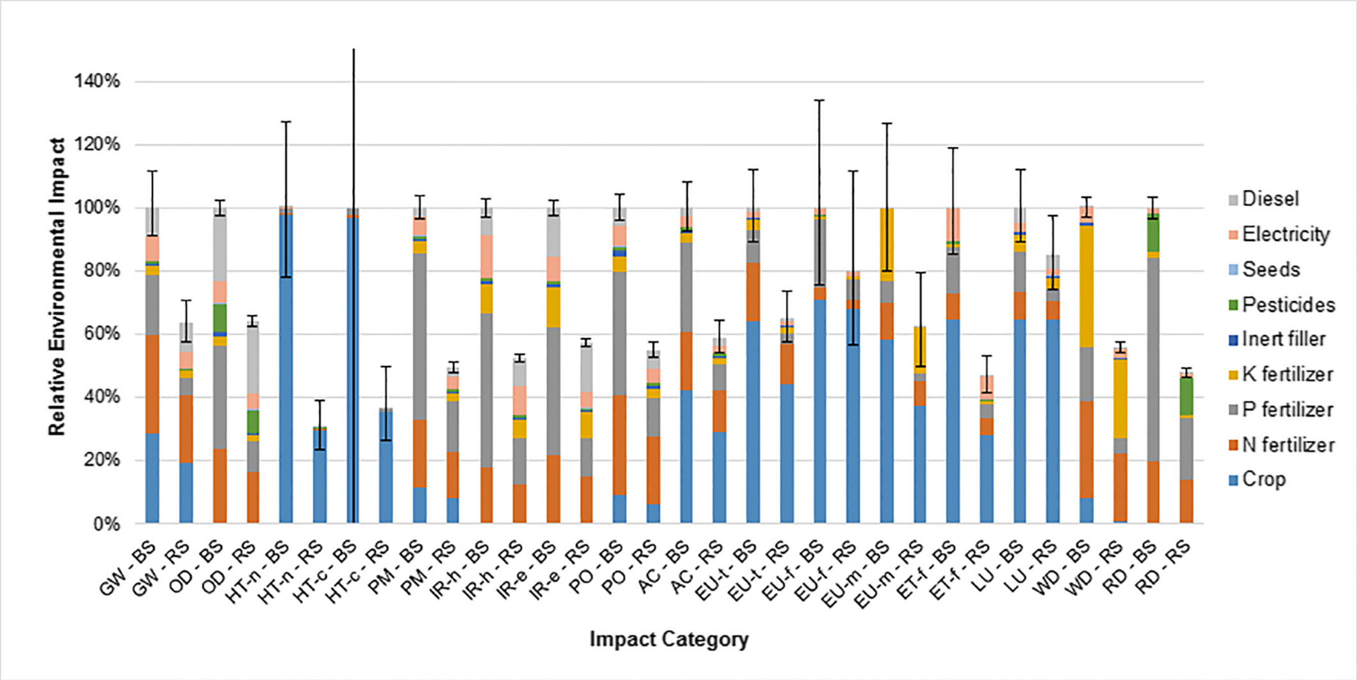

Fig. A.2. Comparison of the environmental impacts of BS and RS carrot production including background and only foreground parameter uncertainties, cradle-to-gate.

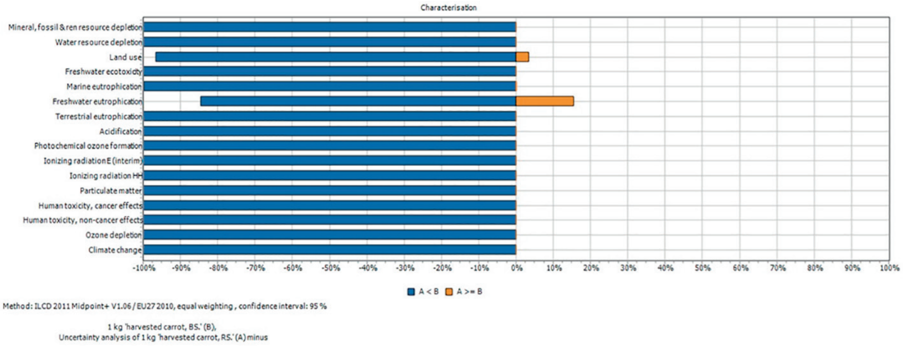

Fig. A.3. Comparative life cycle impact results of base scenario (BS) and recommended scenario (RS) including background and foreground parameter uncertainties, cradle-to-gate.

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