An environmental comparison of techniques to reduce pollutants emissions related to agricultural tractors

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Abstract

Agriculture is responsible for considerable environmental impact. Much of the impact is related to mechanisation and, in particular, to tractor emissions. Agricultural tractor manufacturers have been forced to adhere to increasingly stringent limits on engine exhaust gas emissions in recent decades. Among the most recent technical solutions to reduce pollutant emissions are included exhaust gas recirculation (EGR) and selective catalytic reduction (SCR), both of which involve critical issues, such as the increase in specific fuel consumption (EGR) or the consumption of a urea solution (SCR). Only a few studies have focused on the environmental consequences related to the application of these solutions to operational agricultural tractors to date.

This study employed the life cycle assessment approach to evaluate the environmental impact of ploughing conducted with two very similar tractors, the first being equipped with EGR and the second with SCR. More in details, considering a full set of environmental indicators, the environmental impact of ploughing carried out with the tractor equipped with the EGR is compared with the ones carried out with the tractor equipped with SRC.

The results show that the SCR-equipped tractor reduced all the impact categories affected by NO_X and particulate matter emissions (from –59% for acidification to –73% for marine eutrophication). However, the influence on Climate Change was much lower (-3%), mainly for the increase of Freshwater Eutrophication (due to the consumption of urea solution in the SCR, as well as to the consumption of tractor, and metal depletion for the higher mass of the tractor.

Keywords

Life Cycle Assessment (LCA), pollutants emission, Exhaust Gas Recirculation (EGR), Selective Catalytic Reduction (SCR)

1 Introduction

Manufacturers of agricultural tractors have been forced by both European Union legislation and corresponding US Environmental Protection Agency to place increasingly stringent limits on engine exhaust gas emissions in recent decades. Similar to the automotive sector, some EU directives (97/68/EC, 2010/22/EU, 2010/26/EU) have defined limits for the emission of nitrogen oxides (NO_X), carbon monoxide (CO), particulate matter (PM) and hydrocarbons (HC) by introducing emission controls for off-road vehicles.

In the Italian agricultural sector, farms are characterised by a broad range of machinery fleet compositions. This framework ranges from farms equipped with underused and outdated machinery to farms equipped with modern and updated machinery that possess the most recent technology. Contractors also play a significant role in this framework, since they have modern machinery that allows them to complete jobs in a prompt and efficient manner. Such variability in the agricultural machinery employed thus makes effective quantification of pollutant emissions from agricultural operations difficult. These difficulties are related to both the collection of data and the site and time dependency of variables (Lovarelli & Bacenetti, 2017a; Pitla, Luck, Werner, Lin, Shearer, 2016), as well as the undefined presence of outdated tractors being used due to the average 25-year lifespan of agricultural tractors in Italy (Bietresato, Calcante, Mazzetto, 2015). This last difficulty complicates the analysis of the environmental load from machinery performed within a reliable framework and, consequently, makes it practically impossible to identify the improvements achieved by modern tractors as replacements for older tractors.

Several studies have highlighted that agricultural production plays an important role on the environmental load with mechanisation being one of the most important processes that is linked to a considerable share of the negative impacts (Bacenetti, Fusi, Negri, Fiala, 2015; IPCC, 2006; Lovarelli & Bacenetti, 2017a; Niero et al., 2015). Agricultural machinery is responsible for greenhouse gases emissions (Lovarelli & Bacenetti, 2017b; Notarnicola et al., 2015) due to fossil fuel production and consumption, as well as the release of exhaust gases. Furthermore, even when analysing a single operation, the geographical, temporal and managerial specificities are relevant to both the inventory data fulfilment (Janulevičius, Juostas, Čipliene, 2017; Perozzi, Mattetti, Molari, Sereni, 2016) and the subsequent quantification of environmental impacts (Lovarelli & Bacenetti, 2017a, 2017b).

Regardless, more stringent emission limits for exhaust gases do not necessarily equate to beneficial environmental effects. For example, the exhaust gas recirculation (EGR) system, introduced to reduce the emission of NO_X, entails an increase in specific fuel consumption of 4–10% (i.e. a similar reduction in engine efficiency) (Volvo, 2010) due to the recirculation of exhausts in the combustion chamber instead of clean air. Conversely, selective catalytic reduction (SCR) is a post-combustion treatment that involves a better fuel efficiency, but the production and use of the urea solution must be taken into account for its environmental impact assessment.

The aim of this study is to employ the life cycle assessment (LCA) method to evaluate and quantify the environmental impacts related to the exhaust gases emitted from two agricultural tractors to better understand the importance of such legislative restrictions from an environmental point of view. The two analysed tractors are equipped with the most recent emissions savings technologies (European Stage IIIA with EGR and European Stage IIIB with SCR) and are characterised by different engine efficiency and by the urea solution production and consumption. A ploughing operation was simulated at a test bench with the two different tractor models, one equipped with EGR and the other with SCR.

2 Materials and methods

The analysis has been performed by adopting the Life Cycle Assessment (LCA) method to quantify the environmental impact of ploughing performed with two very similar tractor models, one of which is the technical evolution of the other.

LCA is a standardised method that is adopted worldwide to quantify the potential environmental impacts of processes by considering their whole life cycle. It allows assessments to be made with a holistic approach, thus avoiding the omission of any important environmental issue. LCA is standardised by ISO 14040 Series, which is carried out following four steps:

1. Specification of the goal of the study, selection of the functional unit and descriptions of the system and system boundary;
2. Life cycle inventory (LCI) data collection, which identifies and quantifies the flow of materials and energy from the system and the environment;
3. Life cycle impact assessment (LCIA), where the inventory data are converted to numeric indicators of environmental impacts by means of specific characterisation factors;

4. Interpretation of the results and identification of the process hotspots.

The LCI of agricultural production cannot always be reliably fulfilled and local data are often not directly measured due to pedo-climatic (e.g., soil texture and water content), site-specific (e.g., field shape, slope) and logistic (e.g., annual working time) conditions that can make it unachievable and/or too complex. Specific databases have been developed to overcome this problem, but the processes available only take into account average pedo-climatic and logistic conditions, which can often be unrepresentative. Therefore, the possibility of modifying processes to make them more reliable by using measured data or information estimated with adequate models is very promising.

The achieved outcomes can be useful for:

- LCA practitioners that focus on agricultural systems and on exhaust gas emission control strategies for off-road vehicles, including agricultural tractors;
- Manufacturers and operators of agricultural machinery to better understand both how and to what extent the respective emission Stages contribute to the environmental sustainability of agricultural production;
- Farmers to better understand their role in reducing the environmental load of the operations they conduct;
- Policymakers to obtain information about the sustainability of field operations and potentially develop dedicated subsidies.

2.1 Goal and scope

The EGR is a combustion system with a dedicated valve in the combustion chamber where a portion of the produced exhaust gases is used as intake air (~5–15% volume of the intake air). This solution reduces the production of NO_X (NO and NO_2) by avoiding peak temperatures during combustion. However, the reduction of clean air available for the combustion results in decreased fuel efficiency, thus requiring increased fuel consumption to achieve the same engine performance.

The SCR is a post-combustion treatment that converts the NO_X produced into molecular nitrogen (N_2) and water vapour by using ammonia as the reducing agent. Ammonia (NH_3) is introduced into the process by a urea solution (32% concentration) in water, which converts the NO_X through thermolysis and hydrolysis. However, since the engine normally works with clean air, the system is more effective, and the fuel efficiency is thus higher (4–5% with respect to EGR: Maiboom, Tauzia, Shah, Hétet, 2009; Volvo, 2010), which also increases the engine lifespan.

Because SCR is a post-treatment solution, agricultural SCR-equipped tractors produce lower NO_X and PM emissions with respect to EGR-equipped tractors. However, unlike the EGR, where a valve drives the recirculation of exhaust gases, an SCR-equipped tractor has a more complex treatment system, which includes a specific tank for the urea solution, a nozzle for its distribution and a specific chamber where the chemical reaction is performed. Furthermore, the production and consumption of the urea solution must also be evaluated. LCA was thus adopted in this study to evaluate whether the reduction of pollutant emissions and the increase in fuel efficiency achieved with the most recent tractor model offsets the environmental impacts related to the urea solution production and consumption.

2.2 Functional unit and system boundary

The selected Functional Unit (FU) for the study is "*the ploughing of 1 ha of flat land field*" to analyse the ploughing with a comparable unit. As shown in **Fig. 1**, the system boundary includes all the inputs and outputs associated with the ploughing operations. Inputs include the mass and energy necessary to complete the process, which takes into consideration the production and use of fuel, lubricant and urea solution (only for the SCR-equipped tractor), as well as the manufacture of the tractors, their implementation and their wear. Outputs include all emissions into the environment, which encompasses the emissions into the soil and water due to metals depletion and tyre abrasion, as well as the emissions into the air due to exhaust gas emissions caused from fuel combustion. The simulated ploughing is studied by performing different tasks, which allows the variations in each of the tractor parameters to be measured (e.g., engine speed, torque, engine load, brake specific fuel consumption, effective field capacity), thus providing a detailed sustainability evaluation. The tasks considered were effective work in the field, turning at the headlands, farm preparations and travelling between the farm and field.

Fig. 1. Around here

2.3 Life Cycle Inventory

The main technical characteristics of the two tractors are given in Table 1. Tractor A (Emissive Stage IIIA, EGR-equipped) and Tractor B (Emissive Stage IIIB, SCR-equipped) have only slightly different engine power ratings (179 kW and 191 kW, respectively). The difference of 12 kW is mainly due to the engine setting and to the different technologies adopted for emissions control. In fact, Tractor B is considered as the more recent version of Tractor A, aimed at complying with the more recent European Directive on emissive limits, but designed to maintain the same performance features.

Table 1. around here

Both tractors were tested using a trailed electromagnetic dynamometer coupled through the power-take-off, working at 1000 rpm (104.7 rad s^{-1}). The ploughing operation was simulated by considering the typical work characteristics of a four-furrow reversible mouldboard plough, working at a 35-cm depth in medium-textured clayey soil and then turning with a fish-tail headland manoeuvre (Sabelhaus, Röben, Meier zu Helligen, Schulze Lammers, 2013). Thus, the mechanical assumption was that the two tractors were working at an engine speed of 1880 rpm (196.8 rad s^{-1}) and 80% engine load.

The main inventory data are reported in Table 2. Fuel and urea solution consumptions were measured at the test bench, taking into account the specific fuel consumption (g kWh^{-1}) for a given partial engine load.

The consumed mass represents the machinery mass (tractor and implement) that is “consumed” during the field operation, such that the overall amount of materials that is consumed during the machinery lifespan is taken into account. This involves quantifying the environmental impact related to the machinery production, maintenance and disposal at the end of lifespan. Here the consumed mass was quantified according to the following equation (Lovarelli, Bacenetti, Fiala, 2016):

$$AM = \frac{m \cdot \left(\frac{T}{L}\right)}{A}, \qquad (1)$$

where AM is the consumed mass of the agricultural machinery (kg ha^{-1}), m is the machinery mass (kg), T is the working time of the operation (h), L is the machinery lifespan (h) and A is the field area (ha).

Table 2. around here.

Considering the exhaust gas emission limits related to the emissive stages of Tractor A (Stage IIIA) and Tractor B (Stage IIIB), **Table 3** reports the engine pollutant emissions during ploughing. These values were calculated with reference to EU Directive 97/68/EC and the following amendments (Directives 2010/22/EU and 2010/26/EU), as well as the equation by Schäffeler and Keller (2008), which takes into account the features of the single tasks of the ploughing operations (i.e. effective field work, turnings at headlands and travelling). Therefore, it is assumed that the emission limits are met during all working conditions, even while working at partial engine loads.

Table 3. around here.

It was assumed that the two tractors each worked for a total of 130 h y^{-1} to accomplish the ploughing operations, with a total annual working time of 500 h for each tractor. Therefore, at the theoretical end of their lifespans (i.e. after 12 y) (Lazzari & Mazzetto, 2016), each tractor worked for 6000 h, which is ~50% lower than the average value available in the literature (Lazzari & Mazzetto, 2016). However, this value is in accordance with the common use and lifespan of machinery operated by Italian farmers (Bietresato, Calcante, Mazzetto, 2015). With regard to the annual working times of tractor and plough, the values were identified considering the agricultural context of Northern Italy. More in details, the considered working times refer to medium-size arable or dairy farms of this area.

The effective field capacity was 0.68 ha h^{-1}. The working time per field task was determined as follows:

- Effective work in the field: 61.2% of the total working time;
- Turns at the headlands (with the fishtail turn manoeuvre, as described in Sabelhaus, Röben, Meier zu Helligen, Schulze Lammers, 2013): 25.6% of the total working time;

- Farm preparation (including coupling and uncoupling of the plough, diesel tank filling, etc.): 6.1% of the total working time;
- Travelling between the farm and field, covering an average one-way distance of 1 km at a travelling speed of 15 km h^{-1}: 6.8% of the total working time.

The engine features of these tasks (referring mainly to the engine load) were assumed for the test bench by taking into account this temporal distinction. The engine load thus ranged between 80–85% during ploughing, 20–35% during turning at the headlands and 20–40% during travelling between the farm and field, with the tractor idling during farm preparation.

For the urea solution, the consumption of liquid urea and demineralised and decarbonised water were taken into account, as well as the following specific energy consumptions: electricity at 0.07 kWh kg^{-1} and natural gas at 1.71 MJ kg^{-1} (Yara, 2017; Bacenetti, Lovarelli, Pessina, 2017).

Background data for the raw materials extraction (e.g., fossil fuels and minerals), manufacture (e.g., tractors and implements), use, maintenance and final disposal of the machinery, as well as for the buildings housing the machinery, were retrieved from the Ecoinvent Database v3 (Weidema et al., 2013). The processes retrieved from the Ecoinvent database are listed in Table 4.

Table 4. around here.

2.4 Life Cycle Impact Assessment

LCIA of the updated characterisation factors from the ReCiPe Midpoint methodology (Goedkoop et al., 2008) was conducted for the following impact categories: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), photochemical oxidant formation (POF), particulate matter formation (PM), metal depletion (MD) and fossil depletion (FD).

3 Results and discussion

Table 5 reports the environmental results of the ploughing operations conducted with tractors A and B, as well as the comparison between the related outcomes per environmental impact category.

Tractor B, which is equipped with the most recent pollutant reduction technique (SCR), shows reduced environmental impacts on almost all the evaluated impact categories. This means that the use of the urea solution for the SCR system does not negatively affect any impact category: the benefits arising from the abatement of pollutants, as well as from the reduced fuel consumption, are higher than the impact related to the urea solution consumption. Moreover, those categories affected by NO_X and NMVOC (Non-methane volatile organic compound) emissions (i.e. TA, ME, POF, PM) show the biggest reduction in environmental load, which ranges between –59% and –73% with respect to the results for tractor A. For CC, OD and FD, the reduction is quite restrained (–3% for each impact category) and is completely related to the reduction in fuel consumption by tractor B. However, there is an increase in the environmental impacts of tractor B compared to tractor A for FE and MD (+9% and +7% for FE and MD, respectively), which is primarily due to the production of the tractor (tractor B has a higher mass than tractor A, in part due of the pollutant abatement device) and to the consumption of the urea solution for the SCR. For FE, the impact is mainly related to the mining activities for minerals extraction, while for MD, the impact is mainly due to the metals used during the manufacturing.

Table 5. around here.

Information regarding the contribution of the production processes to the environmental impact results is reported in **Fig. 2**. Here the absolute impact of ploughing with tractors A (lower bars per impact category) and B (upper bars per impact category) are shown in detail. For each of the assessed categories, the production and use of the urea solution for reducing NO_X with the SCR technology involves substantial environmental benefits due to the efficient abatement of emissions. The production of the urea solution never represents a hotspot process, showing a share of less than 2% on all the evaluated impact categories, and involving, in the meantime, a positive and considerable reduction of the environmental load from field operations.

Fig. 2. Around here.

The main process hotspots are:

- Pollutant emissions from the tractor engine for CC, TA, ME, POF and PM of tractor A (ranging from 71% for TA to 83% of impact for ME), and for CC (77%), ME (32%) and POF (43%) of tractor B. This contribution is mostly related to the pollutant emissions, including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_X), particulate matter (PM_{10}), hydrocarbons (HC) and precursors, such as ammonia (NH_3) and sulphates. For tractor B, which is equipped with SCR, the engine exhaust gas emissions are heavily reduced due to the emission control system, such that the process emissions are a hotspot for only three of the nine evaluated impact categories.
- Diesel fuel production for OD and FD of both tractors. For tractor A, the responsibility is 93% and 89% for OD and FD, respectively, whereas it is slightly lower for tractor B due to the higher engine efficiency (and, therefore, lower fuel consumption) and is 91% and 87% for OD and FD, respectively. Diesel fuel production is also a main contributor for TA (38%) of tractor B.
- Tractor production for FE and MD of both tractors. For tractor A, the contribution is 60% for FE and 50% for MD, while the tractor B contribution is 63% for FE 53% for MD and also 29% for POF. The higher impact of tractor production for FE is related to mining activities for the extraction of hard coal and lignite. For MD, this is due to the extraction and industrial production processes that involve high amounts of iron, aluminium, plastic, glass, and other materials for the machinery manufacturing. Plough production also plays a key role on MD (41% and 38% for tractors A and B, respectively).

The processes of shed for machinery and urea solution production never represent hotspot processes for the analysed ploughing with the two tractors, with values on all the evaluated impact categories <4% for the shed and <2% for urea production.

The primary difference in environmental impact is thus due to the tractor selection, with the adoption of the most modern tractor that possesses the most efficient pollutant abatement system achieving marked environmental impact reductions. Only FE and MD show slight impact increases due to the higher mass of tractor B and to the consumption of urea in the SCR. Given the broad importance of the process emissions on the final outcomes of many of the environmental impacts, these environmental benefits would be even more remarkable if compared to older tractors (e.g., older emission Stages, such as Stage 2 and earlier) that are prevalent in traditional farms (Bietresato, Calcante, Mazzetto, 2015).

Moreover, the outcomes of this study also confirm the deeply remarkable importance of the choice of the inventory data on the LCA results of agricultural operations (Lovarelli, Bacenetti, Fiala, 2017; Lovarelli & Bacenetti, 2017a, 2017b). In particular, adopting pollutant emissions data from an average fleet of machinery may have either a negative or positive affect on the environmental results of the analysis. Similarly, fuel consumption must be appropriately measured or quantified, since it also plays a key role in many impact categories.

3.1 Sensitivity analysis

A sensitivity analysis was performed by introducing variations in the input data responsible for a relevant share of environmental impacts, with the goal of testing the output data robustness. Therefore, although the urea solution plays a fundamental role in the abatement of pollutants and in the improvement of sustainability, no sensitivity analysis was performed on it due to the fact that it only has a negligible influence on the environmental impacts.

The variables on which the sensitivity analysis have been made were:

- Annual tractor working time: –50% and +50%, with respect to the collected value (i.e. 250 h and 750 h);
- Annual plough working time: –50% and +50%, with respect to the collected value (i.e. 65 h and 195 h);
- Diesel fuel consumption: –15% and +15%, with respect to the measured data.

With regard to the annual working times, the considered levels of change allow to take into account the operative conditions of small and big farms.

Tables 6 and **7** report the results of the sensitivity analysis performed on the tractor and plough annual working time, respectively, and **Table 8** gives the diesel fuel consumption sensitivity analysis results.

Table 6, **7** and **8.** Around here.

The annual working times of the tractor and plough affect all the evaluated environmental categories. However, changing the annual working time of the tractors involves a higher impact variation compared to changing the annual use of the plough.

FE and MD are the impact categories that are most affected by changing the annual working times of both the tractor and plough. Varying the annual tractor use from 750 h to 250 h causes the impact of FE to range from –20% to +62% for FE and from –17% to +53% for MD, respectively. Similarly, varying the annual use of plough from 195 h to 65 h causes the impact of FE to range from –8% to +24% for FE and from –13% to +40% for MD, respectively. For these two impact categories, the “consumption” of the tractor during fieldwork is the main hotspot (Fig. 2). The effects on the other impact categories are smaller because they are related to the production and consumption of fuel and urea solution, as well as to their emissions to the air, which motivates the impact of these results on all the other impact categories.

The fuel consumed has a rather linear effect and a strong impact on the results, which are >±10% for almost every category, except FE and MD (which are instead affected by both the tractor and plough consumed masses) for both tractors, and also on ME and PM for tractor B, which are characterised by changes of 7–9% due to the influence of the mass of the machinery.

3.2 Comparison with tractor with no emissions control

The environmental impact of ploughing carried out with Tractor A and B was compared with the impact of ploughing performed using a tractor without any emission control system. The same conditions of field shape, soil texture, working depth and typology of implement (a 4-furrow mouldboard plough) were considered; however, a different tractor (Tractor C) was used. Taking into account that the first emissions limits came into force more than 20 years ago when less powerful tractors (in respect to tractor A and B) were available on the market, a 135 kW power tractor (minimum fuel specific consumption 235 g kWh^{-1}, mass 6665 kg) was considered. It is a tractor present on the market since 1996, thus without emission control strategies. Moreover, at that time, it was the suitable tractor available for the operation considered; therefore, it was selected for allowing at best a comparison with tractors A and B. According to its mechanical features and to the work assumptions for ploughing, a lower working speed (4.3 km h^{-1} instead of 6.0 km h^{-1}), a lower field capacity (0.55 ha h^{-1} instead of 0.68

ha h^{-1}) and a higher annual working time for the plough were taken into account (due to the lower field capacity). For the tractor C, instead, the same total annual working time of tractors A and B was considered (i.e. 500 h y^{-1} for 12 years life span), due to the assumption that tractors are commonly used for several different operations at farms. The fuel consumption during ploughing with tractor C was 39.4 kg ha^{-1}.

Figure 3 reports the comparison among the environmental impacts of ploughing carried out with the three tractors (A equipped with EGR, B equipped with SCR and the last Tractor C not equipped with emission control systems).

Fig. 3. Around here.

For all the evaluated impact categories, the ploughing carried out using tractor C (without emission control systems) shows the highest impacts. The impact reduction achieved thanks to the implementation of EGR ranges from 1% for CC to 43% for PM while, for SCR, it ranges from 3% for CC to 83% for ME. The highest impact reductions are achieved for the environmental impacts mainly affected by the emissions of pollutants with the engine exhaust gases (TA, FE, ME, POF and PM). For CC, the ploughing carried out with tractor A, although characterised by a slightly higher fuel consumption, performs better than the one carried out with tractor C. This occurs thanks to the reduction in the emissions of CO and NOx and to a lower consumption of tractor. Finally, for FD, the impact for ploughing with tractor C is higher respect to the other two considered cases because the lower field capacity involves a higher consumption of tractor and, above all, of plough.

4 Conclusions

The SCR technology involves production costs and materials for the urea device manufacturing (tanks, nozzle, sensors, electronics, etc.) and for the production of the urea solution, it also involves higher fuel efficiency and less pollutant emissions with respect to the EGR. The EGR, instead, involves a low increase in production costs but also a less beneficial environmental effect, since fuel combustion efficiency is reduced due to the partial re-introduction of unclean intake air. While the EGR technology reduces pollutant emissions with respect to the previous Stage 2 tractors, it does not reduce the environmental impacts as much as observed with the SCR technology.

The quantification of the environmental load of the tractors that belong to different emissive stages permits a quantitative assessment of the benefits of modern technologies, and also allows policymakers and stakeholders to make decisions on possible incentives and/or measures that support the introduction of newer machinery on agricultural farms. Furthermore, knowing the age of the tractor fleet improves knowledge of the effective pollutant emissions and their role in the environmental impact evaluations of agricultural processes.

The outcomes of this study highlight the impact variations related to the adoption of two of the most used emissions control systems (EGR and SCR). With this regard, the achieved results can be extended to other tractors equipped with the same devices in order to get a figure about their environmental performances. Nevertheless, with regard to the absolute impacts, the achieved results cannot be extended because they depend on site-specific conditions (e.g., soil texture, field shape, distance from the farm) that affect the field capacity and the fuel consumption. Furthermore, it should be noted that the effectiveness of EGR and SCR systems is not always the same, since it varies among the different tractors depending on specific settings (e.g., for the EGR the proportion of exhaust gas recirculated into the engine and for the SCR the amount of urea solution consumption related to the power requirement).

Future evaluation activities must take into account the fact that the adoption of the diesel particulate filter (DPF) will be unavoidable to meet the emissions limits for Stage IV. In particular, tractor manufacturers are moving towards the development of tractors that are no longer equipped with EGR, but with DPF with passive regeneration; this solution will be adopted in substitution of the DPF with active regeneration currently available and characterised by undesired extra consumption of diesel.

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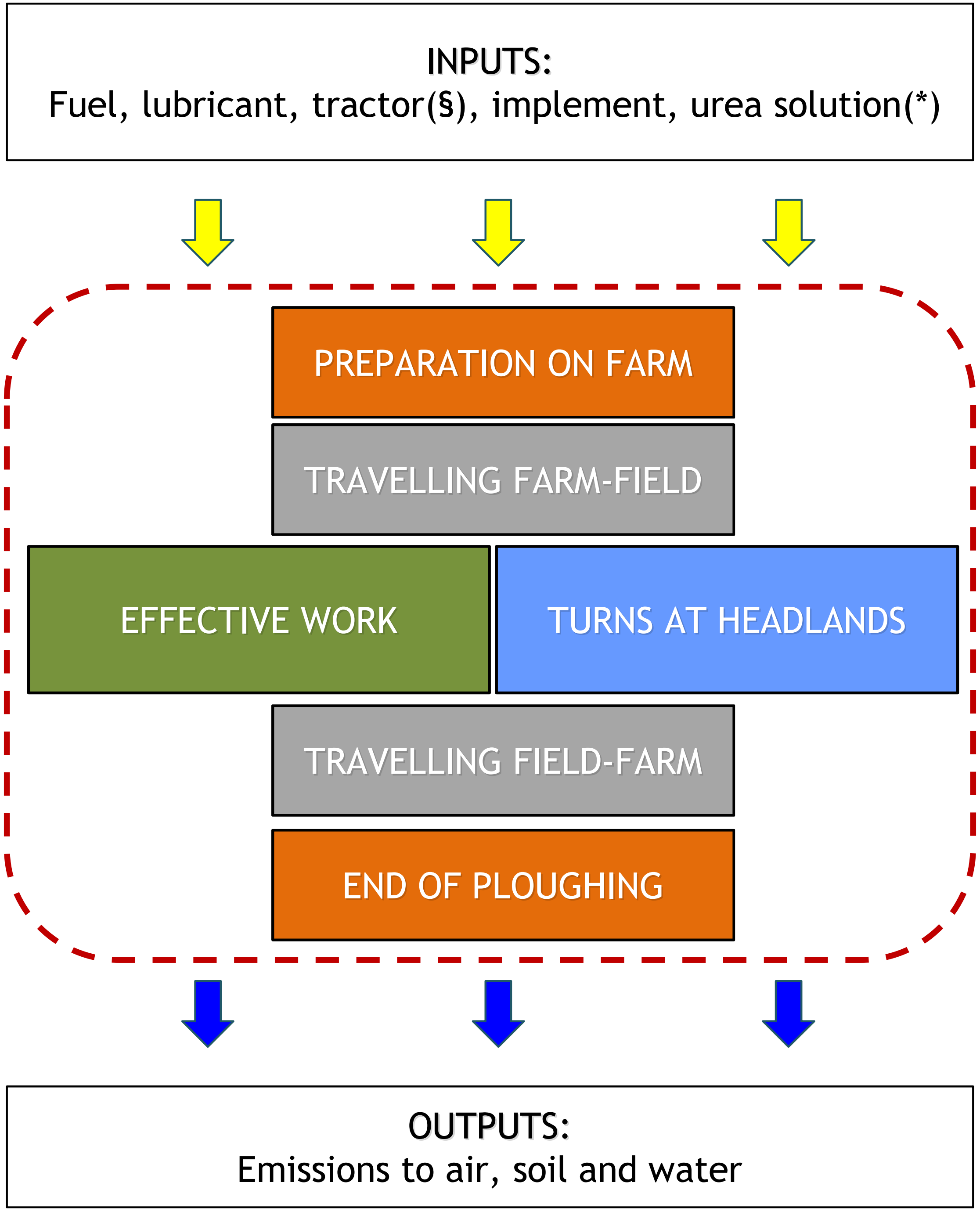
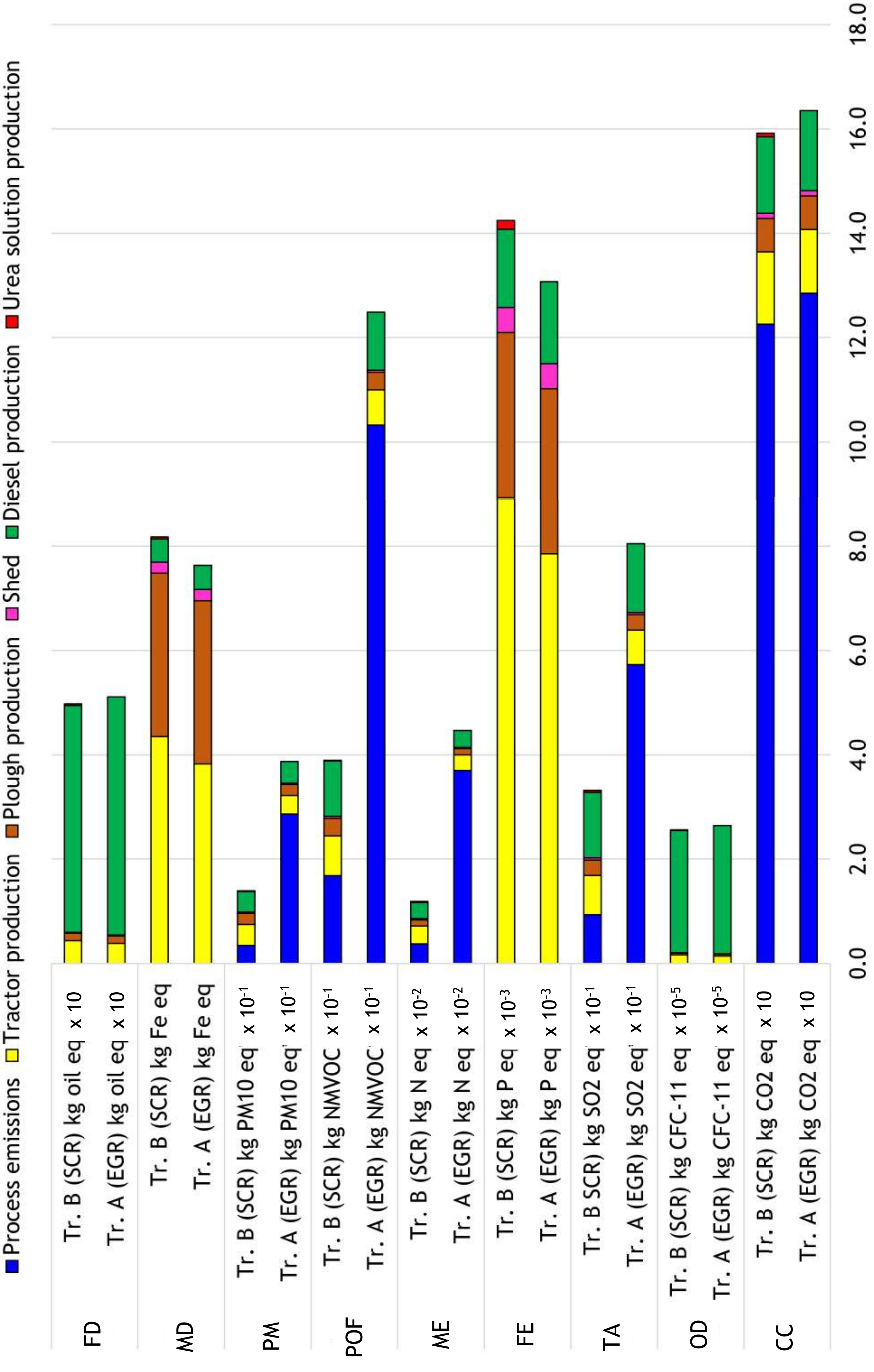
Fig. 1. System boundary for the ploughing process. (§) Two tractors are studied, one equipped with EGR and one with SCR. (*) Only the SCR-equipped tractor is considered for urea solution.

Fig. 2. Hotspot identification of environmental impact results for tractors A (EGR – Stage IIIA; lower bar per category) and B (SCR – Stage IIIB; upper bar per category).

Fig. 3. Comparison among the environmental impacts of ploughing carried out with the three tractors (tractor A with EGR – Stage IIIA, tractor B with SCR – Stage IIIB, and tractor C with no emission control systems).


INPUTS:
Fuel, lubricant, tractor(§), implement, urea solution(*)
PREPARATION ON FARM
TRAVELLING FARM-FIELD
EFFECTIVE WORK
TURNS AT HEADLANDS
TRAVELLING FIELD-FARM
END OF PLOUGHING
OUTPUTS:
Emissions to air, soil and water


■ Process emissions
■ Tractor production
■ Plough production
■ Shed
■ Diesel production
■ Urea solution production
FD
Tr. B (SCR) kg oil eq x 10
Tr. A (EGR) kg oil eq x 10
MD
Tr. B (SCR) kg Fe eq
Tr. A (EGR) kg Fe eq
PM
Tr. B (SCR) kg PM10 eq x 10-1
Tr. A (EGR) kg PM10 eq x 10-1
POF
Tr. B (SCR) kg NMVOC x 10-1
Tr. A (EGR) kg NMVOC x 10-1
ME
Tr. B (SCR) kg N eq x 10-2
Tr. A (EGR) kg N eq x 10-2
FE
Tr. B (SCR) kg P eq x 10-3
Tr. A (EGR) kg P eq x 10-3
TA
Tr. B SCR) kg SO2 eq x 10-1
Tr. A (EGR) kg SO2 eq x 10-1
OD
Tr. B (SCR) kg CFC-11 eq x 10-5
Tr. A (EGR) kg CFC-11 eq x 10-5
CC
Tr. B (SCR) kg CO2 eq x 10
Tr. A (EGR) kg CO2 eq x 10
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0

Nomenclature

SCR	Selective Catalytic Reduction
EGR	Exhaust Gas Recirculation
DPF	Diesel particulate filter
FC	Fuel consumption (kg ha^{-1})
NO_X	Nitrous oxides (g ha^{-1})
CO	Carbon monoxide (g ha^{-1})
CO_2	Carbon dioxide (kg ha^{-1})
PM	Particulate matter (g ha^{-1})
HC	Hydrocarbons (g ha^{-1})
N_2	Molecular nitrogen
NH_3	Ammonia
NMVOC	Non-methane volatile organic compound
AM	Consumed mass of tractor or agricultural machinery (kg ha^{-1})
m	Mass (kg)
T	Working time of the operation (h)
L	Machinery lifespan (h)
A	Field area (ha)
FU	Functional Unit
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
CC	Climate Change (kg CO_2 eq.)
OD	Ozone Depletion (mg CFC-11 eq.)
TA	Terrestrial Acidification (kg SO_2 eq.)
FE	Freshwater Eutrophication (g P eq.)
ME	Marine Eutrophication (g N eq.)
POF	Photochemical Oxidant Formation (kg NMVOC.)
PM	Particulate Matter Formation (kg PM10 eq.)
MD	Metal Depletion (kg Fe eq.)
FD	Fossil Depletion (kg oil eq.)

TABLE

Table 1. Main technical characteristics of the two tractor models considered.

Characteristic	Unit	Tractor A	Tractor B
Rated power	kW	179	191
Emission Stage (§)	-	IIIA	IIIB
Emission control technology	-	EGR	SCR
Minimum specific fuel consumption	g kWh^{-1}	212.7	196.1
Urea solution consumption	%	n.a.	3.4–6.2%(*)

(§) Emission standards regulation from EU Directive 97/68/EC and following amending ones.

(*) With respect to fuel consumption, in percent volume.

Table 2. Inventory data for the Tractor A and Tractor B ploughing operations.

Variables		Unit	Tractor A, Stage IIIA with EGR	Tractor B, Stage IIIB with SCR
Mass of tractor		kg	7200	8140
Mass of plough		kg	1280	1280
Fuel consumption		kg h^{-1}	27.5	26.2
		kg ha^{-1}	40.3	38.4
Urea solution consumption		dm^3 h^{-1}	--	1.08 (3.4% vol. *)
Working time per year	Tractor	h y^{-1}	500	500
	Plough	h y^{-1}	130	130
Consumed mass (AM)	Tractor	kg ha^{-1}	1.53	1.74
	Plough	kg ha^{-1}	1.04	1.04

(*) With respect to fuel consumption, in percent volume.

Table 3. Exhaust gas emissions during ploughing operations.

Exhaust gas	Unit	Tractor A, Stage IIIA with EGR	Tractor B, Stage IIIB with SCR
CO_2	kg ha^{-1}	12.69	12.10
CO	g ha^{-1}	349.1	166.1
NO_X	g ha^{1}	947.2	94.3
PM	g ha^{-1}	69.7	5.5
HC	g ha^{-1}	66.8	48.2

Table 4. Processes retrieved from the Ecoinvent database v3 (Weidema, Bauer, Hischier, Mutel et al., 2013).

Ecoinvent Process	Note
Tractor, four-wheel, agricultural {GLO}| market for | Alloc Def, U	The value reported in the Ecoinvent process "Tillage, ploughing {CH}| processing | Alloc Def, U" was modified considering a life span of 12 y and an annual working time of 500 h
Agricultural machinery, tillage {GLO}| market for | Alloc Def, U	The value reported in the Ecoinvent process "Tillage, ploughing {CH}| processing | Alloc Def, U" was modified considering a life span of 8 y and an annual working time of 130 h
Shed {GLO}| market for | Alloc Def, U	No changes were made to the Ecoinvent process
Diesel {Europe without Switzerland}| market for | Alloc Def, U	The consumption reported in the Ecoinvent process "Tillage, ploughing {CH}| processing | Alloc Def, U" was modified according to the measured data
Water, completely softened, from decarbonised water, at user {GLO}| market for | Alloc Def, U	For the manufacturing of the urea solution consumed in the SCR
Urea, as N {RER}| production | Alloc Def, U	
Electricity, medium voltage {Europe without Switzerland}| market group for | Alloc Def, U	
Heat, district or industrial, natural gas {RER} | Alloc Def, U	

Table 5. Ploughing operation results conducted with tractor B (equipped with SCR) and tractor A (equipped with EGR).

Impact category	Unit	Ploughing with		Δ (*)
		Tractor B, Stage IIIB with SCR	Tractor A, Stage IIIA with EGR	
CC	kg CO2 eq	159.19	163.51	–3%

OD	mg CFC-11 eq	25.62	26.45	–3%
TA	kg SO2 eq	0.33	0.81	–59%
FE	kg P eq	0.014	0.013	+9%
ME	kg N eq	0.012	0.045	–73%
POF	kg NMVOC	0.39	1.25	–69%
PM	kg PM10 eq	0.14	0.39	–64%
MD	kg Fe eq	8.18	7.63	+7%
FD	kg oil eq	49.76	51.11	–3%

Note: CC (Climate Change), OD (Ozone Depletion), TA (Terrestrial Acidification), FE (Freshwater Eutrophication), ME (Marine Eutrophication), POF (Photochemical Oxidant Formation), PM (Particulate Matter), MD (Metal Depletion), FD (Fossil Depletion).

(*) Difference between the environmental impact of ploughing carried out with tractor B and tractor A expressed in percentage terms and for each impact category.

Table 6. Sensitivity analysis of tractor annual working time.

Impact category	**Tractor A, Stage IIIA EGR: tractor 250 h y^{-1}**	**Tractor A, Stage IIIA EGR: tractor 750 h y^{-1}**	**Tractor B, Stage IIIB SCR: tractor 250 h y^{-1}**	**Tractor B, Stage IIIB SCR: tractor 750 h y^{-1}**
CC	+7.46%	–2.49%	+8.66%	–2.90%
OD	+5.38%	–1.79%	+6.28%	–2.11%
TA	+8.21%	–2.74%	+22.50%	–7.54%
FE	+60.06%	–20.02%	+62.33%	–20.90%
ME	+6.72%	–2.24%	+28.59%	–9.58%
POF	+5.40%	–1.80%	+19.56%	–6.56%
PM	+9.21%	–3.07%	+28.95%	–9.71%
MD	+50.13%	–16.71%	+52.92%	–17.74%
FD	+7.46%	–2.49%	+8.67%	–2.91%

Note: CC (Climate Change), OD (Ozone Depletion), TA (Terrestrial Acidification), FE (Freshwater Eutrophication), ME (Marine Eutrophication), POF (Photochemical Oxidant Formation), PM (Particulate Matter), MD (Metal Depletion), FD (Fossil Depletion).

Table 7. Sensitivity analysis of plough annual working time.

Impact category	**Tractor A, Stage IIIA EGR: plough 65 h y^{-1}**	**Tractor A, Stage IIIA EGR: plough 195 h y^{-1}**	**Tractor B, Stage IIIB SCR: plough 65 h y^{-1}**	**Tractor B, Stage IIIB SCR: plough 195 h y^{-1}**
CC	+3.93%	–1.31%	+4.04%	–1.35%
OD	+1.27%	–0.42%	+1.31%	–0.44%
TA	+3.66%	–1.22%	+8.89%	–2.96%

FE	+24.20%	–8.07%	+22.21%	–7.40%
ME	+2.65%	–0.88%	+9.98%	–3.33%
POF	+2.71%	–0.90%	+8.68%	–2.89%
PM	+5.50%	–1.83%	+15.29%	–5.10%
MD	+40.98%	–13.66%	+38.26%	–12.75%
FD	+2.81%	–0.94%	+2.89%	–0.96%

Note: CC (Climate Change), OD (Ozone Depletion), TA (Terrestrial Acidification), FE (Freshwater Eutrophication), ME (Marine Eutrophication), POF (Photochemical Oxidant Formation), PM (Particulate Matter), MD (Metal Depletion), FD (Fossil Depletion).

Table 8. Sensitivity analysis of diesel fuel consumption.

Impact category	Tractor A, Stage IIIA EGR: fuel –15%	Tractor A, Stage IIIA EGR: fuel +15%	Tractor B, Stage IIIB SCR: fuel –15%	Tractor B, Stage IIIB SCR: fuel +15%
CC	–13.31%	+13.36%	–12.75%	+13.04%
OD	–13.95%	+13.95%	–12.00%	+13.80%
TA	–13.06%	+13.06%	–8.75%	+10.09%
FE	–1.81%	+1.81%	–1.53%	+1.76%
ME	–13.42%	+13.42%	–7.73%	+8.93%
POF	–13.65%	+13.65%	–9.21%	+10.63%
PM	–12.62%	+12.62%	–7.03%	+8.11%
MD	–0.91%	+0.91%	–0.77%	+0.88%
FD	–13.40%	+13.40%	–11.48%	+13.20%

Note: CC (Climate Change), OD (Ozone Depletion), TA (Terrestrial Acidification), FE (Freshwater Eutrophication), ME (Marine Eutrophication), POF (Photochemical Oxidant Formation), PM (Particulate Matter), MD (Metal Depletion), FD (Fossil Depletion).