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Faculteit Bedrijfseconomische Wetenschappen

master handelsingenieur

Masterthesis

Environmental comparison of chicory (Cichorium intybus var. foliosum) root cultivation methods by means of an LCA

Alicja Plevoets

Scriptie ingediend tot het behalen van de graad van master handelsingenieur, afstudeerrichting technologie in business

PROMOTOR :
Prof. dr. Sebastien LIZIN

COPROMOTOR :
dr. Freddy NAVARRO PINEDA

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Abstract

As sustainability is becoming more important in our daily life, it is useful to determine the environmental impact of products, processes and services we use and consume. Life cycle assessment (LCA) can be used to calculate the environmental burden of a product or process. To date, an estimation of the environmental impact of chicory (Cichorium intybus var. foliosum) root cultivation, an important export product in Belgium, has not yet been conducted. The emergence of new technologies in agriculture, resulting from the smart farming evolution, enables significant environmental benefits in agricultural systems. The Institution for Agriculture, Fishery and Food Research (ILVO) has developed an electric agro-robotic that can be used for mechanical weeding in the cultivation of chicory roots. The principal aim of this study is to compare the environmental burden of two chicory root cultivation methods, the traditional cultivation process and the modification of this process by introducing the agro-robotic developed by ILVO. The comparison between the cultivation methods shows the potential of the robot for chicory root cultivation in Belgium.

An LCA was executed based on the ISO 14040 and 14044 guidelines with a cradle-to-gate approach. The functional unit for this LCA is the production of 1 ton chicory roots, ready for storage or forcing. The data used in the life cycle inventory is based on quantitative interviews to determine the input values used and the activities executed in the cultivation process. SimaPro 9.3, a life cycle assessment software, was used to calculate the resulting environmental impacts and emissions. The impact assessment was conducted based on the CML-IA baseline- and ReCiPe midpoint (h) method. Land preparation, fertilisation and crop nurturing have the largest environmental impacts in traditional cultivation. The introduction of the electric agro-robotic has a positive effect on all impact categories. The robot has the largest, positive, effect on impact categories regarding human health. The study showed that the robot has the ability to create a more sustainable production process. There are still environmental burdens in the new cultivation process but significantly less than in the traditional cultivation method. Multiple assumptions were made in the research regarding the use of the robot, as it is still under development. Further research using real-world data in the future should be compared with the results of this research. The use of the robot results in environmental benefits for the chicory cultivation process, but more innovation is needed to create environmental neutral processes in chicory farming.

Keywords: Life cycle assessment (LCA), chicory root cultivation, smart farming, precision farming, electric unmanned vehicle, electric agro-robotic

1. Introduction

The importance of agriculture is expected to grow as the world population is increasing and will reach 9.9 billion people by 2050. The agricultural industry is pressured to answer to the population's increasing food demand within the planet's natural boundaries. Governments are taking action to enforce more sustainability in agricultural systems through different goals and objectives such as the Green Deal or the Sustainable Development Goals (SDG) (Cleland, 2013; EU, 2015; Ofori & El-Gayar, 2020; UN, n.d.; Wang, Wang, Wang, Li, & Wu, 2019). Simultaneously, agriculture is facing pressure from society. Society demands healthy produced food, taking environmental sustainability into account. Agriculture plays a key role to achieve food security while decreasing its environmental impact (Brown, Schirmer, & Upton, 2021). Farmers have to find alternative ways to produce healthy products, using environmentally neutral processes. They can go beyond environmental neutral processes by using production methods that restore the damage to the environment and biodiversity (Brentrup, Küsters, Kuhlmann, & Lammel, 2004; Brown, Schirmer, & Upton, 2021).

Farmers also have to actively search for and implement new production methods to keep their competitive advantage (Keating et al., 2010). As such they have to increase the quantity and quality of the produced crops using fewer inputs such as water, land, nutrients, energy, labour and capital (Steenwerth et al., 2014). One way to tackle this problem is the optimization of agricultural vehicles to decrease labour costs, which led to the usage of heavier, bigger and more expensive machinery. However, this resulted in increased fuel consumption and compact soils, thus causing productivity losses (Balafoutis, Evert, & Fountas, 2020; Bechar & Vigneault, 2017; Ramin Shamshiri et al., 2018).

To answer current needs, a new evolution occurred that led to the emergence of smart- and precision farming (Moysiadis, Sarigiannidis, Vitsas, & Khelifi, 2021). Smart- and precision farming will be used synonymously in this paper and are defined as: "A set of techniques that allows localised management, and its success depends on three elements: information, technology and management." (Gunjan & Zurada, 2020). Smart farming doesn't focus on the usage of heavy machinery but tries to minimise the usage of inputs while cultivating as cost-efficiently as possible. Traditional farming only takes in-field data into account (Ramin Shamshiri et al., 2018; Wolfert, Ge, Verdouw, & Bogaardt, 2017). Whereas smart farming emphasises the use of information and communication technology in the cyber-physical farm management cycle (Rayhana, Xiao, & Liu, 2021; Wolfert et al., 2017). This evolution enables the production of healthy products using a durable production process (Yazdinejad et al., 2021).

One technology that emerged due to smart farming is the unmanned electric vehicle, which can be used for field operations in agriculture. This technology allows for a more profitable, resilient and green agricultural system. It can stimulate food security and reduce environmental impacts (Balafoutis et al., 2020; Cambra Baseca, Sendra, Lloret, & Tomas, 2019; Musa & Basir, 2021). This technology enables farmers to use both labour and other input materials more efficiently and thus leads to environmental benefits (Adamides et al., 2020; Godin, Belousova, Belousov, & Terekhova, 2020; Moysiadis et al., 2021; Rayhana et al., 2021; Saiz-Rubio & Rovira-Más, 2020).

One of the focus points of the Institution for Agriculture, Fishery and Food Research (ILVO) is the development of unmanned electric agro-robotics. ILVO is currently developing a multipurpose electric unmanned vehicle, part of the CIMAT project. This robot makes the use of herbicides abundant in the cultivation of roots and carrots. A weeding hoe can be attached to the robot to mechanically weed in order to avoid spraying herbicides with a tractor. As this robot has the potential to decrease the amount of herbicides used in agricultural systems, it has the opportunity to decrease the environmental burden of the agricultural industry (Cool, 2021; ILVO, 2020). The robot can be used for mechanical weeding in the cultivation process of Belgian chicory (Cichorium intybus var. foliosum) roots. Chicory is an important economic product for Belgium as the export of fresh lettuce and chicory was valued at 83 million dollar in 2020. It is important to determine the environmental impact of chicory root cultivation, in Belgium, as this product is shown to be important for food supply and due to the increasing need for environmental sustainability in agriculture.

This research aims to assess, for the first time, the theoretical environmental performance of a multi-purpose agro-robotic electric vehicle, and compare it to the environmental performance of traditional agricultural systems for the cultivation of Belgian chicory roots in Flanders (Belgium). It will determine whether the use of an agro-robotic is environmentally feasible for Belgian chicory root cultivation. The assessment will help to expose environmental hotspots in the cultivation process. Hotspots are process steps with significant contributions to environmental burdens. The focus of the research solely lies on the production of chicory roots and not chicory vegetables, as the robot has no function in the forcing of the roots, that ultimately produce the vegetables. The environmental performance will be calculated using a life cycle assessment (LCA), which takes the use of inputs into account as well as the industrial and agricultural processes for the production of the inputs and their resulting emissions (Baitz et al., 2012; Hauschild, Rosenbaum, & Olsen, 2018).

2. Methodology

The environmental performance of chicory root cultivation in Belgium will be assessed using an attributional LCA. This LCA technique describes the environmental consequences of a decision using average input data (Schmidt, 2008; Thomassen, Dalgaard, Heijungs, & De Boer, 2008). In this research, the LCA technique will be used to assess the environmental consequences resulting from the decision to use an electric agro-robotic for mechanical weeding in the cultivation of chicory roots. It will help to determine which production process has an environmental advantage, using limited data.

The LCA will be performed following the ISO 14040 and 14044 guidelines which include the following sections: (1) goal and scope definition, (2) life cycle inventory, (3) environmental impact assessment and (4) interpretation (Brentrup et al., 2004; ISO EN, 2018; ISO TC, 2006). The goal and scope contain a description of the intention of the analysis and the system boundaries. The life cycle inventory describes all the inputs and outputs used and produced, as well as all emissions that result from the production process. The third step regards the assessment methods chosen to calculate the environmental impacts that result from the process. All these steps are followed by an interpretation (Gradin & Björklund, 2020; Guinée, Gorrée, & Heijungs, 2002). Further reading regarding the application of LCA can be found in the following researches: (Baitz et al., 2012; Brentrup et al., 2004; Finkbeiner, Inaba, Tan, Christiansen, & Klüppel, 2006; Klopffer, 2012; Mälkki & Alanne, 2017; Pryshlakivsky & Searcy, 2013).

2.1 Goal and scope

The goal of the LCA is to compare the environmental performance of chicory root cultivation in Belgium for two distinct cultivation conditions: (1) the first method comprises the traditional cultivation of chicory roots using chemical herbicides, pesticides and fungicides; (2) and a method that considers the use of an electric agro-robotic for mechanical weeding. This robot is part of the CIMAT-project from ILVO. The robot will only be used for mechanical weeding in the cultivation process. To date, the robot has not been developed further to execute other activities. We have no available real-world data regarding the electric energy consumption of the robot for mechanical weeding. This information is based on assumptions from one of the developers, Simon Cool. The calculations for the energy consumption are based on the power (P) of the robot and the working width (Baitz et al., 2012; Cool, 2021; ILVO, 2020).

The assessment will help to determine if the use of an electric robot for mechanical weeding results in smaller environmental impacts. Little to no herbicides are used and less diesel is consumed by eliminating herbicide spraying activities and other weeding activities executed by a tractor. Chicory farmers and developers of the robot can use the assessment to detect environmental hotspots in the cultivation process and determine the environmental potential of the robot.

The cultivation process of chicory roots is researched and described. This cultivation process is only one part of the production process of chicory vegetables. The vegetables are cultivated in three steps: (1) the production of chicory roots, (2) storing the roots and (3) forcing the harvested roots (after storage). The second-and third steps are not considered in this LCA as the robot cannot be used in these process steps. This implies that there will be no difference in the environmental impacts between both processes regarding the storage and forcing of the roots. The forcing generally happens at the chicory farm in dark rooms using a hydroculture after the cultivation of the roots. All the impacts of the LCA are related to the production of 1 ton of chicory roots ready for storage and/or forcing, this is the functional unit of the LCA (Baitz et al., 2012; Brentrup et al., 2004). The LCA is cradle-to-gate, this implies that the analysis only includes on-field activities, the impacts related to the usage of raw materials and other inputs used such as fertilisers, tractor fuels, crop protection and more, as described in figure 1. All steps after the production of chicory roots: transport, storage, forcing, harvesting, selling and consumption are out of scope, as they are the same for both processes studied.

2.2 Life cycle inventory

This section describes the cultivation process of the chicory roots, together with a detailed overview of the input- and output flows of both cultivation processes.

Primary data was collected using quantitative interviews with a chicory farmer (Laurens De Meerleer), a cultivation expert (Tim De Clercq) and one of the project leaders from the CIMAT-project (Simon Cool). The interviews were conducted to review the cultivation process and to identify all the inputs needed and the outputs that result from the production process. The inputs consist of all the materials and energy used to cultivate the roots. The outputs, that result from the production process, are the yields and the emissions that result from the inputs used and produced. The first part of the interview consisted of open questions regarding the production process. The second part of the interview was conducted based on the life cycle inventory, which was an index that was answered by the interviewees regarding the inputs, outputs and corresponding quantities for one production cycle. The interview guideline can be found in appendix 1. The information gathered during the interviews will be used to validate the information on the cultivation process found in the literature and to create the life cycle inventory to calculate the impact assessment.

Secondary data was collected regarding the cultivation process of chicory, the emissions that result from the production process and the input and output flows of the cultivation process. The literature review was meant to answer the following query: "What does the production process of chicory roots look like in Belgium and what types of inputs are used?". Two databases: (1) Google scholar and (2) UHasselt Discovery were used to collect scientific literature. The research terms used for the literature review were: smart farming in chicory cultivation/production, chicory root cultivation/production, LCA regarding chicory cultivation, cultivation/production process of chicory, Belgian endive production, Belgian endive cultivation, LCA for the cultivation of Cichorium intybus var. foliosum, LCA for herbicide usage and LCA in agriculture. Next to a literature review, secondary data was collected regarding the emissions and environmental impacts resulting from the production process using the following databases: Ecoinvent 3 and Agri-footprint 5, provided by the analyse software SimaPro version 9.3, a life cycle impact assessment software.

The description of the cultivation process of Belgian chicory roots is primarily based on the cultivation manual by Van Kruistum (1997). This manual is based on field research carried out in Flanders (van Kruistum, 1997). The manual will be used as a guideline for the traditional cultivation process of chicory. An interview with a chicory cultivation expert and a chicory farmer gave a deeper insight into the cultivation process. A case study, based on input values for one crop cycle, given by Laurens De Meerleer, the chicory farmer, will be used for the impact assessment (De Clercq, 2022; De Meerleer, 2022). All production steps, inputs and outputs taken into consideration are shown in figure 1. The fabrication, commission and dismantling of infrastructure are not considered as well as the ploughing of the chicory plants, that stay behind after cultivation, because there was no data available.

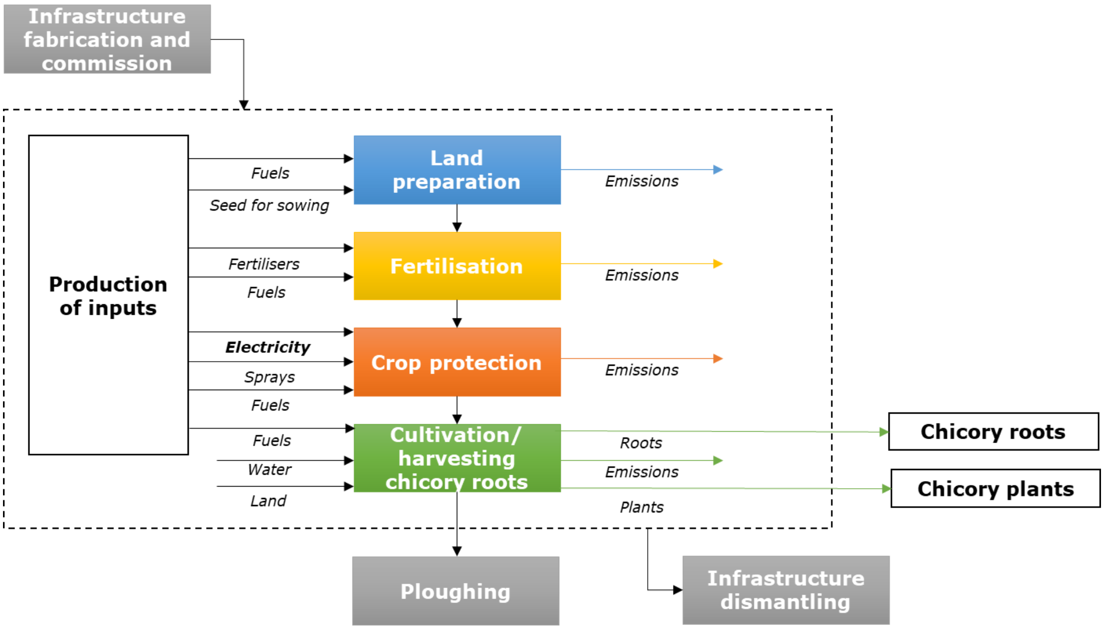

Figure 1 *Production process chicory roots*

Information regarding the application of the electric agro-robotic in the cultivation process of chicory roots and the energy used is solely based on interviews with the project leader Simon Cool. Table 1 shows the difference between the two cultivation methods.

***Table 1** Difference between chicory root cultivation methods*

Activity	Traditional cultivation	Electric agro-robotic
Fertilisation	Inorganic and organic	Inorganic and organic
Crop protection	Mechanical weeding with tractor Inorganic herbicides	Mechanical weeding with robot

According to the manual by van Kruistum (1997), there are three phases in the traditional production process of chicory vegetables: (1) cultivation-, (2) preservation- and (3) forcing of the roots. The cultivation of chicory vegetables can take approximately up to two years. During the first year, only roots and leaves are cultivated and harvested. This phase is part of the scope of the research. The second phase consists of root preservation by storing the roots to cultivate vegetables all year round. In the last phase, after preservation, the roots are forced and the vegetables are cultivated and harvested (van Kruistum, 1997). The preservation and forcing steps will not be taken into account in this LCA. Based on the manual by van Kruistum (1997), and the interviews with the cultivation expert and farmer, chicory root cultivation can be divided into four activities that are executed during the first year of the cultivation cycle:

1. Land preparation is the first activity to cultivate chicory roots in open fields. This generally takes place at the end of March. Depending on the farmer, different field operations take place (van Kruistum, 1997). The field can be ploughed with a chisel plough up to 30 cm deep to break through the plough- and other non-pervious layers. Afterwards, the field is ploughed up to 70 centimetres deep with a deep subsoiler. This is followed by ploughing the field, again, with a chisel plough. Then a mouldboard plough is used to plough the soil one last time (De Meerleer, 2022). After the different ploughing operations, the soil can be treated with lime, depending on the needs of the crop and the nutrients in the soil. Not every field needs a lime treatment, this will be decided based on a soil analysis (De Meerleer, 2022). After ploughing, the field should be prepared for sowing, this generally takes place in April. The field is levelled out, and afterwards, the seed beddings can be prepared (De Clercq, 2022). Two types of seed beddings can be used for the cultivation of chicory roots: flat field cultivation or ridged cultivation. The most commonly used method in Belgium is the ridged seed bedding (De Clercq, 2022; van Kruistum, 1997). Ridged seed beddings are preferred as it increases nutrient replenishment for rooted crops (Scotson, Duncan, Williams, Ruiz, & Roose, 2021). Because minimal fertilisers are used in the cultivation of chicory roots, it is important that the nutrients can be taken up by the crops as efficiently as possible (De Clercq, 2022). Ridged cultivation also enables more efficient use of water distribution when there is heavy rainfall, which is apparent in the Belgian climate (Scotson et al., 2021). The ridges can be formed using a milling cutter (van Kruistum, 1997). Sowing ideally takes place between

mid-April and mid-May, using a precision sowing machine. The review by Bais and Ravishankar (2001) also mentioned that May is the ideal sowing period. The seeds should be planted 1 to 5 centimetres deep (Bais & Ravishankar, 2001; van Kruistum, 1997). It is also possible to create the ridges and sow the field simultaneously by connecting the milling cutter and precision seeder behind each other. This is usually done by Laurens De Meerleer (De Meerleer, 2022).

2. The second step, fertilisation, is important for the cultivation of chicory roots. The amount of fertiliser needed depends on the degree of (organic) minerals in the soil. Different fertilisers can be used depending on the mineral that is missing in the soil (van Kruistum, 1997). In general, not many fertilisers are used, as chicory plants are expected to use all minerals in the soil, which makes it a very soil exhaustive cultivation process. Therefore, chicory is only cultivated every four years in a specific field. After the cultivation of chicory or other crops can be cultivated such as corn or grain (De Clercq, 2022; De Meerleer, 2022). The review by Bais and Ravishankar (2001) implies that manure or well-rotted compost can be used before sowing and ploughed in the soil at a depth of 10 to 15 cm, but that the advantages are not yet proven (Bais & Ravishankar, 2001). The cultivation expert and farmer stated otherwise. Due to the high nitrogen degree in natural manure as well as the uncertainty regarding precision when dispensed on the field, natural manure is not often used in the production of chicory roots (De Clercq, 2022; De Meerleer, 2022).
3. The third activity consists of nurturing the plants and roots. Chicory plants need around 30 ml of water during the cultivation cycle which takes up to 8 months (De Clercq, 2022). But even when there isn’t enough rainfall, chicory plants are rarely irrigated with water as this is a very expensive procedure for farmers. Water is seldom used to activate the germination of the seeds (De Meerleer, 2022). Weed control is also important to nurture the crops. Different herbicides are used throughout the entire cultivation process. In traditional cultivation three chemical sprayings with herbicides are executed. Herbicides can be used during the land preparation, right after sowing (before germination) and during the growth phase of the plant (De Clercq, 2022; De Meerleer, 2022). During the growth stage, there are specific timings when herbicides are sprayed to avoid damage to the crop. Herbicides should be sprayed before the emergence of the third leaf and again before the emergence of the fourth or fifth leaf of the plant (De Clercq, 2022). Spraying with herbicides can be executed up until the end of June or the beginning of July (De Meerleer, 2022). There is also the possibility of mechanical weeding, which is part of the traditional cultivation process and the cultivation process using an electric robot. Hoeing the ridges is a mechanical weeding activity that can be used in the cultivation of chicory roots. Even when herbicides are used for traditional cultivation, it is still advised to hoe the ridges at least once. Hoeing can take place between the end of July and the beginning of August. When mechanical weeding is executed using an electric agro-robotic, the process becomes part of the smart farming cultivation process. Then, the weeding hoe is not pulled by heavy a vehicle but by a robot (van Kruistum, 1997). The farmer stated that the robot could be used to hoe up to three times and eliminate all herbicide treatments. Hoeing is not suggested to be used more than 3 times because during mechanical weeding soil is scraped from the ridges. Scraping soil over and over would lead

to exposure of the roots. After hoeing in the traditional cultivation process, one more layer of herbicide is sprayed on the ridges to avoid the germination of new weeds (De Meerleer, 2022). It is also important to observe the plants and fields to detect diseases, bacteria, pests and physiological problems. Depending on the disease, insects or other problems, different fungicides and insecticides are used. This step is different for each field, depending on the needs (Bioboost, 2019; De Meerleer, 2022; van Kruistum, 1997).

4. The last activity is the harvesting of the chicory roots. Ideally, the roots should be 15 to 18 cm long and have a maturity of at least 20 weeks. Generally speaking, the harvesting takes place between September and November. Sometimes, before the cultivation of the roots has been executed, the foliage is cut down and left behind on the field. After the cultivation of the roots, the foliage is ploughed through the soil (De Clercq, 2022). The yield of chicory roots depends on the harvesting date. The research by Bioboost (2019) suggests that there is an average production of approximately 200,000 roots/ha which corresponds to approximately 30 ton roots/ha. This is in line with the average yield of the interviewed chicory farmer (Bioboost, 2019; De Meerleer, 2022). The biomass of the plant itself, which is not used, is left on the field and will be used as green manure for the next crop that is cultivated on the field. It is advised to plough the soil after the cultivation of the roots to make the field ready for the next crop to be cultivated (De Clercq, 2022).

The life cycle inventory comprises all the resources used, outputs produced and emissions released for the production of 1 ton chicory roots ready for storage and forcing (Brentrup, Küsters, Kuhlmann, & Lammel, 2001). If there was no information available regarding certain inputs, outputs and/or emissions, they are omitted from the analysis and will be reported.

Data regarding the traditional cultivation process is based on the production process executed by Laurens De Meerleer (L.D.M.), a chicory farm owner based in Erpe-Mere (East Flanders). The climate of Belgium is maritime also known as cold and moist (EEA, 2012). Erpe-Mere is characterised by a dry loamy soil type according to Belgian statistics (Flemish Government, n.d.). Data regarding the traditional cultivation process, retrieved from the chicory root expert, Tim De Clercq (T.D.C), is also added to the inventory. This input data is not analysed in the impact assessment because data regarding fuel- and water consumption, as well as the use of fertilisers, is missing. Therefore the emissions produced in this case study are not calculated. The electronic agro-robot that can be used for mechanical weeding in the cultivation process, part of the CIMAT project, is currently being tested in field operations. The robot has a four-wheel drive and different types of machinery can be connected, such as as a sensor or a weeding hoe. The robot can be steered using a remote controller. As the robot is still in a testing phase and is not yet available on the market, the case study for this cultivation process is based on the input and output values of the traditional cultivation process. The difference between both processes is that there are fewer to none herbicides used. This assumption was made based on the interview with Simon Cool. This also means that there is no diesel consumed for the weeding and spraying of herbicides in the new process, but electricity is consumed instead (ILVO, 2020). The robot has 20 kW power (P), and it is assumed by the developers that it will use 10 kW when it is mechanically weeding the field (Cool, 2021). The robot can weed mechanically with a span of 1.5 metres. To weed 1 hectare field, the robot will take 1.34 hours. As only 1/30 hectare field is used for the cultivation of one functional unit, the actual electricity use is equal to 1.60008E-03 MJ. The calculations can be found in table 2. A detailed description of the robot with videos and pictures can be found on the website of the CIMAT-project[1].

Table 2 *Calculations of energy consumption for the robot*

Parameter	Source or formula	Value
Total power (P)	Interview	20 kW
Working width	Interview	1.5 m
Power used for mechanical weeding	Interview	10 kW
Working speed	Interview	5 km/h
Average root output for the working area	Interview	30 ton
Total working area	Interview guideline	1 hectare (10,000 m²)
Total distance the robot weeds for 1 FU	$\frac{total\ working\ area\ (m^2)}{working\ width\ (m)}$	6,667 m (6.67 km)
Time used to weed one hectare	$\frac{total\ distance\ the\ robot\ weeds\ (km)}{working\ speed\ (\frac{km}{u})}$	1.3334 hours
Working area for 1 FU	$\frac{total\ working\ area\ (ha)}{total\ output\ (ton)}$	1/30 ha
Time used for weeding the working area of 1 FU	$time\ used\ to\ weed\ one\ hectare * working\ area\ for\ 1\ FU$	0.044467 hours
Electric energy consumed for 1 FU	$\frac{power}{1000}\ (kw) * time\ used\ to\ weed\ 1\ FU\ (hours)$	0.44467 Wh
Electric energy consumed for 1 FU	$electric\ energy\ consumed\ for\ 1\ FU\ * 0.0036\ MJ$	1.60008E-03 MJ

Table 3 shows the life cycle inventory for all inputs used, outputs (roots and plants) produced and resulting emissions in relation to the functional unit. The data taken into account is based on information for the cultivation cycle of 2021. The field activities are carried out by a tractor that consumes diesel, which is expressed in tonne-kilometres (tkm). This is a unit measure for freight transport of one ton of goods (machinery, tractor) on land over a distance of one kilometre. This unit is used in the SimaPro software. The robot uses low voltage electricity expressed in Megajoule (MJ), which does not result in any output emissions. It is possible to use the robot up to three times and eliminate all the herbicide sprayings according to the interviewees. If mechanical weeding happens too often, it is necessary to add new soil to the ridges, as the roots might be exposed. Laurens de Meerleer, who is familiar with the robot, assumed that it is possible to hoe up to three times without having to add new soil layers to the ridges (De Meerleer, 2022). As there is no information regarding the amount of soil that needs to be added when mechanical weeding is used more than three times, there is a maximum of three hoeing activities used in this research to avoid new soil addition (ILVO, 2020). The materials for the production of fertilizers, insecticides, fungicides and herbicides are taken into account, as well as the use of these inputs and the emissions that result from the utilization, which are shown in Table 3. The information regarding the use of these inputs is modelled based on the SimaPro software and calculation models that assess the emissions produced. The output yield of the chicory plants consisting of leaves is equal to zero, as they are left on the field and used as green manure in the cultivation cycle of the next crop.

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[1] https://www.cimat.be/

Table 3 *LCI of the four sub-steps of chicory root cultivation reported per FU*

Parameter **Inputs and outputs by activity**	**Unit (/ton roots)**	**Traditional farming (L.D.M.)**	**Traditional farming (T.D.C)**[1]	**Smart-farming Electric robot**[2]	**Data source**
Field preparation					
Field operations					
Ploughing (with Amazone Pegasus)	tkm	1.5266E+01	-	1.5266E+01	Interviews
Ploughing (with Steeno)	tkm	1.7174E+01	-	1.7174E+01	Interviews
Ploughing (with Amazone Pagasus)	tkm	1.4630E+01	-	1.4630E+01	Interviews
Ploughing (with scissor plough)	tkm	1.7174E+01	-	1.7174E+01	Interviews
Ploughing (creating fine soils)	tkm	1.9083E+01	-	1.9083E+01	Interviews
Prepare and sow (ridges + sowing)	tkm	1.5902E+01	-	1.5902E+01	Interviews
Fertilisation					
Field operations					
Lime soil/ fertilisers	tkm	1.2722E+01	-	1.2722E+01	Interviews
Production of fertilisers (non-organic)					
N (12,12,17)	kg	0.0000E+00	-	0.0000E+00	Interviews
P2O5 (0,45,0)	kg	0.0000E+00	-	0.0000E+00	Interviews
K20 (0,0,60)	kg	0.0000E+00	-	0.0000E+00	Interviews
Ammonium nitrate (18,0,0)	kg	6.0000E-01	-	6.0000E-01	Interviews
Calcium nitrate (15.5,0,0)	kg	3.8750E-01	-	3.8750E-01	Interviews
Use of fertilisers (non-organic)					
Dinotrogen monoxide (emission to air)	kg	5.6000E-01	-	5.6000E-01	Data modelled
Nitrogen oxides (emission to air)	kg	1.1733E-01	-	1.1733E-01	Data modelled
Ammonia (emission to air)	kg	2.3967E-02	-	2.3967E-02	Data modelled
Carbon dioxide (emission to air)	kg	8.0000E-01	-	8.0000E-01	Data modelled
Nitrate (emission to water)	kg	7.1333E+00	-	7.1333E+00	Data modelled
Phosphorous (emission to water)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Cadmium (emission to water)	kg	5.3333E-08	-	5.3333E-08	Data modelled
Copper (emission to water)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Zinc (emission to water)	kg	4.8000E-07	-	4.8000E-07	Data modelled
Lead (emission to water)	kg	2.4733E-08	-	2.4733E-08	Data modelled
Nickel (emission to water)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Chromium (emission to water)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Cadmium (emission to soil)	kg	7.1667E-07	-	7.1667E-07	Data modelled
Copper (emission to soil)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Zink (emission to soil)	kg	8.3333E-07	-	8.3333E-07	Data modelled
Lead (emission to soil)	kg	7.4667E-07	-	7.4667E-07	Data modelled
Nickel (emission to soil)	kg	1.3900E-06	-	1.3900E-06	Data modelled
Chromium	kg	0.0000E+00	-	0.0000E+00	Data modelled
Crop nurture					
Field operations					
Spraying 1 (herbicides)	tkm	1.1450E+01	-	0.0000E+00	Interviews
Spraying 2 (herbicides)	tkm	1.1450E+01	-	0.0000E+00	Interviews
Mechanical weeding (weeding hoe)	tkm	1.0177E+01	-	0.0000E+00	Interviews
Spraying 3 (herbicides)	tkm	1.1450E+01	-	0.0000E+00	Interviews
Spraying (fungicides and insecticides)	tkm	1.1450E+01	-	1.1450E+01	Interviews
Mechanical weeding with robot	MJ	0.0000E+00	0.0000E+00	4.8024E-03	Interviews

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[1] This case study will not be used in the calculation of the environmental impact assessment due to a lack of data

[2] The information used in this case study is based on assumptions from one of the project leaders of the CIMAT-project who stated that all herbicides can be eliminated once the robot is introduced

Table 3 continued *LCI of the four sub-steps of chicory root cultivation reported per FU*

Production of herbicides					
Propyzamide	kg	1.6091E-02	7.5428E+00	0.0000E+00	Interviews
Befuraline	kg	6.3285E-02	2.1698E+00	0.0000E+00	Interviews
Bentazone	kg	5.2000E-03	4.6800E-01	0.0000E+00	Interviews
(S-)metolachlor	kg	0.0000E+00	0.0000E+00	0.0000E+00	Interviews
Dinotefuran	kg	6.6667E-04	0.0000E+00	0.0000E+00	Interviews
Carbetamide	kg	2.3600E-02	0.0000E+00	0.0000E+00	Interviews
Isoxaben	kg	1.2083E-03	0.0000E+00	0.0000E+00	Interviews
Glyphosate	kg	0.0000E+00	1.7000E+00	0.0000E+00	Interviews
Use of herbicides					
Promanide (emission to soil)	kg	1.6091E-02	-	0.0000E+00	Data modelled
Benfluralin (emission to soil)	kg	6.3285E-02	-	0.0000E+00	Data modelled
Bentazone (emission to soil)	kg	5.2000E-03	-	0.0000E+00	Data modelled
Metolachlor, (s) (emission to soil)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Pyriproxyfen (emission to soil)	kg	6.6667E-04	-	0.0000E+00	Data modelled
Carbetamide (emission to soil)	kg	2.3600E-02	-	0.0000E+00	Data modelled
Isoxaben (emission to soil)	kg	1.2083E-03	-	0.0000E+00	Data modelled
Glyphosate (emission to soil)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Production of insecticides and fungicides	kg				
Pirimicarb	kg	0.0000E+00	1.3924E+00	0.0000E+00	Interviews
Dinotefuran 40%	kg	0.0000E+00	6.7600E-01	0.0000E+00	Interviews
Vinclozolin	kg	0.0000E+00	2.2801E+00	0.0000E+00	Interviews
Lambda-cyhalothrin	kg	0.0000E+00	4.4223E-02	0.0000E+00	Interviews
Cyantraniliprole	kg	0.0000E+00	1.0260E-01	0.0000E+00	Interviews
Boscalid	kg	0.0000E+00	5.2332E-01	0.0000E+00	Interviews
Pyraclostrobin	kg	0.0000E+00	1.1323E-01	0.0000E+00	Interviews
Fosetyl	kg	0.0000E+00	8.0000E-01	0.0000E+00	Interviews
Profenofos	kg	1.2500E-02	1.1250E+00	1.2500E-02	Interviews
Azoxystrobin	kg	8.3973E-03	4.2197E-01	8.3973E-03	Interviews
Difenoconazole	kg	5.7083E-03	4.6923E-01	5.7083E-03	Interviews
Spirotetramat	kg	3.0500E-03	2.2326E-01	3.0500E-03	Interviews
Use of insecticides and fungicides					
Methyl carbamate (emission to soil)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Dimethoate (emission to soil)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Vinclozolin (emission to soil)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Lambda-cyhalothrin (emission to soil)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Chlorantraniliprole (emission to soil)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Boscalid (emission to soil)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Benfluralin (emission to soil)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Fosetyl (emission to soil)	kg	0.0000E+00	-	0.0000E+00	Data modelled
Deltamethrin (emission to soil)	kg	1.2500E-02	-	1.2500E-02	Data modelled
Azoxystrobin (emission to soil)	kg	8.3973E-03	-	8.3973E-03	Data modelled
Difenoconazole (emission to soil)	kg	5.7083E-03	-	5.7083E-03	Data modelled
M-methoxyphenol (emission to soil)	kg	3.0500E-03	-	3.0500E-03	Data modelled
Harvesting roots field operations					
Harvesting	tkm	1.5266E+01	-	1.5266E+01	Interviews
Water consumption	l	8.3333E+00	-	8.3333E+00	Interviews
Yield produced					
Chicory roots	kg	1.0000E+00	-	1.0000E+00	Interviews
Chicory plants	kg	0.0000E+00	0.0000E+00	0.0000E+00	Interviews

2.3 Environmental Impact assessment

This section discusses the chosen assessment methods. The inputs used and emissions released during the cultivation of chicory roots will be calculated and converted to impact values using the CML-IA baseline (version 3.07) and the ReCiPe-midpoint (h) (version 1.06) assessment methods. Both methods are taken into account because other LCA researches regarding agriculture use both assessment methods. The execution of both methods enables the comparison of the results to other current LCA research and new researches in the future (Mälkki & Alanne, 2017; Russo, Strever, & Ponstein, 2021). Both methods result in midpoint impact values. Midpoints can be useful to inform developers and chicory farmers, who do not want uncertain endpoint indicator results. Midpoint modelling means that the assessment considers an indicator between the emission and the endpoint in the environmental mechanism (Pizzol, Christensen, Schmidt, & Thomsen, 2011; Yi, Kurisu, & Hanaki, 2011).

The impact categories taken into account for the CML method are: abiotic depletion (AD), abiotic depletion (AD) (fossil fuels), global warming (GWP100a), ozone layer depletion (ODP), human toxicity (HT), freshwater aquatic ecotox. (freshwater AE), marine aquatic ecotoxicity (marine AE), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification (acidif.) and eutrophication (eutro.). For the ReCiPe midpoint (h) method, the following impact categories are taken into account: global warming (GW), stratospheric ozone depletion (SOD), ionising radiation (IR), ozone formation regarding human health (OZ, HH), fine particulate matter formation (FPMF), ozone formation regarding terrestrial ecosystems (OF, TF), terrestrial acidification (TA), freshwater eutrophication (freshwater E), marine eutrophication (marine E), terrestrial ecotoxicity (TE), freshwater ecotoxicity (freshwater ecotox.), marine ecotoxicity (marine ecotox), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (H non-CT), land use, mineral resource scarcity (MRS), fossil resource scarcity (FRS) and water consumption (water cons.).

Even though the CML-IA baseline and ReCiPe-midpoint (h) assessment methods are both midpoint analyses, there are multiple differences between them. A review of all differences between both methods can be found in the study by Bach and Finkbeiner (2016). The researchers concluded that the CML-IA baseline method provides characterization factors for 52 elementary flows, whereas the ReCiPe method only considers 16 elementary flows (Bach & Finkbeiner, 2016). The difference it challenging to make comparisons between the methods. Elementary flows can be defined as follows: "Essential data inputs used in the life cycle inventory for which the life cycle impact assessment provides impact characterization factors so that the impacts can be calculated.". Elementary flows take materials, energy, or space into account that is taken directly from the environment or released directly back into the environment. These flows are automatically taken into account by the SimaPro software when inputs are selected from the databases (Edelen et al., 2017).

2.4 Interpretation

The interpretation phase can be defined as follows: "This phase quantitatively and qualitatively identifies, checks, and evaluates the outcomes of the life cycle inventory (LCI) and the life cycle impact assessment (LCIA) steps, concerning the goal and scope definition." (Laurent et al., 2020).

2.4.1 Identification of significant issues

The identification of issues in the LCA is the first step of the interpretation (Laurent et al., 2020). The first issue regards the life cycle inventory. All sprays (herbicides, fungicides and insecticides) used in the cultivation process are composed of two product groups: active ingredients and other ingredients. The other ingredients mostly consist of water and their environmental impact is negligible because they only account for a small part of the sprays. Other LCA researchers also solely take the active ingredients of the sprays into account (Ault et al., 2016; Navarro Pineda, n.d.). Some of the active ingredients in the production process can be traced in the SimaPro databases. But for some active ingredients, no input variable could be detected in the software. Therefore related chemical active ingredients are traced in the databases. If there was no similar active ingredient found, the sprays are described as unspecified. Table 7 in appendix 2 lists all active ingredients that are used for the cultivation of chicory roots, the input models retrieved from the SimaPro software and the emission that results from the use of the active ingredients. Table 8 in appendix 2 shows the input models that were chosen in SimaPro to conduct the impact assessment.

A second problem tackled the input of data on herbicides, fungicides, insecticides and fertilizers. Primary data regarding these inputs were mostly collected in litre/hectare. Although the SimaPro software does not accept litre/hectare as an input unit, it does accept input values in kilograms. Therefore, the composition of the sprays and the density of the active ingredients are taken into account to calculate the input value in kg. The data regarding the composition of the sprays as well as the density of the active ingredients are secondary and are retrieved from product labels and the national library of medicine (NIH, n.d.). The databases in SimaPro (Agri-footprint 5 and Ecoinvent 3) were mainly used to retrieve the impacts that result from the production and use of these specific inputs. The same calculations were made regarding the diesel consumption of the tractor for field operations. The density of diesel had to be taken into account to determine the amount of diesel used in kg, which then had to be converted to the unit of tonne-km (tkm) (Goedkoop et al., 2016).

Emission output flows had to be calculated through various data models. For the sprays (herbicides, fungicides and insecticides), the amount (kg) of emission outflows of the cultivation process is equal to the amount (kg) of active ingredients that are used as inputs in the cultivation process because no other data was available regarding the emissions that occur (Navarro Pineda, n.d.). Fertilizers produce multiple emissions. An overview of the emissions produced as a result of their use can be found in table 3. These emissions were calculated using an emission modelling file provided by dr. Freddy Navarro Pineda (Navarro Pineda, n.d.). To calculate the emissions produced resulting from the treatment of fertilizers, the yearly average precipitation in Belgium had to be taken into account which is equal to 700mm (Koninklijk Meteorologisch Instituut, 2022). Other inputs regarding the climate and soil type of the region also had to be taken into account. Due to limited choice options in the calculation model provided, the chosen climate in the model is 'cold temperature, moist' and the soil type is 'inceptisol' (Navarro Pineda, n.d.).

A last significant issue regards the amount of data that was collected during the interviews to set up the case studies. All process steps, for which data primary data could be found, are taken into account in this LCA. Data regarding the usage of green manure, that possibly stayed behind from previous crop cultivations on the field, are not taken into account, as there was no data. Data was also missing regarding the ploughing of the chicory plants in the field after harvesting the roots. A last important input value, that is not taken into account due to a lack of data, is the amount of energy consumed to recharge the battery of the electric agro-robotic. Including these inputs in the life cycle inventory could lead to changes in the impact values.

2.4.2 Completeness check

The completeness of information in the life cycle inventory is discussed as one of the significant issues in this LCA. There is data missing regarding three inputs: (1) the use of green manure from previous cultivation cycles, (2) ploughing after root cultivation and (3) the energy used to recharge the battery of the electric agro-robotic. The use of green manure depends on the farmer and the type of crop cultivated before chicory roots. Some crops do not leave foliage on the field, this results in zero environmental impacts in the next cultivation process (De Meerleer, 2022). Ploughing after cultivation can be typed as part of the cultivation cycle of the next crop as one of the field preparation steps. Only recharging might have a significant impact. Therefore it is recommended to be researched further in the future. In this research, only the direct electricity consumption of the robot is taken into account.

2.4.3 Consistency check

This interpretation step comprehends the process of verifying that the assumptions, methods and data are consistently applied throughout the study and are in accordance with the goal and scope definition (Weidema, 2018).

The LCA conducted in this research followed the ISO 14040 and 14044 guidelines as stated in the methodology. The life cycle inventory and impact assessment method were conducted regarding the goal and scope defined in the paper. There is one inconsistency in the choice of data, as some emission and impact calculations are based on unpublished work by dr. Freddy Navarro Pineda, which was strictly provided for the execution of this research. The second inconsistency is the use of assumptions for the inputs used in the new cultivation process as real-world applications are currently missing.

2.4.4 Sensitivity analysis

The last part of the interpretation consists of a sensitivity analysis (Ault et al., 2016). The sensitivity analysis is executed for the CML-IA baseline and the ReCiPe midpoint (h) methods. Three input variables: (1) the power (P) of the agro-robotic (2) the number of mechanical weeding operations executed by a tractor (3) and the number of herbicides used are examined as part of a sensitivity analysis. Also, the assumptions made for the new cultivation process are examined. This analysis is used to verify the relevance of the information to reach conclusions and give recommendations on the impacts calculated (Ault et al., 2016). A sensitivity analysis is also used to deal with uncertainties in the LCA (Mälkki & Alanne, 2017). An overview of the absolute impact values that result from the sensitivity analysis can be found in appendix 3.

The impact of electricity consumption of the robot is studied in the sensitivity analysis by increasing and decreasing the power (P) of the robot, which results in a change of electricity (MJ) consumed for mechanical weeding. The power of the robot is decreased and increased at intervals of 2 kW. The power can increase up to 20 kW as this is the maximum power of the robot and can decrease to 0 kW (Cool, 2021). The environmental impacts were calculated with the power of the agro-robot ranging from 0 to 20 kW, comparing 11 scenarios and holding all other inputs constant. The results can be found in table 9 in appendix 3. Only the two extreme scenarios are shown. The analysis showed that the power of an electric robot, not taking the inputs and emissions of recharging the battery into account, has no significant impact change on the environment. The difference between the two extreme scenarios P=0 kW and P=20 kW is equal to zero for all environmental impact categories, except for abiotic depletion, marine aquatic ecotoxicity, ionizing radiation, terrestrial ecotoxicity, land use and mineral resource scarcity. But these changes never exceed one percent.

A second sensitivity analysis regards mechanical weeding executed by a tractor that consumes diesel. The results are shown in table 10 of appendix 3. For this scenario, it is assumed that a maximum of three mechanical weeding activities can be executed. For simplicity purposes, and to solely show the impact of the diesel consumption for mechanical weeding, all other inputs are held constant. A linear increase in the consumption of diesel due to increasing the number of mechanical weeding operations with a tractor leads to a linear increase in the absolute environmental impact values. The consumption of diesel shows to have a linear effect on all impact categories. For the CML-IA assessment method, the following categories are impacted the most by increasing fuel consumption: abiotic depletion, ozone layer depletion and photochemical oxidation. The ReCiPe midpoint (h) method shows that the following categories have the largest impact value changes: ozone formation in terrestrial ecosystems, ozone formation regarding human health and fossil resource scarcity.

Based on the interviews conducted, two scenarios with the robot were examined: (1) replace the diesel consumption for mechanical weeding and replace one spraying activity for two mechanical weeding activities with the robot and (2) replace all the herbicide sprayings and the diesel consumed for three mechanical weeding activities with the robot (Cool, 2021; De Meerleer, 2022). Mechanical weeding with the tractor is replaced in both scenarios. Table 11 in appendix 3 shows the environmental impact values for the three scenarios. There is no linear effect between the elimination of one spraying activity at a time and increasing the number of mechanical weeding activities with the robot. Already established in the sensitivity analysis is that the robot does not change the environmental impact values. Therefore increasing the number of weeding activities of the robot does not explain the irregular changes in environmental impacts. The decrease in fuel consumption results in linear impact changes and also does not explain the irregular differences in impact values. It can be concluded that the different herbicides, used in the cultivation process, have different environmental impacts because they hold different active ingredients resulting in different environmental impacts.

The last sensitivity analysis is executed because the information regarding the robot solely rests on assumptions as the robot is not yet used in real-world applications. It is important to evaluate what would happen if the assumptions made, would not come true in real life. One of the project leaders from the CIMAT-project stated that the robot would result in the total elimination of the herbicides in the cultivation process. This might not be the case for every field, as different fields have different needs. Therefore a scenario was conducted, which examines the use of all herbicides sprayed with the tractor and only eliminates the mechanical weeding activity with the tractor to replace it with mechanical weeding with the robot. This means that all inputs are held constant and are the same as the traditional cultivation process, except for the fuel consumed by the tractor for mechanical weeding, which is equal to 0. The results are shown in table 12 in appendix 3. If this scenario happens in real life, different results occur. Almost all impact values decrease, but never with more than 6%. This implies that the elimination, of the smallest amount of fuel and replacing it with the use of an electric robot has environmental benefits. Marine eutrophication is not affected by the elimination of fuel for mechanical weeding. Water consumption is negatively influenced after the introduction of the robot in order to replace mechanical weeding with the tractor. This results in an increase of 0.07%. This implies that the use and production of electricity deplete more water sources than the use and production of fuels.

3. Results and discussion

This section comprehends the main results and findings of the impact assessment for chicory root cultivation in Belgium using two distinct cultivation methods. The absolute impact values of both cultivation methods are discussed. This is followed by a discussion of the differences in impact values between the two cultivation methods.

3.1 Impact assessment values

Table 4 shows the absolute environmental impacts of the two cultivation methods that result from the production of 1 ton chicory roots (FU). A distinction is made between the two impact assessment methods. Also, the percentage change of the absolute impact values for each impact category is shown in table 4. A negative percentage change implies a decrease in the absolute environmental impact values. A negative percentage change occurred for all categories after the introduction of the robot. The introduction of the robot results in an environmental benefit for each impact category when compared to traditional cultivation. The use of an electric agro-robotic has the largest effect on the impact category of human toxicity (HT) when the CML method is used. The absolute value of HT resulting from the new cultivation process is equal to 2.9756E+00, decreasing the environmental impact by 63.32% compared to the traditional cultivation process. Five other impact categories for the CML method show a significant decrease, larger than 15%, in absolute impact values. These impact categories are: abiotic depletion (fossil fuels), ozone layer depletion, marine aquatic toxicity, photochemical oxidation and acidification. The ReCiPe midpoint (h) method also shows a decrease in all environmental impact categories. The use of the robot has the largest effect on mineral resource scarcity, equal to 40.50%. The elimination of all herbicides in the cultivation process after the introduction of the robot has the smallest effect on marine eutrophication, which is equal to 0.04%.

Table 4 *Impact categories for both LCA methods and their absolute values of the cultivation process for 1 FU*

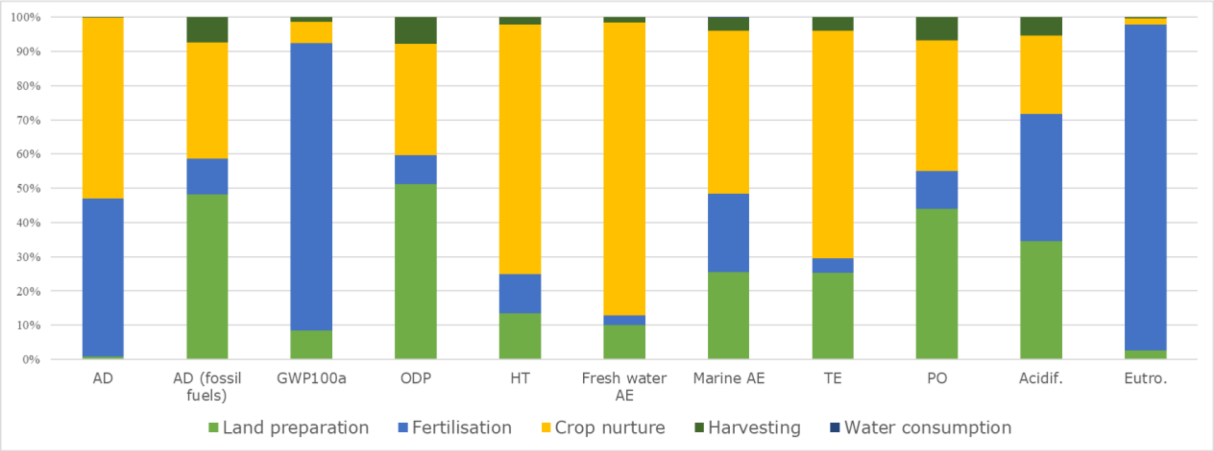
Impact category	Unit	Traditional cultivation	Electric agro-robotic	Percentage change (%)
CML-IA baseline				
Abiotic depletion	kg Sb eq	7.4727E-05	6.9634E-05	-6.82
Abiotic depletion (fossil fuels)	MJ	4.4274E+02	3.3856E+02	-23.53
Global warming (GWP100a)	kg CO2 eq	1.8261E+02	1.7512E+02	-4.10
Ozone layer depletion (ODP)	kg CFC-11 eq	5.5327E-06	4.1894E-06	-24.28
Human toxicity	kg 1.4-DB eq	8.1129E+00	2.9756E+00	-63.32
Freshwater aquatic ecotox.	kg 1.4-DB eq	1.6280E+00	1.4785E+00	-9.18
Marine aquatic ecotoxicity	kg 1.4-DB eq	1.5857E+03	1.2355E+03	-22.09
Terrestrial ecotoxicity	kg 1.4-DB eq	2.1394E-01	1.8648E-01	-12.83
Photochemical oxidation	kg C2H4 eq	3.9130E-03	2.8963E-03	-25.98
Acidification	kg SO2 eq	3.1956E-01	2.6767E-01	-16.24
Eutrophication	kg PO4--- eq	9.3691E-01	9.2543E-01	-1.23
ReCiPe midpoint (h)				
Global warming	kg CO2 eq	3.2406E+01	2.4701E+01	-23.78
Stratospheric ozone depletion	kg CFC11 eq	4.4423E-05	3.7566E-05	-15.43
Ionizing radiation	kBq Co-60 eq	2.3613E-01	1.7276E-01	-26.84
Ozone formation, Human health	kg NOx eq	2.7602E-01	1.9467E-01	-29.47
Fine particulate matter formation	kg PM2.5 eq.	1.3637E-01	1.1415E-01	-16.29
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.5402E-01	2.7193E-01	-23.19
Terrestrial acidification	kg SO2 eq	7.1575E-01	6.7527E-01	-5.66
Freshwater eutrophication	kg P eq	3.7805E-03	2.6571E-03	-29.72
Marine eutrophication	kg N eq	4.7890E-01	4.7871E-01	-0.04
Terrestrial ecotoxicity	kg 1.4-DCB	6.5742E+01	5.3958E+01	-17.93
Freshwater ecotoxicity	kg 1.4-DCB	3.2068E+00	2.5739E+00	-19.74
Marine ecotoxicity	kg 1.4-DCB	2.0425E+00	1.9769E+00	-3.21
Human carcinogenic toxicity	kg 1.4-DCB	7.0162E-01	6.6879E-01	-4.68
Human non-carcinogenic toxicity	kg 1.4-DCB	7.3451E+02	6.9886E+02	-4.85
Land use	m2a crop eq	8.4459E-02	6.2443E-02	-26.07
Mineral resource scarcity	kg Cu eq	1.5797E-02	9.3990E-03	-40.50
Fossil resource scarcity	kg oil eq	9.8530E+00	7.3883E+00	-25.01
Water consumption	m3	4.1350E-02	3.2347E-02	-21.77

3.2 CML-IA baseline assessment method

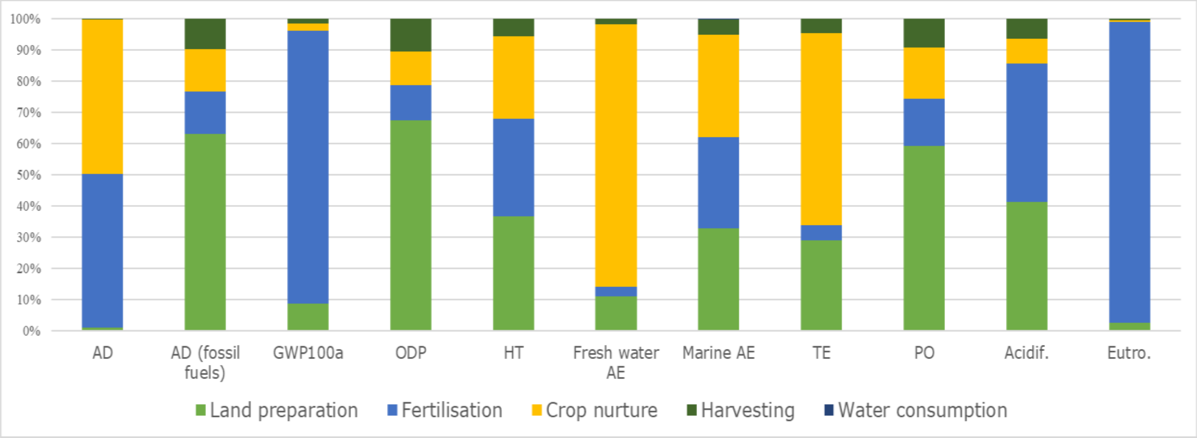
Results were first reported as absolute environmental impact values in Table 4. In this section, the relative environmental impacts and the percentage change between the two cultivation methods are discussed, using the CML-IA baseline assessment method. A distinction was made between the different cultivation activities to show the individual impacts. Graphs 1A and 1B show the relative impacts of the different cultivation activities for the traditional cultivation process and the cultivation process with the robot. All activities used for the production of chicory roots show to have an impact on one or more impact categories, except for water consumption. The relative impact of water consumption never exceeds 1% and will not be further discussed. For both cultivation methods, the impact of harvesting is also negligible, as no relative impact value exceeds 10%. The low relative impact of harvesting can be explained by the use of only one input, the consumption of diesel for one field operation.

Fertilisation and land preparation show significant impacts on multiple categories, the relative impacts increase between both processes due to input changes in crop nurturing. The input variables used for field preparation solely consist of diesel consumption by the tractor and show the biggest relative impacts on the abiotic depletion (AB) of fossil fuels, ozone layer depletion (ODP) and photochemical oxidation (PO) ranging between 44 and 51 percent for traditional cultivation and 41 and 68 percent for the innovated cultivation process. This significant relative impact stems from the use of diesel, made of fossil fuels which release multiple greenhouse gas emissions (Acero, Rodríguez, & Ciroth, 2015). Fertilisation shows to have a significant relative impact on abiotic depletion (AD), global warming (GWP100a) and eutrophication (Eutro.). These relative impact values range between 46 and 96 percent for both processes. The inputs used for fertilisation mostly consist of chemicals and minerals that lead to nitrogen and carbon dioxide emissions. These emissions directly influence global warming due to the emission of greenhouse gasses (LaHue, Kessel, Linquist, Adviento-Borbe, & Fonte, 2016). The use of minerals and chemicals in fertilizers has a direct impact on eutrophication and abiotic depletion. The inputs for land preparation, fertilisation, water consumption and harvesting are held constant throughout both cultivation methods. Therefore, the absolute impacts of these activities do not change, but relative impacts do due to the changes in inputs for crop nurturing.

In the new cultivation method, herbicides and diesel consumption are eliminated for the spraying of herbicides in crop nurturing and the usage of electricity, consumed by the robot, is introduced. In the traditional cultivation process, crop nurturing showed a significant relative impact, larger than 10%, on all impact categories except global warming (GWP100a) and eutrophication (Eutro.). After the introduction of the electric agro-robotic for mechanical weeding, the relative impact of crop nurturing is still significant for multiple impact categories, but all relative impacts decreased. In the new cultivation process, the crop nurturing activity does not have a significant impact on three categories: global warming (GWP100a), acidification (acidif.) and eutrophication (Eutro.). The small impact on global warming can be allocated to the significant impact of fertilisation due to a large amount of carbon dioxide and nitrogen oxide that are released (Daripa et al., 2014; Ozilgen, 2017). The main contributors to acidification are sulphur dioxide (SO2), nitrous oxides (NOx), and reduced nitrogen (NHx). These emissions result from field preparation, fertilisers and crop nurturing. After the elimination of the herbicides, the impact of crop nurture decreases, resulting in a relative impact smaller than 10% (Farinha, Brito, & Veiga, 2021). The last impact category that is not significantly affected by the inputs from crop nurturing is eutrophication. This impact category takes the excessive productivity in the ecosystem into account, which mostly results from the use of fertilizers (Balasuriya, Ghose, Gheewala, & Prapaspongsa, 2022). The impact of crop nurturing is still significant for multiple impact categories, due to the use of insecticides and fungicides to protect the crop, as well as the diesel, that is consumed to spray these inputs.



Graph 1A *Relative impact according to the CML method of the process steps used in the traditional process*

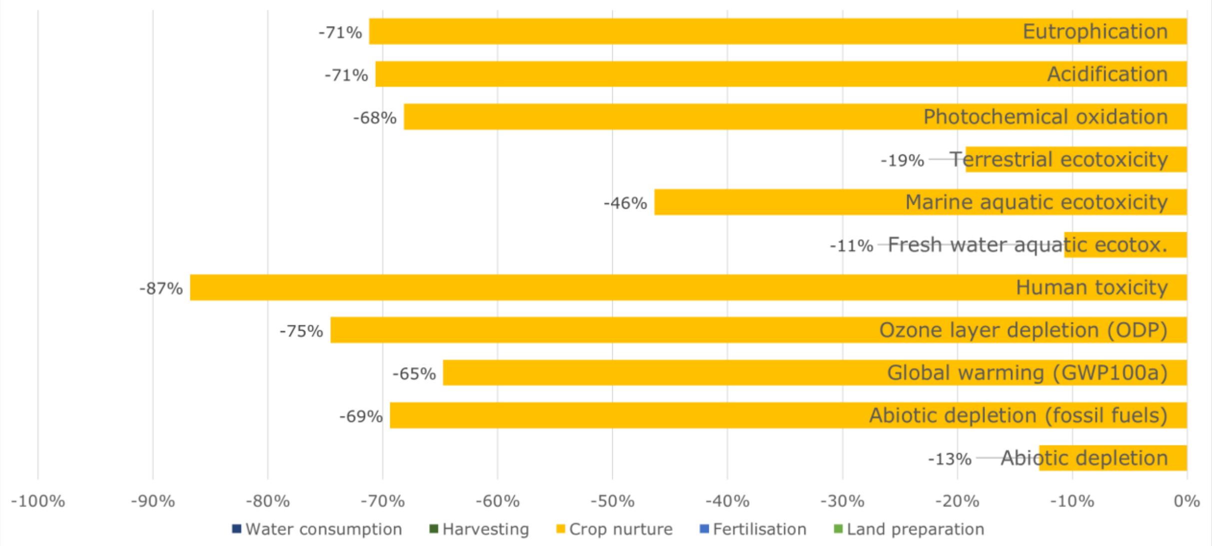


Graph 1B *Relative impact according to the CML method of the process steps used in the innovative cultivation process*

Only inputs used for crop nurturing activities were altered between the two cultivation processes. Therefore, all changes in both the relative and absolute impact values for the whole process can be explained by the crop nurturing activity. Graph 2 shows the percentage change in absolute impact values for all impact categories. A distinction was made between the different cultivation activities. Because all inputs are held constant for the activities except crop nurture, only crop nurture shows changes in absolute impact values. The percentage change values in graph 2 differ from the values in table 4. This is because the values in table 4 take the absolute impact for the whole cultivation process into account and graph 2 allocates the impact change to a specific cultivation activity.

The elimination of herbicides and the introduction of an electric agro-robotic for mechanical weeding had the largest impact on human toxicity (HT). Human toxicity, which refers to the effects of chemicals on human health, takes the potentially dangerous chemicals to humans into account that are absorbed through inhalation, ingestion, and even contact (Acero et al., 2015). The elimination of herbicides has a significant benefit on human health, as the absolute impact value change accounted for 87%. Eutrophication, acidification and ozone layer depletion are also significantly affected when the robot is used. The percentage change is 71%, 71% and 75% respectively. The elimination of diesel consumption for the spraying activities as well as one mechanical weeding activity contributed the most to the decrease of this absolute impact category

(Daripa et al., 2014; Ozilgen, 2017). Acidification and ozone layer depletion, result from the emissions released when herbicides are used and are eliminated in the new cultivation method. The other percentage impact changes range from 11 to 69% and show significant environmental benefits (Balasuriya et al., 2022).

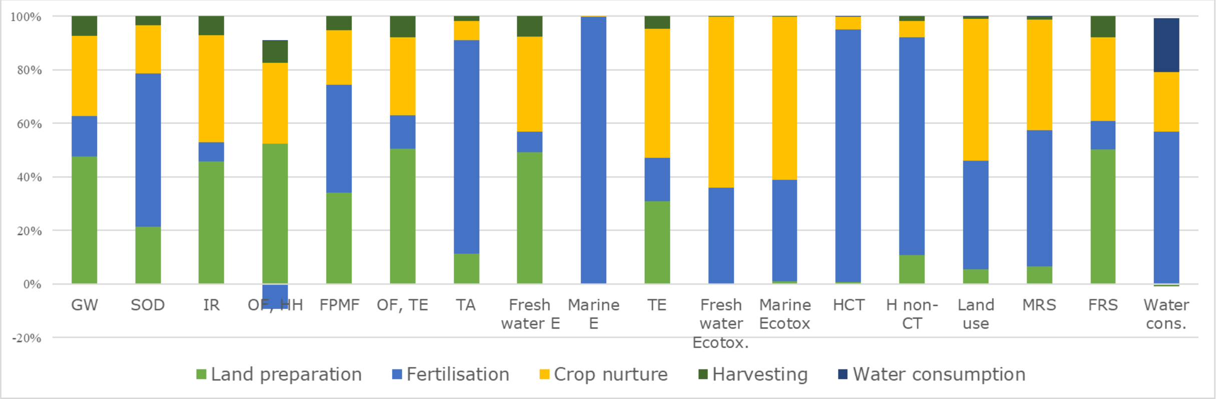


***Graph 2** Absolute impact percentage change per cultivation activity for the CML assessment method*

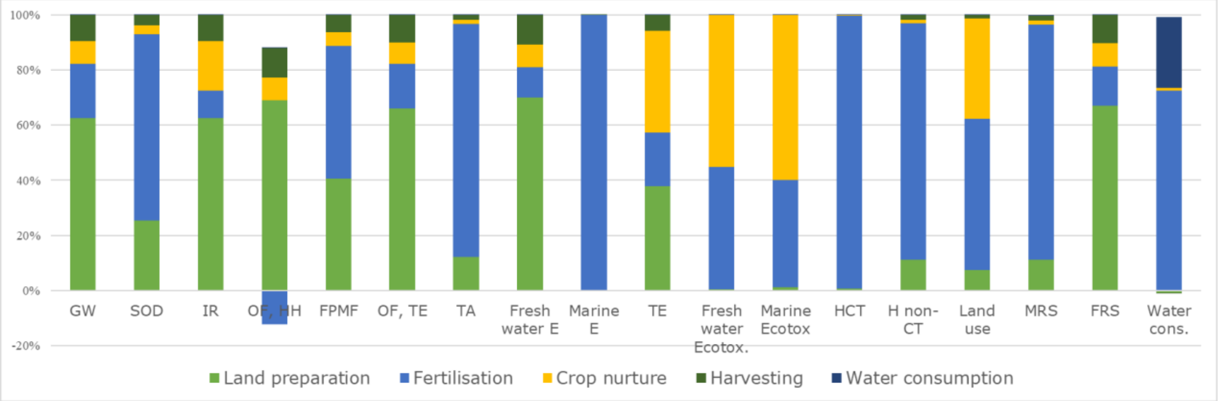
3.3 ReCiPe midpoint (h) assessment method

In this section, the results regarding the ReCiPe midpoint (h) method are discussed and compared between both cultivation processes. Graphs 3A and 3B demonstrate the relative impacts of both production processes, taking all cultivation activities into account. Water consumption does show to have one significant impact, which differs from the CML-IA assessment method. The water consumption activity has an impact equal to 20 and 26 percent for the traditional and new cultivation methods, respectively. This assessment method devoted a specific impact category to water consumption (water cons.). For this impact category, the usage of chemicals and minerals in fertilisation and crop nurture activities have a larger relative impact than the water consumption activity itself. The sprays and fertilizers used in the cultivation process have a significant impact on the consumption of water because it makes the resource more scarce due to pollution (Manjarres-López et al., 2021).

Land preparation and fertilisation show significant relative impacts on multiple categories. The relative impacts of marine eutrophication (Marine E), human carcinogenic toxicity (HCT) and human non-carcinogenic toxicity (H non-CT) can be mainly allocated to fertilisation, which accounts for over 90%. Fertilizers have significant impacts on the abnormal productivity of, for example, algae (Acero et al., 2015). Distinct in this assessment method is that fertilizers have a negative impact on ozone formation regarding human health. This implies that NOx triggers the generation of ozone in the atmosphere. The land preparation activity only shows a relative impact, over 50%, on ozone formation (OF), for the traditional cultivation process. This is in line with the findings of the CML-IA baseline method. In this assessment method, the inputs regarding land preparation, fertilisation, harvesting and water consumption are also constant between both cultivation processes. Therefore changes in relative impacts for these activities result from the changes in absolute impacts from the crop nurture activities. Herbicides are eliminated as well as mechanical weeding with a tractor. They are replaced by mechanical weeding with a robot. Crop nurture shows to have a significant relative impact on all categories in the traditional cultivation process. This implies that the elimination of inputs used for crop nurturing could lead to multiple environmental benefits. Comparing the traditional to the new cultivation process, the elimination of diesel and herbicides in the crop nurturing activity showed multiple relative impact changes, as can be seen in graph 3B.

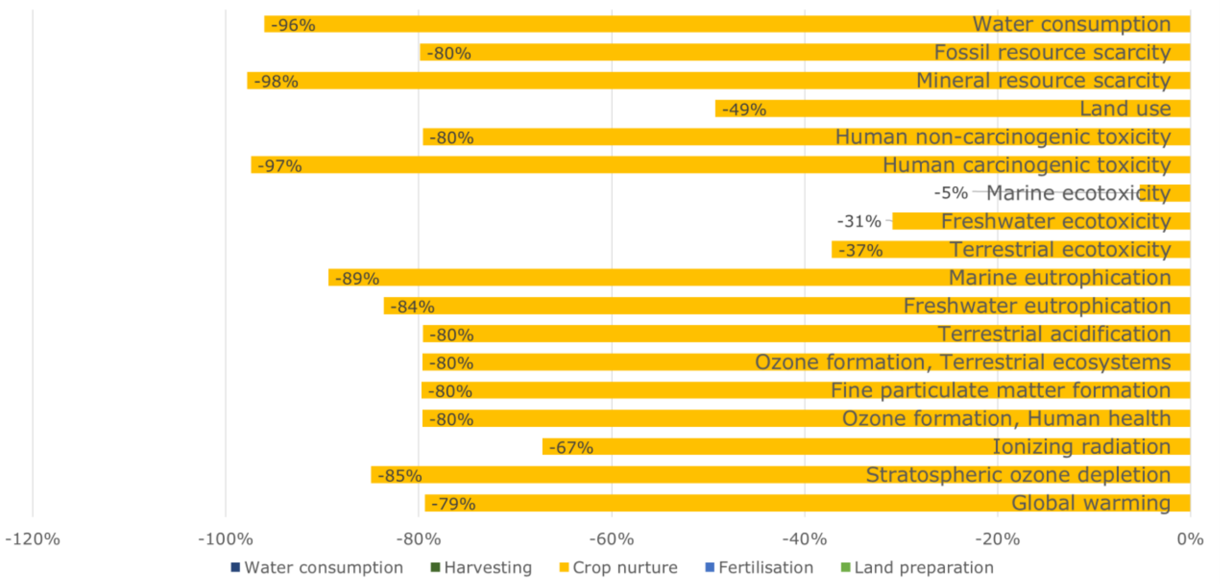


Graph 3A *Relative impact according to the ReCiPe method of the process steps used in the traditional cultivation process*



Graph 3B *Relative impact according to the ReCiPe method of the process steps used in the innovative cultivation process*

The percentage change in absolute impact values, taking the cultivation activities into account for the ReCiPe method, are shown in graph 4. The general percentage change in absolute impacts for crop nurturing is equal to 72.05%, implying a significant decrease in all environmental impacts. The new cultivation process affects all impact categories over 40%, except for terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity, with 37, 31 and 5 percent respectively. The five largest percentage changes will be discussed. Mineral resource scarcity (MRS) is affected the most by the elimination of herbicides and diesel, with a percentage change equal to 98%. Diesel and herbicides are inorganic materials made from different chemicals and minerals. The use of herbicides and fuels demands different minerals to be mined, produced and used, therefore showing a significant impact on this category. This impact category refers to the reduction of geological and natural stocks over time (Acero et al., 2015). The second-largest change occurred for human carcinogenic toxicity (HCT). This impact is defined as: "The change in lifetime disease incidence due to a change in intake of the substance.". The decrease in this impact category implies a decrease in human health risks (Huijbregts et al., 2017). Water consumption is also largely impacted. The elimination of herbicides, thus positively affects the depletion of water sources as less water is used and contaminated (Acero et al., 2015). The absolute impact value of marine eutrophication (Marine E) decreased by 89% for crop nurturing. Marine eutrophication is a process driven by the enrichment of water with nutrients. Other studies showed that the predominant nitrogen load primarily comes from diffuse input materials on land in agricultural areas (EC, n.d.). The last impact category discussed is stratospheric ozone depletion. Stratospheric ozone depletion (SOD) is defined as the time-integrated decrease in stratospheric ozone concentration over an infinite time horizon (Huijbregts et al., 2017). This implies that the robot can decrease the depletion of ozone, causing environmental benefits.



Graph 4 *Absolute impact percentage change per cultivation activity for the ReCiPe assessment method*

4. Conclusion

The comparison of chicory root cultivation methods was assessed by means of an LCA. The traditional cultivation process showed to have larger environmental impacts than the cultivation process using an electric agro-robotic for mechanical weeding, eliminating herbicide treatments. The research focused on the use of a robot, still under development, to mechanically weed in crop nurturing activities. Two LCA assessment methods were used, CML-IA baseline and ReCiPe midpoint (h), resulting in an average decrease in environmental burdens of 19.05% and 18.56%, respectively, for the cultivation process as a whole. The LCA was based on one case study using real data from a chicory farmer in Belgium. The robot is currently not used in real cultivation processes, therefore, the environmental impacts calculated for the new cultivation process are based on assumptions. The result from this research are case-specific averages and could be different for other chicory farmers. The recharging of the battery was also excluded from this research. If the robot is introduced into the market, it is important to revisit the results from this research and compare them to real-world data.

Only a comparison between traditional cultivation, which uses inorganic input materials, and a new, innovative cultivation process using a robot, was conducted. There is also the possibility of biological farming, which is much more labour intensive but few to no chemicals or inorganic materials are used. A comparison between all these cultivation methods is needed in the future to assess if the use of the robot results in the smallest environmental burden. It contributes to conclude which cultivation method truly is the least harmful to the environment.

The introduction of the robot showed to have the largest impact on human toxicity when the CML-IA baseline assessment method was used. This result stems from the elimination of the chemicals used in herbicides that potentially harm human health. For the application of the ReCiPe midpoint (h) assessment method, a similar impact category, human carcinogenic toxicity also showed to have the largest impact change, which is related to the toxins that possess high acute toxicity. The input data used stems from one chicory farmer in Belgium. If another farmer, used other types of herbicides, the impact changes could differ. Therefore, it is advised to use other case studies in the future and compare the results to this research.

Field preparation, fertilisation and crop nurturing activities are the main contributors to environmental burdens in the traditional cultivation process. When herbicides are eliminated in the production process, as well as diesel consumption by heavy vehicles for weeding, the environmental impacts decrease significantly. This forces field preparation and fertilisation to be the main contributors to the environmental burdens or hotspots in the cultivation process. It is necessary to develop new technologies or make adjustments to the robot to further decrease the environmental impact of the cultivation activities because there is still a long way to go if we want to minimize the environmental burden of the cultivation process as a whole.

5. Acknowledgements

The research was conducted in a partnership with the Institution for Fishery, Agriculture and Food Research (ILVO) situated in Merelbeke. This research will be used as an information resource for the CIMAT-project which is co-executed by ILVO. The project is meant to get a better understanding of the usage of high tech agriculture vehicles for the cultivation of multiple products (ILVO, 2020). ILVO developed a multi-purpose agro-robot based on panel discussions and co-creation with farmers. One of the most important success factors for such robotics is flexibility, which has been a disadvantage for new machinery. Next to flexibility, the robot is expected to facilitate environmental benefits, which is studied in this research (ILVO, 2020).

Multiple people were interviewed to gather knowledge and insights regarding the cultivation of chicory roots as well as the inputs used in the cultivation process. Laurens De Meerleer provided input data used in the cultivation process which was reviewed as a case study for the impact assessment. Tim De Clercq, a chicory cultivation expert, contributed valuable insights regarding the cultivation process of chicory. A last external contributor is Simon Cool, one of the project leaders of the CIMAT-project, who provided information on the need for environmental impact assessments as well as information regarding the robot itself

This paper was written with the guidance of Prof dr. Sebastien Lizin, the promotor of this thesis, and dr. Freddy Navarro Pineda, the co-promotor. They contributed important knowledge on the execution of quantitative research as well as the impact assessment used in this research. A lot of models and methods used in this research are first time practices of theories learned at the

University of Hasselt. They provided feedback throughout the whole process that contributed to the final results.

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7. Appendices

7.1 Appendix 1: Interview guidelines

Table 5 *Interview guideline part 1*

Input type	Unit
Inputs	
Field operations	
Process green manure	l/ha
Ploughing	l/ha
Lime soil	l/ha
Spraying	l/ha
Ploughing (to create fine soils)	l/ha
Prepare for sowing (create ridges)	l/ha
Sowing	l/ha
Spraying (herbicides)	l/ha
Mechanical weeding (with a hoe for weeding)	l/ha
Spraying (fungicides, diseases and other)	l/ha
Cultivating/ harvesting	l/ha
Ploughing (sometimes done after cultivation of the roots)	l/ha
Mechanical weeding (Robot CIMAT project)	kWh
Herbicides:	
Propyzamide (Kerb)	l/ha
Befuraline (Bonalan)	l/ha
Bentazone (Boa)	l/ha
(S-)Metolachlor (Dual gold)	l/ha
Dinotefuran (Safari)	kg/ha
Carbetamide (Legurame)	l/ha
Isoxaben (AZ)	l/ha
Glyphosate (Trend 90%)	l/ha
Diseases and insecticides:	l/ha
Pirimicarb	l/ha
Dimethoate 40%	l/ha
Vinclozolin	l/ha
Lambda-cyhalothrin (Karate)	l/ha
Cyantraniliprole (Benevia)	l/ha
Boscalid (Signum)	l/ha
Pyraclostrobin (Signum)	l/ha
Fosetyl (Aliette)	l/ha
Profenofos (Delstar 50%)	l/ha
Azoxystrobin (Norios)	l/ha
Difenoconazole (Geyser)	l/ha
Spirotetramat (Bandaka or Movento)	l/ha
Water	l/ha
Fertilisers	
N (KAS) (12,12,17)	kg/ha
P2O5 (Tripelsuper) (0,45,0)	kg/ha
K20 (kali-60) (0,0,60)	kg/ha
Ammonium nitrate (18,0,0)	kg/ha
Calcium nitrate (15.5,0,0)	kg/ha
Output	
Yield roots	ton (DM)/ha
	#

Table 6 *Interview guideline part 2*

Part	Question/ Description	Answer	Remarks
Introduction	Introduce interviewer	-	
	Describe research	-	
	Describe the goal of the conversation	-	
Cultivation process of chicory roots	Can you describe every step taken to produce chicory roots?	Open	Differs for every interviewee
	Is thinning still used?	Yes or no	
	What happens to the chicory plant because only the roots are used?	Open	
	Do you have any information regarding the mass balance?	Open	None of the interviews had information
Inputs used for the cultivation of chicory roots and the amount used	Can you tell me if and how much of a certain input is used for each of the following inputs?	Show table and fill in together	

7.2 Appendix 2: Fungicides, herbicides, insecticides and fertilizers equivalents in SimaPro and input models in SimaPro

Table 7 *Active ingredients of the herbicides, fungicides and pesticides used in the cultivation and their equivalent SimaPro input*

Name of the active ingredient (name of the spray)	Density of the ingredient (kg/l)	Equivalent name in the software database	Emission	Amount of active ingredients present in the spray (%)
Herbicides				
Propyzamide (Kerb)	1.13	Benzoic-compound	Promanide	35.60
Benfluralin (Bonalan)	1.42	Dinitroaniline	Benfluralin	19.10
Bentazone (Boa)	1.30	Bentazone	Bentazone	48
(S-)metolachlor (Dual gold)	1.10	Metolachlor	Metolachlor. (s)	88
Dinotefuran (Safari)	-	Unclassified herbicides	Pyriproxyfen	20
Carbetamide (Legurame)	1.18	Carbamate-compound	Carbetamide	30
Isoxaben (AZ)	0.58	Unclassified herbicides	Isoxaben	45
Glyphosate (Trend 90%)	1.70	Glyphosate	Glyphosate	90
Insecticides. fungicides				
Pirimicarb	1.18	Carbamate-compound	Methyl carbamate	100
Dimethoate 40%	1.30	Aliphatic organothiophosphate	Dimethoate	40
Vinclozolin	1.51	Fungicide unspecified	Vinclozolin	100
Lambda-cyhalothrin (Karate)	1.33	Insecticide unspecified	Lambda-cyhalothrin	2.50
Cyantraniliprole (Benevia)	1*	Insecticide unspecified	Chlorantraniliprole	10.26
Boscalid (Signum)	1.50	Fungicide unspecified	Boscalid	26.70
Pyraclostrobin (Signum)	1.34	Fungicide unspecified	Pyraclostrobin	6.70
Fosetyl (Aliette)	1*	Organophosphorus-compound. unspecified	Fosetyl	80
Profonos (Delstar 50%)	1.50	Organophosphorus-compound. unspecified	Deltamethrin	50
Azoxystrobin (Norios)	1.34	Fungicide. at plant	Azoxystrobin	24
Difenoconazole (Geyser)	1.37	Fungicide. at plant	Difenoconazole	25
Spirotetramat (Bandaka)	1.22	Fungicide. at plant	M-methoxyphenol	15
Fertilizers (N%,P%,K%)				
Ammonium nitrate (18,0,0)	-	Ammonium nitrate	(Navarro Pineda. n.d.)	-
Calcium nitrate (15.5,0,0)	-	Calcium nitrate	(Navarro Pineda. n.d.)	-

*No information found regarding the density of the active ingredients thus assumed to be equal to 1 (same as water)

Table 8 *Inputs used and SimaPro version 9.3 model equivalents used*

Input used	Model chosen in SimaPro 9.3
Field preparation	
Field operations	
Ploughing (with Amazone Pegasus)	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Ploughing (with Steeno)	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Ploughing (with Amazone Pagasus)	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Ploughing (with scissor plough)	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Lime soil/ fertilisers	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Ploughing (creating fine soils)	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Prepare and sow (ridges + sowing)	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Fertilisation	
Field operations	
Lime soil/ fertilisers	1 tkm Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Production of fertilisers (non-organic)	
N (12,12,17)	Inorganic nitrogen fertiliser, as N {BE}| market for inorganic nitrogen fertiliser, APOS, S
P2O5 (0,45,0)	Inorganic phosphorus fertiliser, as P2O5 {BE}
K20 (0,0,60)	Inorganic potassium fertiliser, as K2O {BE}| market for inorganic potassium fer as K2O | APOS, S
Ammonium nitrate (18,0,0)	Ammonium nitrate {RoW}| market for ammonium nitrate | APOS, S
Calcium nitrate (15.5,0,0)	Calcium nitrate {RER}| market for calcium nitrate | APOS, S
Crop nurture	
Field operations	
Spraying 1 (herbicides)	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Spraying 2 (herbicides)	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Mechanical weeding (weeding hoe)	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Spraying 3 (herbicides)	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Spraying (fungicides and insecticides)	Transport, tractor and trailer, agricultural {RoW}| processing | APOS, S
Mechanical weeding with Robot	**1 MJ Electricity, low voltage {BE}| market for | APOS, S**
Production of herbicides	
Propyzamide	Benzoic-compound {GLO}| market for | APOS, S
Befuraline	Dinitroaniline-compound {GLO}| market for | APOS, S
Bentazone	Bentazone, at plant/RER Mass
(S-)metolachlor	Metolachlor {GLO}| market for | APOS, S
Dinotefuran	Unclassified herbicides, at plant/RER Mass
Carbetamide	[thio]carbamate-compound {GLO}| market for | Alloc Def, U
Isoxaben	Unclassified herbicides, at plant/RER Mass
Glyphosate	Glyphosate {GLO}| market for | APOS, S
Production of insecticides and fungicides	
Pirimicarb	[thio]carbamate-compound {GLO}| market for | Alloc Def, U
Dinotefuran 40%	Aliphatic organothiophosphate insecticides, at plant/RER Mass
Vinclozolin	Fungicide, at plant/RER Mass
Lambda-cyhalothrin	Insecticide, at plant/RER Mass
Cyantraniliprole	Insecticide, at plant/RER Mass
Boscalid	Fungicide, at plant/RER Mass
Pyraclostrobin	Fungicide, at plant/RER Mass
Fosetyl	Organophosphorus-compound, unspecified {GLO}| market for | APOS, S
Profenofos	Organophosphorus-compound, unspecified {GLO}| market for | APOS, S
Azoxystrobin	Fungicide, at plant/RER Mass
Difenoconazole	Fungicide, at plant/RER Mass
Spirotetramat	Insecticide, at plant/RER Mass

7.3 Appendix 3: Results sensitivity analysis

***Table 9** Absolute impact values sensitivity analysis for the power of the agro-robotic*

Impact category	Unit	P robot= 0 kW	P robot = 20 kW	Difference between the two extreme scenarios (%)
CML-IA baseline				
Abiotic depletion	kg Sb eq	6.9704E-05	6.9714E-05	0.01
Abiotic depletion (fossil fuels)	MJ	3.6324E+02	3.6325E+02	0.00
Global warming (GWP100a)	kg CO2 eq	1.7690E+02	1.7690E+02	0.00
Ozone layer depletion (ODP)	kg CFC-11 eq	4.5165E-06	4.5166E-06	0.00
Human toxicity	kg 1.4-DB eq	3.1016E+00	3.1018E+00	0.00
Fresh water aquatic ecotox.	kg 1.4-DB eq	1.4974E+00	1.4974E+00	0.00
Marine aquatic ecotoxicity	kg 1.4-DB eq	1.2821E+03	1.2822E+03	0.01
Terrestrial ecotoxicity	kg 1.4-DB eq	1.9271E-01	1.9272E-01	0.00
Photochemical oxidation	kg C2H4 eq	3.0947E-03	3.0948E-03	0.00
Acidification	kg SO2 eq	2.8041E-01	2.8042E-01	0.00
Eutrophication	kg PO4--- eq	9.2821E-01	9.2821E-01	0.00
ReCiPe midpoint (h)				
Global warming	kg CO2 eq	2.6653E+01	2.6654E+01	0.00
Stratospheric ozone depletion	kg CFC11 eq	3.9443E-05	3.9443E-05	0.00
Ionizing radiation	kBq Co-60 eq	1.8616E-01	1.8621E-01	0.03
Ozone formation. Human health	kg NOx eq	2.1570E-01	2.1570E-01	0.00
Fine particulate matter formation	kg PM2.5 eq	1.2011E-01	1.2011E-01	0.00
Ozone formation. Terrestrial ecosystems	kg NOx eq	2.9314E-01	2.9315E-01	0.00
Terrestrial acidification	kg SO2 eq	6.8641E-01	6.8641E-01	0.00
Freshwater eutrophication	kg P eq	2.9063E-03	2.9063E-03	0.00
Marine eutrophication	kg N eq	4.7876E-01	4.7876E-01	0.00
Terrestrial ecotoxicity	kg 1.4-DCB	5.7298E+01	5.7301E+01	0.01
Freshwater ecotoxicity	kg 1.4-DCB	2.9352E+00	2.9352E+00	0.00
Marine ecotoxicity	kg 1.4-DCB	2.0099E+00	2.0099E+00	0.00
Human carcinogenic toxicity	kg 1.4-DCB	6.9376E-01	6.9378E-01	0.00
Human non-carcinogenic toxicity	kg 1.4-DCB	7.0806E+02	7.0806E+02	0.00
Land use	m2a crop eq	6.6724E-02	6.6775E-02	0.08
Mineral resource scarcity	kg Cu eq	1.4254E-02	1.4258E-02	0.03
Fossil resource scarcity	kg oil eq	8.0146E+00	8.0148E+00	0.00
Water consumption	m3	3.3888E-02	3.3888E-02	0.00

***Table 10** Absolute impact values sensitivity analysis for the number of weeding activities with a tractor, holding the amount of herbicides constant*

Impact category	Unit	Traditional cultivation (base case)	2 times mechanical weeding with tractor (% change to base case)		3 times mechanical weeding with tractor (% change to base case)	
CML-IA baseline						
Abiotic depletion	kg Sb eq	7.4727E-05	7.4793E-05	0.09%	7.4860E-05	0.18%
Abiotic depletion (fossil fuels)	MJ	4.4274E+02	4.6465E+02	4.95%	4.8655E+02	9.89%
Global warming (GWP100a)	kg CO2 eq	1.8261E+02	1.8419E+02	0.86%	1.8577E+02	1.73%
Ozone layer depletion (ODP)	kg CFC-11 eq	5.5327E-06	5.8231E-06	5.25%	6.1136E-06	10.50%
Human toxicity	kg 1.4-DB eq	8.1129E+00	8.2249E+00	1.38%	8.3369E+00	2.76%
Fresh water aquatic ecotox.	kg 1.4-DB eq	1.6280E+00	1.6447E+00	1.03%	1.6614E+00	2.06%
Marine aquatic ecotoxicity	kg 1.4-DB eq	1.5857E+03	1.6272E+03	2.62%	1.6686E+03	5.23%
Terrestrial ecotoxicity	kg 1.4-DB eq	2.1394E-01	2.1947E-01	2.59%	2.2501E-01	5.18%
Photochemical oxidation	kg C2H4 eq	3.9130E-03	4.0892E-03	4.50%	4.2654E-03	9.01%
Acidification	kg SO2 eq	3.1956E-01	3.3087E-01	3.54%	3.4218E-01	7.08%
Eutrophication	kg PO4--- eq	9.3691E-01	9.3938E-01	0.26%	9.4185E-01	0.53%
ReCiPe midpoint (h)						
Global warming	kg CO2 eq	3.2406E+01	3.3992E+01	4.89%	3.5578E+01	9.79%
Stratospheric ozone depletion	kg CFC11 eq	4.4423E-05	4.5403E-05	2.21%	4.6383E-05	4.41%
Ionizing radiation	kBq Co-60 eq	2.3613E-01	2.4719E-01	4.69%	2.5826E-01	9.37%
Ozone formation, Human health	kg NOx eq	2.7602E-01	2.9425E-01	6.61%	3.1249E-01	13.21%
Fine particulate matter formation	kg PM2.5 eq	1.3637E-01	1.4113E-01	3.49%	1.4590E-01	6.99%
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.5402E-01	3.7241E-01	5.19%	3.9080E-01	10.39%
Terrestrial acidification	kg SO2 eq	7.1575E-01	7.2416E-01	1.18%	7.3258E-01	2.35%
Freshwater eutrophication	kg P eq	3.7805E-03	3.9716E-03	5.05%	4.1626E-03	10.11%
Marine eutrophication	kg N eq	4.7890E-01	4.7890E-01	0.00%	4.7890E-01	0.00%
Terrestrial ecotoxicity	kg 1.4-DCB	6.5742E+01	6.7833E+01	3.18%	6.9923E+01	6.36%
Freshwater ecotoxicity	kg 1.4-DCB	3.2068E+00	3.2079E+00	0.03%	3.2090E+00	0.07%
Marine ecotoxicity	kg 1.4-DCB	2.0425E+00	2.0447E+00	0.11%	2.0470E+00	0.22%
Human carcinogenic toxicity	kg 1.4-DCB	7.0162E-01	7.0214E-01	0.08%	7.0267E-01	0.15%
Human non-carcinogenic toxicity	kg 1.4-DCB	7.3451E+02	7.4261E+02	1.10%	7.5071E+02	2.21%
Land use	m2a crop eq	8.4459E-02	8.4942E-02	0.57%	8.5425E-02	1.14%
Mineral resource scarcity	kg Cu eq	1.4254E-02	1.4258E-02	0.69%	1.6013E-02	1.37%
Fossil resource scarcity	kg oil eq	8.0146E+00	8.0148E+00	5.15%	1.0869E+01	10.31%
Water consumption	m3	3.3888E-02	3.3888E-02	-0.07%	4.1293E-02	-0.14%

***Table 11** Absolute impact values sensitivity analysis for the number of weeding activities and decreasing the number of herbicide sprayings*

Impact category	Unit	Traditional cultivation (TC)	Eliminating 1 herb. spraying (% change to TC)		liminating 2 herb. sprayings (% change to TC)	
CML-IA baseline						
Abiotic depletion	kg Sb eq	7.4727E-05	7.4588E-05	-0.19%	6.9709E-05	-6.71%
Abiotic depletion (fossil fuels)	MJ	4.4274E+02	3.9599E+02	-10.56%	3.6324E+02	-17.96%
Global warming (GWP100a)	kg CO2 eq	1.8261E+02	1.7924E+02	-1.85%	1.7690E+02	-3.13%
Ozone layer depletion (ODP)	kg CFC-11 eq	5.5327E-06	4.9131E-06	-11.20%	4.5166E-06	-18.37%
Human toxicity	kg 1.4-DB eq	8.1129E+00	7.8744E+00	-2.94%	3.1017E+00	-61.77%
Fresh water aquatic ecotox.	kg 1.4-DB eq	1.6280E+00	1.5923E+00	-2.19%	1.4974E+00	-8.02%
Marine aquatic ecotoxicity	kg 1.4-DB eq	1.5857E+03	1.4938E+03	-5.80%	1.2822E+03	-19.14%
Terrestrial ecotoxicity	kg 1.4-DB eq	2.1394E-01	2.0217E-01	-5.50%	1.9272E-01	-9.92%
Photochemical oxidation	kg C2H4 eq	3.9130E-03	3.5341E-03	-9.68%	3.0948E-03	-20.91%
Acidification	kg SO2 eq	3.1956E-01	2.9544E-01	-7.55%	2.8041E-01	-12.25%
Eutrophication	kg PO4--- eq	9.3691E-01	9.3166E-01	-0.56%	9.2821E-01	-0.93%
ReCiPe midpoint (h)						
Global warming	kg CO2 eq	3.2406E+01	2.9018E+01	-10.45%	2.6654E+01	-17.75%
Stratospheric ozone depletion	kg CFC11 eq	4.4423E-05	4.2328E-05	-4.72%	3.9443E-05	-11.21%
Ionizing radiation	kBq Co-60 eq	2.3613E-01	2.1117E-01	-10.57%	1.8619E-01	-21.15%
Ozone formation. Human health	kg NOx eq	2.7602E-01	2.3725E-01	-14.05%	2.1570E-01	-21.86%
Fine particulate matter formation	kg PM2.5 eq	1.3637E-01	1.2622E-01	-7.44%	1.2011E-01	-11.92%
Ozone formation. Terrestrial ecosystems	kg NOx eq	3.5402E-01	3.1492E-01	-11.04%	2.9315E-01	-17.20%
Terrestrial acidification	kg SO2 eq	7.1575E-01	6.9780E-01	-2.51%	6.8641E-01	-4.10%
Freshwater eutrophication	kg P eq	3.7805E-03	3.3741E-03	-10.75%	2.9063E-03	-23.12%
Marine eutrophication	kg N eq	4.7890E-01	4.7890E-01	0.00%	4.7876E-01	-0.03%
Terrestrial ecotoxicity	kg 1.4-DCB	6.5742E+01	6.1118E+01	-7.03%	5.7299E+01	-12.84%
Freshwater ecotoxicity	kg 1.4-DCB	3.2068E+00	3.0479E+00	-4.96%	2.9352E+00	-8.47%
Marine ecotoxicity	kg 1.4-DCB	2.0425E+00	2.0221E+00	-1.00%	2.0099E+00	-1.59%
Human carcinogenic toxicity	kg 1.4-DCB	7.0162E-01	7.0049E-01	-0.16%	6.9377E-01	-1.12%
Human non-carcinogenic toxicity	kg 1.4-DCB	7.3451E+02	7.1729E+02	-2.34%	7.0806E+02	-3.60%
Land use	m2a crop eq	8.4459E-02	8.0167E-02	-5.08%	6.6749E-02	-20.97%
Mineral resource scarcity	kg Cu eq	1.5797E-02	1.5565E-02	-1.47%	1.4256E-02	-9.75%
Fossil resource scarcity	kg oil eq	9.8530E+00	8.7698E+00	-10.99%	8.0147E+00	-18.66%
Water consumption	m3	4.1350E-02	4.1377E-02	0.07%	3.3888E-02	-18.05%

***Table 12** Absolute impact values sensitivity analysis if the herbicides can not be eliminated in the new cultivation process*

Impact category	Unit	Traditional cultivation	Only elimination of mechanical weeding with tractor	Difference between two scenarios (%)
CML-IA baseline				
Abiotic depletion	kg Sb eq	7.4727E-05	7.4662E-05	-0.09%
Abiotic depletion (fossil fuels)	MJ	4.4274E+02	4.2084E+02	-4.95%
Global warming (GWP100a)	kg CO2 eq	1.8261E+02	1.8103E+02	-0.86%
Ozone layer depletion (ODP)	kg CFC-11 eq	5.5327E-06	5.2423E-06	-5.25%
Human toxicity	kg 1.4-DB eq	8.1129E+00	8.0010E+00	-1.38%
Freshwater aquatic ecotox.	kg 1.4-DB eq	1.6280E+00	1.6112E+00	-1.03%
Marine aquatic ecotoxicity	kg 1.4-DB eq	1.5857E+03	1.5443E+03	-2.61%
Terrestrial ecotoxicity	kg 1.4-DB eq	2.1394E-01	2.0840E-01	-2.59%
Photochemical oxidation	kg C2H4 eq	3.9130E-03	3.7368E-03	-4.50%
Acidification	kg SO2 eq	3.1956E-01	3.0825E-01	-3.54%
Eutrophication	kg PO4--- eq	9.3691E-01	9.3445E-01	-0.26%
ReCiPe midpoint (h)				
Global warming	kg CO2 eq	3.2406E+01	3.0820E+01	-4.89%
Stratospheric ozone depletion	kg CFC11 eq	4.4423E-05	4.3443E-05	-2.21%
Ionizing radiation	kBq Co-60 eq	2.3613E-01	2.2507E-01	-4.68%
Ozone formation, Human health	kg NOx eq	2.7602E-01	2.5779E-01	-6.61%
Fine particulate matter formation	kg PM2.5 eq	1.3637E-01	1.3160E-01	-3.49%
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.5402E-01	3.3563E-01	-5.19%
Terrestrial acidification	kg SO2 eq	7.1575E-01	7.0733E-01	-1.18%
Freshwater eutrophication	kg P eq	3.7805E-03	3.5895E-03	-5.05%
Marine eutrophication	kg N eq	4.7890E-01	4.7890E-01	0.00%
Terrestrial ecotoxicity	kg 1.4-DCB	6.5742E+01	6.3653E+01	-3.18%
Freshwater ecotoxicity	kg 1.4-DCB	3.2068E+00	3.2058E+00	-0.03%
Marine ecotoxicity	kg 1.4-DCB	2.0425E+00	2.0402E+00	-0.11%
Human carcinogenic toxicity	kg 1.4-DCB	7.0162E-01	7.0109E-01	-0.07%
Human non-carcinogenic toxicity	kg 1.4-DCB	7.3451E+02	7.2641E+02	-1.10%
Land use	m2a crop eq	8.4459E-02	8.3984E-02	-0.56%
Mineral resource scarcity	kg Cu eq	1.5797E-02	1.5689E-02	-0.68%
Fossil resource scarcity	kg oil eq	9.8530E+00	9.3451E+00	-5.15%
Water consumption	m3	4.1350E-02	4.1378E-02	0.07%