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To cite this version:

Marilys Pradel, Lucas Mastromatteo, Maeve Malone, Cédric Seguineau. Does autonomy improve the environmental impacts of agricultural robots? The case of vineyard weeding robots. AGRITECH DAY The conference of innovations and solutions for efficient and sustainable agriculture 6TH EDITION, AXEMA, Oct 2023, Rennes, France. hal-04250152

HAL Id: hal-04250152
https://hal.inrae.fr/hal-04250152

Does autonomy improve the environmental impacts of agricultural robots? The case of vineyard weeding robots

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Abstract

In France, the Ecophyto II+ program aims to reduce pesticide use in agriculture by 50% by 2025. Viticulture, as well as other crops, has to develop alternative solutions to chemical weed control. These alternatives can be achieved by mechanical weeding either using tractors or weeding robots. An initial Life Cycle Assessment (LCA) study conducted in 2022 showed that scenarios using weeding robots for intra row management have either greater or lower environmental impacts than conventional ones depending on the impacts considered.

This paper aims to present the updated LCA results of vineyard weeding practices with respect to two main improvements identified from the first study: (i) the transition to operating a robot with and without human intervention, (ii) the updated Life Cycle Inventory of agricultural tractors in order to have a fairer comparison with agricultural robots.

The main results show:

- a drastic reduction of acidification, eutrophication and photochemical oxidation impacts due to the depollution system of the agricultural tractor in the updated LCI
- an increase of mineral depletion and terrestrial ecotoxicity impacts due to the sensors and electronic components of the agricultural tractor in the updated LCI
- a decrease of all environmental impacts when the robot is operated in autonomous mode

These results show the added value of conducting a LCA in order to improve agricultural robot and tractor ecodesign. However, there are still methodological challenges to face with regards to the additional services and functions provided by robots that question the LCA methodology (such as increased security, less soil compaction).

Keywords: Agricultural robot, full autonomy, Life Cycle Assessment, vineyard, mechanical weeding, updated tractor Life Cycle Inventory

1. Introduction

The agricultural sector is facing the double challenge to feed an increasing population while reducing its impact on the natural environment and human health. In consequence, crop yields need to be maintained at a high level in order to secure food supply at the same time as developing sustainable agriculture practices. It involves especially reducing chemical inputs, including pesticides and herbicides. To achieve such goals, the European Union established a framework for community action to achieve the adoption of pesticides compatible with sustainable development (i.e. Directive 2009/128/EC) in 2009. In France, this European Directive was transformed into French national law as the Ecophyto II+ program. This program aimed to reduce pesticide use in agriculture by 50% by the horizon 2025 and to phase out glyphosate use by the end of 2020 for its main uses and by 2022 at the latest for all other uses. Consequently, one of the main actions is to develop alternatives solutions to chemical weed control (French Ministry of Agriculture, 2020).

The most studied alternatives to chemical herbicide use for row crops are selective chemical spraying (that is Drop-on-Demand technologies where only the weed is sprayed and not the entire field) and mechanical weeding. Other solutions such as flaming, hot water, steam or high voltage

(Blasco et al., 2002) exist, but their adoption has been low (Fountas et al., 2020; Steward et al., 2019). Cultivation tillage, often referred to as tertiary tillage, is the most adopted method for mechanical weeding in agricultural crops. It is carried out after crop sowing and consists of shallow tillage by a variety of tools often categorized as hoes or harrows (Rueda-Ayala et al., 2010). For perennial crops, such as vineyards, the most adopted alternatives to chemical herbicides in the main wine-producing countries (Europe, United States, Australia, New Zealand, Chili) are inter-row (between the vine rows) and intra-row (between the vine plants) mechanical weeding and the use of cover crops, also known as grassing. Inter-row mechanical weeding is conducted using cultivation tillage standard tools such as disc harrows, French ploughs, or rotary cultivators while specific tools such as finger, torsion or spring-hoe weeders are used for intra-row mechanical weeding (Cloutier et al., 2007). The intra-row weed management is challenging, as accurate steering is needed to avoid damaging the vine trunks, especially the young ones, by the tools. An accurate guidance system is then required (Manzone et al., 2020; Reiser et al., 2019).

The improvement in precision agricultural tools such as navigation system, distance sensors, cameras and algorithms for weed recognition has created wide opportunities for autonomous weed management in vineyard, market gardening and arable crops and may become a key element of modern weed control (Bajwa et al., 2015; Reiser et al., 2019). Precision agriculture technologies have progressed in two broad classes: large, automated tractor with driver-assist systems such as RTK-GNSS display and autonomous robotic solutions capable of carrying out agricultural tasks with no human intervention (Basu et al., 2020; Pedersen et al., 2006). Development of robotic platforms was allowed by the convergence of precision agricultural tools and maturing mechatronics technology, making autonomous units technically feasible (Lowenberg-DeBoer et al., 2020). Autonomous units identified here have mobile machineries able to perform complex automated functions, without any interaction with humans, and being able to ensure the safety of the operations by themselves. No longer is an operator is needed during autonomous operations to ensure safety. Automation for weed control has been one major fields of research in agricultural robotics in the last few decades. Research had especially focused on the following four core technologies: guidance and perception sensors, level of weed detection and identification, precision intra-row weed removal and mapping (Bechar and Vigneault, 2016, 2017; Fennimore et al., 2016; Fountas et al., 2020; Steward et al., 2019; Utstumo et al., 2018).

Commercial agricultural robots are scarce (Fountas et al., 2020; Shamshiri et al., 2018) and face a low adoption rate in farms (Gil et al., 2023). The most recent publications by Koerhuis (2020) and Lenain et al. (2021) show that about five hundred units of field and harvest robots were commercially available in 2021. Most of the robots intend to eliminate weeds in row crops. France is the country with the most agricultural and field operational robots in use with at least hundreds of units for weed management and about fifty units being used by viticulture entrepreneurs (Koerhuis, 2020). High-added value crops such as vines appear to be the best business cases for the first generation of weeding robots. Indeed, the cultivation of vines is historically a crop that consumes the most chemical inputs compared to arable crops or market gardening. Expectations for robotic alternatives, with high investment capabilities in new technologies, are highest for this crop which explains the significant emergence of agricultural robots in vineyards these recent years. Most of the weeding robots identified within this overview rely on mechanical weed removal (75%) or on local spraying to reduce herbicide use by up to 95% (Koerhuis, 2020).

A recent study by Pradel et al (2022) was conducted to assess the environmental impacts of mechanical weeding practices in vineyards with the TED robot from Naïo Technologies. The main results showed that scenarios using weeding robots for the intra-row management have greater impacts than conventional ones on mineral resource depletion, human toxicity, freshwater ecotoxicity and marine eutrophication due to the manufacture, the lifetime (when assumed short) and the relative specialization of robots for specific tasks. However, these same scenarios have fewer impacts than conventional ones on climate change, fossil resources depletion, ozone depletion, acidification and particle formation, especially when robots are used on plots closed to the winery. This study also highlighted a need for consolidating LCI data for agricultural tractors in order to achieve equivalent comparison between the two technologies and for robot use in the field that is work performance, electrical consumption, autonomous mode.

This new study aims to present the updated LCA results of vineyard weeding practices with respect to two main improvements identified from the first study: (i) the transition to operating a robot with and without human intervention, (ii) the updated Life Cycle Inventory of agricultural tractors in order to have a more accurate comparison with agricultural robots. This study is focused on the intra-row weeding with inter vine hoe in Languedoc vineyard.

2. Materials and Methods

LCA is designed to be the most exhaustive multi-criteria assessment method reflecting the current knowledge on the environmental impacts. LCA aims to quantify all the impacts of human activities on the environment. The LCA method is described by the ISO 14040 standards (ISO, 2006a, b) and recommended by the European Union (ILCD Handbook, 2010). This method is commonly used by industries to eco-design products in various economic sectors (energy, transport, chemical industry, agriculture). LCA follows a four-step procedure that consists of goal and scope definition of the study, inventory data collection, environmental impact assessment and result interpretation according to the goal, the system boundaries, the assumptions and sensitivity analyses made.

Goal and Scope

Our study aims to provide a comparative environmental impact assessment of robotic technologies used to control weeds in vineyard compared to historically in-use technologies (i.e. tractors). As weeding practices are numerous, this study focuses on intra-row weeding practices in Languedoc vineyard for which experimental data is available.

To be consistent with the objectives of the study, the general function of the system studied is to control the development of weeds located under the row in the Languedoc vineyard. This vineyard is characterized by a density of 4,000 vines per hectare, an inter-row width of 2.50 m and an absence of plant cover, whether on the intra-row (90% of the vineyard concerned) or the inter-row (70% of the vineyard concerned). The majority of the intra-row are not grassed (90%). The management of weeds in Languedoc is therefore essentially mechanized. The function studied will therefore be as follows: **to control weeds under the rows of a vine plot in Languedoc by means of mechanized weeding**.

Mechanized weeding practices are very varied. They can be carried out by different weeding tools with different levels of performance depending on the pedoclimatic conditions of the wine-growing area and the annual meteorological variations. In view of the objectives of the study and the function of the system, the functional unit has been defined as **the weeding control under the row for 1 hectare of vines in Languedoc by means of inter vine hoe**.

The concept of temporality is absent from the functional unit because it is assumed that the technological solutions compared: (i) have the same weeding efficiency since they use the same tools (interceps), a single pass is therefore necessary to compare the solutions with each other, and (ii) are carried out under the same pedoclimatic conditions.

Two systems are compared in the study: a conventional system based on the use of a tractor and a robotic system based on the use of a vineyard-weeding robot (TED robot from Naïo Technologies). Each system uses a specific type of machine (tractor or TED robot) as well as agricultural material, energy, and human resources. The system boundaries and the studied systems are described in Figure 1.

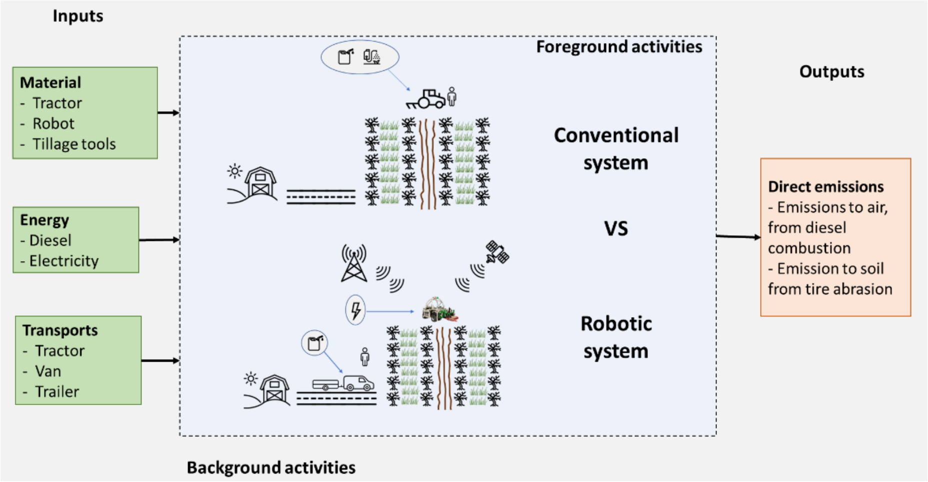

Figure 1. System boundaries and studied systems

To carry out the intra row weeding task, tractor and inter vine hoe were used by the conventional system. When not in use, the tractor and the agricultural equipment were stored in a shed. The distance from the winery to the plot is considered to be 4km. The mounting of the implement, the filling of the tank and the maintenance operations are carried out manually (Figure 1).

TED robot equipped with inter vine hoe is used by the robotic system. The TED robot is guided in the plot by Network Real Time Kinematic Global Navigation Satellite System (NRTK-GNSS). It relies on GNSS satellites, a reference beacon and relay antennas (GSM). When not in use, the TED robot is stored in a shed. Robots are exclusive off-road machinery and are transported to the plot using a van equipped with a trailer. A same distance of 4 km is assumed. The assembly and disassembly of the robot's tools, the recharging of its battery and the maintenance operations are carried out manually (Figure 1).

We assessed three modalities in this study:

- LCI of agricultural tractor was modelled according to data from Ecoinvent database (Te) or updated data from Pradel (2023) (Ta).
- TED robot was operated with a human operator (TEDna) or without a human operator (TEDfa). The TED energy autonomy directly linked to the batteries capacity is reported to be 6h for TEDna and 12h for TEDfa.
- The weeding was carrying out on a square plot (P1: 1 ha, length = 100 m, width = 100 m) or a rectangular plot (P2: 1 ha, length = 152,15 m, width = 65,72 m). For each plot, the vines are planted in the direction of the width.

The studied scenarios are explained in Table 1.

Table 1. Studied scenarios

Scenario code	Scenario characteristic
TEDna_P1	TED robot operated by a human operator in plot P1 – 6 h autonomy
Te_P1	Ecoinvent data used for agricultural tractor LCI and the tractor operated in plot P1
TEDfa_P1	TED robot operated without a human operator in plot P1 – 12 h autonomy
Ta_P1	Updated data from Pradel (2023) used for agricultural tractor LCI and the tractor operated in plot P1
TEDfa_P2	TED robot operated without a human operator in plot P2 – 12 h autonomy
Ta_P2	Updated data from Pradel (2023) used for agricultural tractor LCI and the tractor operated in plot P2

Life Cycle Inventory (LCI) data collection:

Three main types of data were collected: data from the literature available, data from Ecoinvent database, and data provided by manufacturers developing the robotic solutions evaluated (robot composition, energy consumption).

Data for tillage tool, diesel and electricity production came from Ecoinvent V3.7.1 database. The 50-60Kw tractor was modelled based on BCS Valiant 500 AR. This model was chosen based on the availability of the specific fuel consumption among the tractor OCDE test catalogue published by Agroscope[1]. The data for tractor manufacturing came from the Ecoinvent database (Te) or Pradel (2023) (Ta).

A lifetime of 7,200 hours was considered for the tractor and the TED robot. Data for lifetime, masses of tractor and tillage tools as well as fuel consumption come from Agribalyse V3 (Asselin-Balençon et al., 2020). Data for working operation speed came from IFV Occitanie website (https://www.vignevin-occitanie.com/entretien-sol-vie/). Emissions of potentially toxic elements due to tire abrasion and fuel combustion were included in the LCI and came from Nemecek and Kägi (2007). Emissions reduction due to the use of the depollution system for the newly modelled tractor came from the Swiss Federal Office for the Environment (FOEN, 2015). Values used are provided in Table 2. AdBlue® consumption was estimated to be 5% of the fuel consumption.

Table 2. Emission reduction due to depollution system used by tractors solution

Type of emissions	Emission stage		Reduction
	Pre-EU A (before 1995)	EUIV (from 2014)	
CO	3,62	0,5	-86%
HC	0,91	0,17	-81%
NOx	12,52	0,4	-97%
PM	0,61	0,03	-95%
CH_4	0,0218	0,0031	-86%
N_2O	0,035	0,035	0%
C_6H_6	0,0014	0,0002	-86%

Data for TED robot production came from its manufacturer Naïo Technologies. The robot composition is based on the material production of the robot (steel, electronic component). The electricity consumption by TED robot for a working operation was calculated based on the electricity consumption per hour of operation (limited by the battery capacity) multiplied by the operation time (h/ha).

Life Cycle Impact Assessment (LCIA):

Two methods usually used in LCA were chosen for the analysis of the results: the ReCiPe2016 method and the CML-IA method.

3. Results and Discussion

In this section, we will focus on some of CML-IA results. Results are related to intra-row weed control using inter vine hoe of a vineyard plot with an area of 1 hectare for 1 year (equal to 1 crop rotation for vineyards). The comparative results are presented on graphs based on 100%, that is for a given indicator, the most impacting scenario represents 100% and the result of the other scenarios are expressed in relation to this maximum impact.

The impact categories abbreviations are as follows: Abiotic depletion fossil (ADP Fossil), Abiotic

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[1] https://www.agroscope.admin.ch/agroscope/fr/home/publications/recherche-publications/test-tracteurs.html

depletion ultimate reserves (ADP UR), Acidification potential (Acid), Eutrophication potential (Eutro), Global Warming Potential 100 years (GWP), Human Toxicity Potential (HTP), Photochemical Ozone Creation Potential (POCP), and Terrestrial Ecotoxicity Potential (TETP), Particule matter formation (FPMF), freshwater consumption (FC), Freshwater ecotoxicity (Feco), Ionizing radiation (IR°, Land Use (LU), Marine eutrophication (meutro), Stratospheric ozone depletion (SOD).

Figure 2 shows the results obtained for the P1 plot with the tractor modelled either using Ecoinvent data (Te) or data from Pradel (2023) (Ta) and results obtained for the TED robots operated with or without a human operator (respectively TEDna and TEDfa).

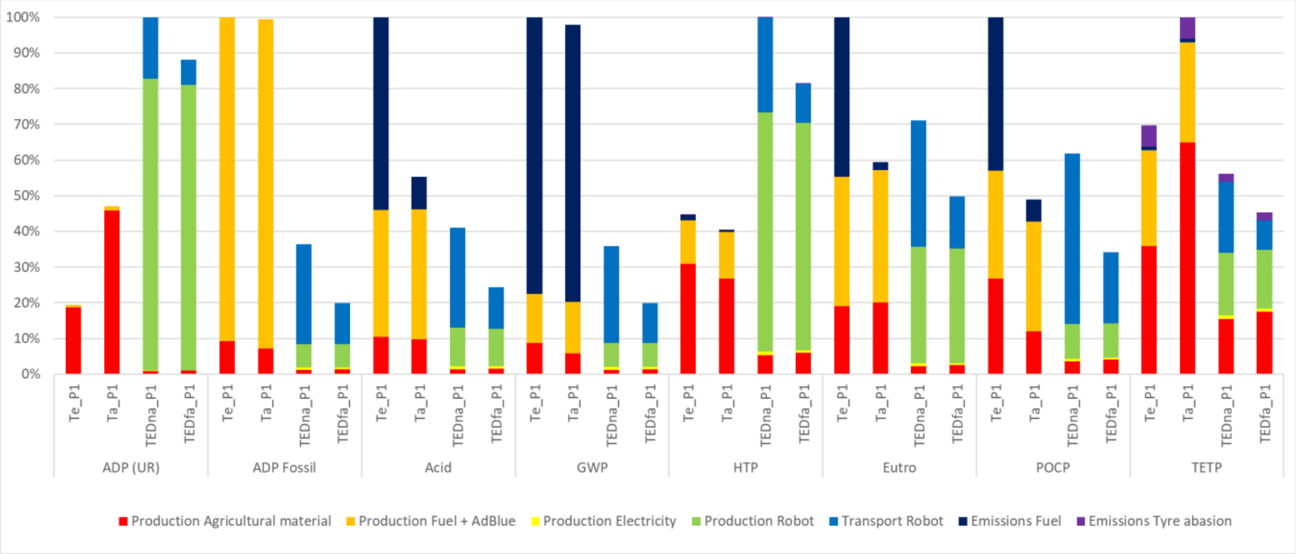

Figure 2. LCA results obtained for 1 ha of intra row weeding with inter vine hoe for P1 plot

The impacts on the mineral resource depletion (ADP (UR)) are much greater for the robotic scenarios (TEDna_P1 and TEDfa_P1) than for the conventional scenarios (Te_P1 and Ta_P1). This difference is mainly due to the production of active electronic components, electric motors and electric cables using for the robot manufacturing. For the conventional scenarios, the impact on the mineral resource depletion is mainly due to the production of the tractor (94% for Te_P1 and 97% for Ta_P1). The LCI update for the tractor shows a 2.48 increase for the ADP(UR). This difference is mainly linked to the lead-acid battery and the on-board electronics which represent respectively 55% and 41% of the ADP(UR) impact. The same explanation is valid for the human toxicity impact category.

The impacts on the fossil resources depletion (ADP Fossil) are much greater for the conventional scenarios (Te_P1 and Ta_P1). These impacts are mainly due to the fuel production used by the tractor. For robotic scenarios, the main contributor is the transport of robots from the farm up to the plot to be weeded (17 to 58% of the impact).

Regarding the impacts on acidification (Acid), the conventional scenarios have a greater impact than the robotic scenarios. The large reduction of the emissions due to the use of a depollution system explains the significant reduction for Ta_P1 (81%). The finding is similar for the eutrophication (Eutro) and photochemical ozone (POCP) impact categories (93% and 85% respectively).

Climate change impact (GWP) is also much greater for conventional scenarios which are the emissions related to fuel combustion (78% for Te_P1 and 79% for Ta_P1). Here we observe very similar values between Te_P1 and Ta_P1 as the depollution system only reduces CH_4 emissions, which is a negligible amount is compared to the amount of CO_2 emitted.

Finally, the terrestrial ecotoxicity (TETP) impact category is much greater for the conventional scenarios, particularly for the Ta_P1 scenario. The main contributor is the production of agricultural equipment. The update LCI of the tractor (Ta), especially the depollution system and the electronic components, explains this increase.

The degree of variation in the impacts between Ta and Te and TEDna and TEDfa is shown in Table 3. The variation between the Ta and Te impacts are very significant for CML-ADP (UR), ReCiPe-FC and ReCiPe-Meutro and in a lesser extent for CML – TETP, ReCiPe – IR, ReCiPe – LU and SOD. For all the other impact, the Ta impacts are lower than for the Te ones. All the impacts of TEDfa are lower than those of TEDna.

Table 3. Impact variation according to the tested modalities Ta/Te and TEDfa/TEDna

Impact	Te	Ta	Variation	TEDna	TEDfa	Variation
CML – ADP (UR)	2,98E-04	7,22E-04	**142,14%**	1,54E-03	1,36E-03	-11,84%
CML – ADP Fossil	8,52E+02	8,46E+02	-0,63%	3,11E+02	1,70E+02	-45,24%
CML - Acid	2,39E-01	1,34E-01	-43,68%	9,80E-02	5,81E-02	-40,71%
CML - GWP	6,01E+01	5,88E+01	-2,18%	2,16E+01	1,20E+01	-44,47%
CML - HTP	2,00E+01	1,81E+01	-9,37%	4,47E+01	3,64E+01	-18,55%
CML - Eutro	6,53E-02	3,95E-02	-39,59%	4,65E-02	3,26E-02	-29,93%
CML - POCP	2,31E-02	1,14E-02	-50,81%	1,43E-02	7,89E-03	-44,78%
CML - TETP	2,28E-01	3,27E-01	43,36%	1,84E-01	1,48E-01	-19,17%
ReCiPe - FPMF	8,90E-02	3,87E-02	-56,49%	3,51E-02	2,13E-02	-39,33%
ReCiPe - FC	4,38E-02	2,45E-01	**458,59%**	1,08E-01	7,63E-02	-29,43%
ReCiPe - Feco	7,33E-01	7,18E-01	-2,12%	2,95E+00	2,48E+00	-15,83%
ReCiPe - IR	5,10E+00	8,56E+00	67,92%	6,31E+00	4,18E+00	-33,80%
ReCiPe - LU	2,37E-01	4,30E-01	81,62%	6,73E-01	3,95E-01	-41,26%
ReCiPe - Meutro	3,06E-04	2,22E-03	**627,12%**	1,71E-03	1,66E-03	-3,19%
ReCiPe - SOD	5,01E-05	5,45E-05	8,76%	1,71E-05	8,97E-06	-47,66%

Figure 3 shows the sensitivity of the plot size on the LCA results for the tractor modelled using data from Pradel (2023) (Ta) and results obtained for the TED robots operated without a human operator (TEDfa).

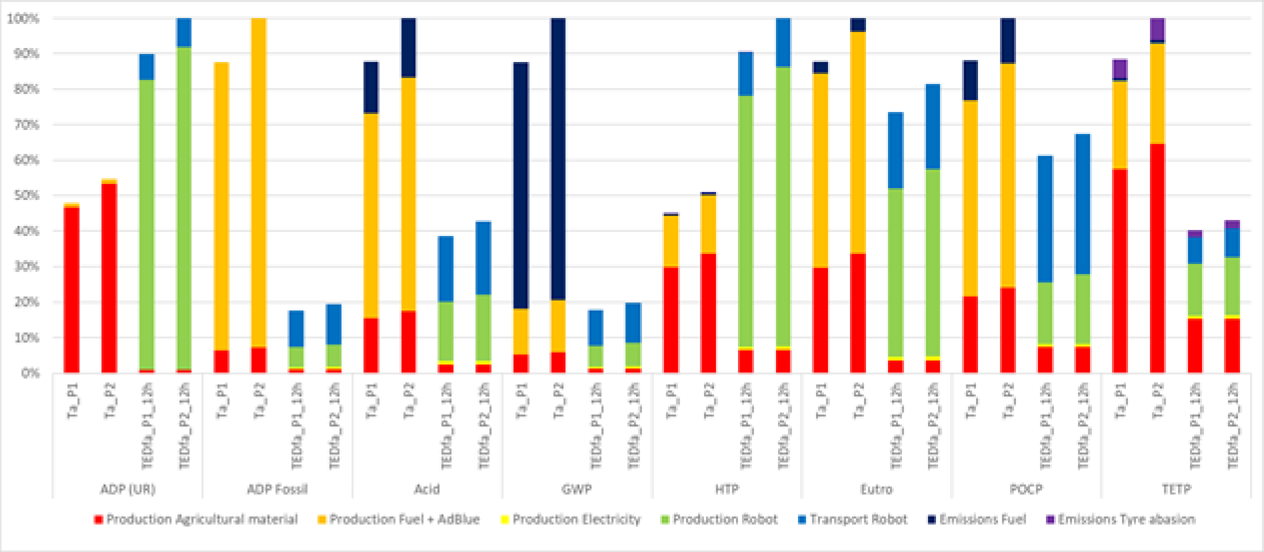

Figure 3. Comparison of LCA results regarding the type of plot weeded (P1 = square shape; P2 = rectangular shape) for 1 ha of intra row weeding with inter vine hoe

Vines in P2 plot are planted, and therefore weeded, in the direction of the width of the plot (shorter side). In consequence, there are more rows to weed than for a square plot such as P1. Thus, the number of turns made by the robot, or the tractor in conventional scenarios, is much greater than in P1. The work performance is therefore lower in P2 than in P1 plot and induces greater impacts for weeding in P2 plot than in P1 due to a greater allocation of the mass of the robot and tractor to the mission as well as a greater consumption of fuel and electricity. A rectangular plot cultivated in the direction of its length could certainly allow a more signification reduction of environmental impacts.

Figure 4 shows the sensitivity analysis of LCA results regarding the autonomy of the TED robot operated with and without a human operator.

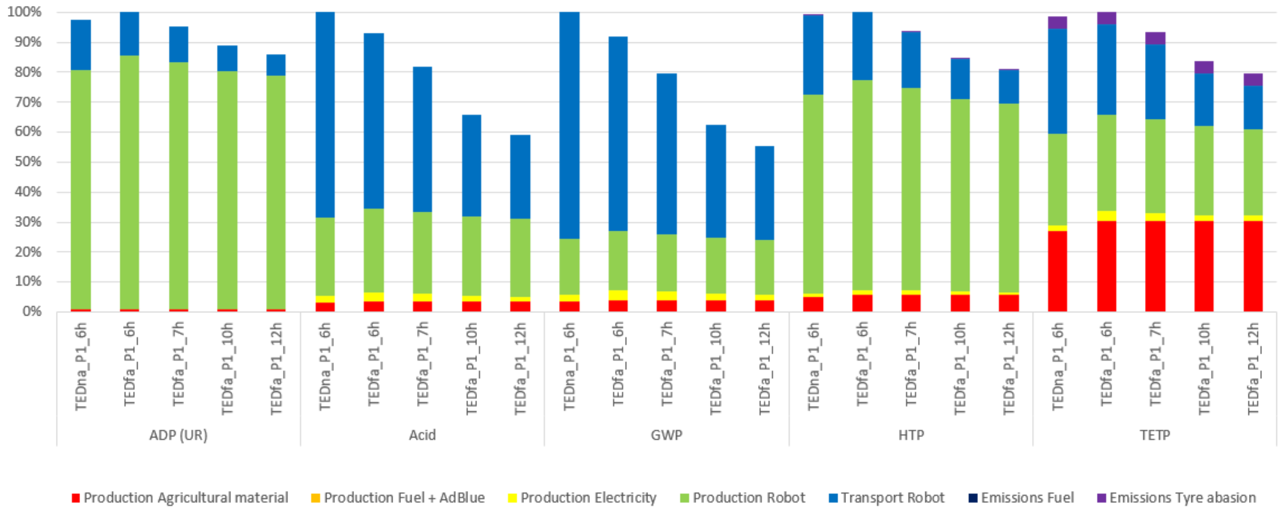

Figure 4. Sensitivity analysis of the TED autonomy with ad without a human operator for 1 ha of intra row weeding with inter vine hoe in P1 plot

The availability of the robot has been increased up to 12 hours per day. That increase from 6 hours to 12 hours is the result of two factors: the increase of the batteries capacity, and the fact that the autonomous operations shall be performed at 0.6m/s or below, in order to ensure the safety of TED operations. In consequence, for one hour of effective work in the field, transport time is divided by two. This is highlighted by LCA results (Figure 4).

When comparing the two scenarios for which the robot's autonomy is identical (6h), we observe greater impacts for TEDfa than for TEDna regarding some impacts such as mineral abiotic depletion, human toxicity (HTP) and terrestrial ecotoxicity. However, we note that the increase in the autonomy of TEDfa (from 6h to 12h) makes it possible to globally reduce the environmental impacts. Indeed, moving from 6h to 12h autonomy allows a reduction of the environmental impacts between 9% (Marine eutrophication – RECIPE) and 46% (fossil resource depletion – CML) depending on the impact category.

4. Conclusions

This paper is aimed at focusing on the main improvements identified for agricultural robots and to answer the following questions:

1. What will be the environmental impacts of agricultural robots that become autonomous? What will be the orders of magnitude of environmental impacts changes for autonomous robots compared to those that are human-operated?

2. What will be the orders of magnitude of environmental impacts changes by using updated inventory data of agricultural tractors?

This study addressed these questions by using the TED robot as an example of technologies available on the market that can operate in an autonomous mode. Indeed, we highlight that robots operated without a human operator relies on technologies and safety strategies which result in a lower speed and work rate of robots but with a longer availability on field. It results in a reduced need to recharge the batteries and to transport the robot to the farm for recharging.

The life cycle inventory for agricultural tractors was updated by integrating the electronics devices, the sensors and the depollution system that have been mandatory for 20 years. This update highlights an increase in impact categories related to mineral depletion and terrestrial ecotoxicity due to the modelling of the electronics devices and the depollution system (that contain vanadium, rhodium and tungsten) and a decrease in impact categories related to acidification and eutrophication due to a severe decrease of air pollution thanks to the depollution system.

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