Environmental impact assessment of field mechanisation for a sustainable agriculture

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Abstract

For the assessment of the environmental impact of agricultural machinery operations the collection of primary data is very useful because it permits to consider the local pedo-climatic and operative variables. However, only with recent technologies installed on modern tractors this can be more easily carried out.

In this study, the aim is to present a methodology that permits to improve the reliability of inventories for environmental sustainability studies carried out with the Life Cycle Assessment (LCA) approach. The tool ENVIAM is presented; it is characterised by the construction of an agricultural machinery operation made of single working times. In each of them, fuel consumption and engine exhaust gases are calculated and finally summed in a total value for the operation. To improve the capabilities of this tool, measurements have been carried out on field using a tractor equipped with CAN-bus, a data-collection software, GPS and engine exhaust gas analyser in order to measure fuel consumption and engine exhaust emissions data and to develop a prediction model for these variables.

The combination of CAN-bus, GPS and engine exhaust gas analyser is very effective and results having a widespread and promising role on several points of view, among which the environmental one. In particular, monitoring the field operation permits to identify the conditions in which improvements and inputs reductions can be reached.

Keywords: Agricultural machinery, big data processing, efficiency improvement, environmental sustainability, Life Cycle Assessment

1. Introduction

During recent decades, there has been a growing interest in quantifying and reducing the environmental impact of agricultural productions, mainly for freshwater pollution and emissions of greenhouse gases (Notarnicola et al., 2015). Among the agricultural activities, mechanisation is related to a substantial share of these negative effects (Niero et al., 2015).

Although lately standardised and extensively accepted methods for environmental impact assessment were developed (ISO 14040 series, 2006), their application to mechanical field operations is still limited (Lovarelli et al., 2017). This is due, on one side, to the difficulties in inventory data collection since they are site and time dependent and, on the other side, to the carefulness of machinery manufacturers that are developing concerns about the consumer (farmer) perceptions. With regard to inventory data collection, data can be obtained from both a primary source (i.e. directly collected or measured) and a secondary source (i.e. databases, scientific literature). Certainly, primary data are the most reliable but also the most difficult and time consuming to get. Especially for agricultural productions, the geographical, temporal and managerial specificities are much relevant on the inventory fulfilment and on the subsequent environmental impacts quantification. This is mainly because the local variables (soil texture, field shape, climate and seasonality, machinery adopted and management choices) can affect most of the environmental loads (Bacenetti et al., 2015).

Considering mechanisation of field operations, the availability on the market of modern tractors and implements and of new techniques or management strategies determines the importance of collecting primary data for appropriate assessments. In particular, thanks to modern technologies installed on modern tractors such as CAN-bus (Controller Area Network), a huge amount of data is accessible and is measurable constantly and simultaneously to the work on field (Fellmeth, 2003; Pitla et al., 2016). These data describe how the engine works as well as instant working features and interactions in the tractor, which encompasses the possibility of deeply increasing the analyses reliability on modern machinery and of optimising inputs use and management (Bietresato et al., 2015).

Primary data are needed. In fact, although secondary data are more easily available, they may include simplifications and average values that do not describe correctly the studied system. Specifically, the most important side effect of secondary data is that it results unfeasible to quantify the reduction in environmental load achievable with new machines and innovations in technologies, with machines already available on the market (e.g., minimum and strip tillage, sod-seeding) but not included in databases or, merely, by selecting more suitable machines or performing a proper coupling between implement and tractor. In fact, in the most used database applied in Life Cycle Assessment (LCA) studies (i.e. ECOINVENT®), the impact of the most common field operations is included; however, it is assessed considering average pedo-climatic (e.g., soil texture and moisture), operative (field shape, slope and transfer distance) and mechanical conditions (engine features during transfers, turns and working phases) and, consequently, is not always reliable.

In this context, the tool ENVIAM (ENVironmental Inventory of Agricultural Machinery operations) was developed to support the environmental impact evaluation by fulfilling inventories for field machinery operations used in defined local working conditions (Lovarelli et al., 2016). Its application already showed that site and time specific data are very important and can show considerably different results from the average ones (Lovarelli et al., 2017). Therefore, improving the capabilities of a tool such as ENVIAM is essential. The high-level modelling can be reached by monitoring field operations through the modern technology and instrumentation, which is a very useful step forward to agricultural sustainability assessment, efficiency increase and inputs use.

The aim of this study is to describe the main methodological steps to follow to have a reliable quantification model and tool appropriate for inventories that can be obtained thanks to the technological capabilities of recent machinery. In fact, by monitoring a tractor working in several different conditions, it is possible to model the behaviour of the engine also along other field operations with high accuracy. Moreover, this determines the possibility of understanding how the inventory reliability affects the environmental impact results of agricultural machinery operations got through the Life Cycle Assessment (LCA) method.

2. Materials and Methods

The study is inserted in the context of:

(i) the Life Cycle Assessment (LCA) approach, with focus on the inventory fulfilment and on its reliability, and on the consequent environmental impact assessment;

(ii) the mechanisation efficiency improvement, monitoring of work conditions, optimisation of inputs use and technological innovations.

2.1. Life Cycle Assessment

The Life Cycle Assessment (LCA) (ISO 14040, 2006) is a standardised method adopted worldwide for quantifying the potential environmental impacts of processes for products or services during their whole life cycle using a holistic approach. In more details, there are four steps in LCA:

(i) goal of the study, selection of the functional unit, description of the system and of the system boundary;

(ii) Life Cycle Inventory (LCI) data collection, in which the flow of materials and energy from the studied systems and the environment are identified and quantified;

(iii) Life Cycle Impact Assessment; during which, thanks to specific characterisation factors, the inventory data are converted in few numeric indicators of environmental impact;

(iv) interpretation of the results and identification of the process hotspots.

The Life Cycle Inventory is the most complex phase, due to the inputs and outputs data collection that must be trustworthy, in order to obtain correct environmental results. In particular, often, inventory data are obtained from databases (e.g., ECOINVENT®), which may represent a simplification and/or an inappropriate inventory of data for the specific studied system. This occurs because, as explained previously for field operations, the collection of data concerning working times, fuel and lubricant consumption and pollutants emitted into air with the engine exhaust gas emissions is not easy.

2.2. ENVironmental Inventory of Agricultural Machinery operations (ENVIAM)

ENVIAM was developed at the Department of Agricultural and Environmental Sciences, Production, Landscape, Agroenergy at the University of Milan to fulfil the Life Cycle Inventory phase of a LCA study for the most common field operations for crop production (Figure 1).

The strength is that the inventory is completed thanks to the accurate quantification of mechanical parameters (e.g., tractor and machinery characteristics and coupling), of fuel, lubricant and materials consumption, and of engine exhaust gases emissions. In more details, this tool permits to couple tractors and implements having a wide selection of alternative machinery in two databases and permits to fulfil the inventory following a more detailed method: the operation is split in several working times and variables such as absorbed power, fuel consumption and related exhausts emissions are calculated in each of these single working times. The identified working times have been selected from Reboul (1964) and are most significantly distinguished in the effective work on field, turns at the headlands, transfers, refilling/emptying, maintenance, etc. The mechanical and operative variables (e.g., engine load, engine speed, brake specific fuel consumption, working time) affecting power, fuel and engine exhausts are selected for each of the working times and are used to calculate the related fuel consumption and exhaust gases emission; finally, they are summed to obtain the total value of the whole operation.

A user-friendly system characterised by tests is also available to highlight possible inconsistencies on the mechanisation point of view. Further details can be found in Lovarelli et al. (2016, 2017).

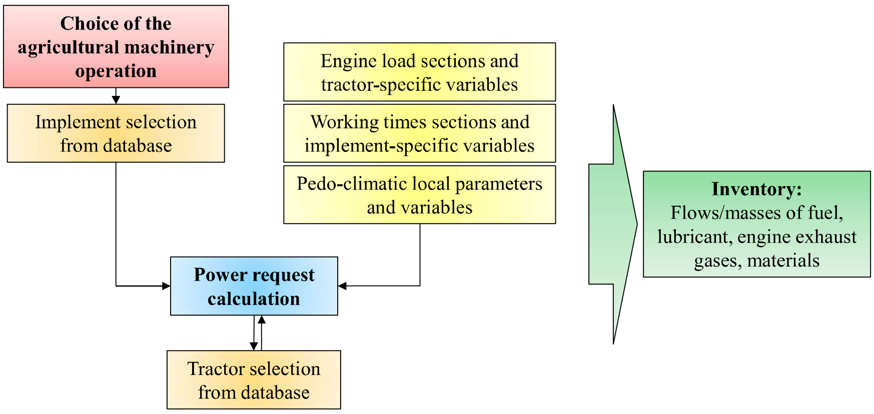

Figure 1. Schematic flow of ENVIAM steps.

One of the major benefits of ENVIAM is that the mechanical calculations permit to couple tractor and implement at the user discretion; therefore, the data about coupling can be referred either to already existing contexts (e.g., from interviews with farmers/workers) or to hypothesised conditions of which studying the inventory results. Another benefit is related to the possibility of building the operation (and therefore the inventory) as sum of working times that compose the operation, which permits to recognise directly what are the most affecting portions on the inventory. Moreover, the alternative implements available on the market also affect the environmental impact, due to different material composition and mass; therefore, the availability in the databases of different implements among which to choose is essential for inventory reliability.

Adopting ENVIAM, the substantial differences in environmental impacts of analyses carried out with local data instead of average data have already been proved through case studies. The deepening of knowledge and the improvement of the quantification tool capabilities has resulted being a much interesting step in view of more accurate assessments related to the machinery innovations.

2.3. Researched improvement

As a first concern, in ENVIAM are available calculation methods and models that require a quite small amount of input information and therefore, although giving very interesting results, may represent a simplification of the complex engine-tractor-implement system. Among these, fuel consumption is one of the major variables that also affects engine emissions.

In particular, it is well known that fuel consumption is affected by several engine characteristics, as well as by operative ones. As regard to the operative characteristics, they involve the pedo-climatic working conditions, the operation in progress, the driver abilities and the sudden variations in engine characteristics (e.g., torque and engine speed). Similarly, and even much more sharply, are again the operative variables that mostly affect (together with the Emissive Stage of belonging) the exhaust gases emissions. Although both fuel and exhaust gases' quantification is already performed in the actual version of ENVIAM, a progress has been foreseen as an essential step in the improvement of inventory data collection. This has been carried out by involving the monitoring, measurement and model development of fuel consumption and exhaust gases emissions following the steps shown in Figure 2.

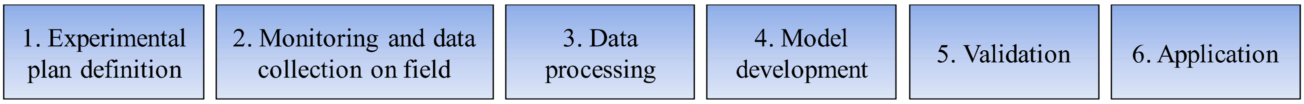

Figure 2. Steps completed from the experimental trials to the model conclusion.

2.3.1. CAN-bus application

Among the techniques developed to map, understand and study the activity of the tractor engine and of the related devices while working on field, the most widespread system is CAN-bus (Controller Area Network). CAN-bus is a frequently available serial high-speed wired data network connection present on modern tractors that permits to electronic devices to communicate with each other and that, coupled with storing instrumentation, permits to collect a huge amount of data directly deriving from the tractor while working on field and with a very detailed time scale (Speckmann and Jahns, 1999). CAN-bus was introduced by Robert Bosch GmbH in 1986, firstly for an automotive application. Applied to agricultural tractors, it is normed with SAE J1939 that defines the connections of electronic devices installed on machinery and then also following the standard protocol ISO 11898 (ISO, 2003).

CAN-bus has permitted to use and take advantage of electronics on agricultural machinery, which results in substantial improvements in the monitoring and big data collection. Mostly, the use of big data is very helpful in the sustainability evaluations because it permits to study each operation, improve the efficiency and control (and potentially reduce) inputs introduction. However, the electronic communication can be applied to other several scopes, such as diagnostics on board, maintenance scheduling, precision agriculture, etc.

Considering the application to data collection for both mechanisation and sustainability assessments, the application of CAN-bus and other instrumentation has two main advantages: first, the continuous monitoring of the operation on field and second, the model prevision that can reach a very high precision thanks to the data collected in a very detailed temporal scale. Implementing such big data of the tractor engine features (e.g., engine speed, engine torque, power) as well as of the working time and speed and of the pedo-climatic features (e.g., soil texture, field shape), permits to build a detailed map of the work of the tractor and, when applied to ENVIAM, to calculate its outputs with additional precision on the operation under study.

The most interesting progress completed with big data referred to tractor engines is that, once the data are collected for the tractor on different working conditions, a robust prevision model can be created. Furthermore, the model itself can be used to predict the behaviour of the tractor working with other implements and during other operations. This means that the monitored tractor is mapped and its behaviour can be reconstructed, although without having further primary data. Therefore, once enough data are available for a robust model development, the prevision becomes essential to further analyses.

2.4. Methods

In order to have the primary data for the improvement of the reliability and applicability of inventories about agricultural machinery, field experiments were carried out at the Swedish Machinery Testing Institute (Umeå, Sweden) and at the Department of Energy and Technology at the Swedish University of Agricultural Sciences in Uppsala. Field experiments were made using: (i) CAN-bus for registering engine data and tractor-related data and a software for data collection and storage; (ii) GPS (Global Positioning System) to have the tractor position and to link this position to the collected data; (iii) a portable emission analyser for exhaust gases emissions measurement and storage (CO_2, CO, NO_X).

Figure 3 shows the tractor and the on-board mounted gas analyser system. The software for storing CAN-bus data is shown in Figure 4.

Figure 3. Valtra N101 tractor with the implemented system to collect exhaust gases for the gases analyser.

Figure 4. On-board software for the collection and storage of CAN-bus data.

The modelled variables were:

(i) fuel consumption (FC; dm^3/h) and

(ii) exhaust gases emissions (EM; g CO_2/h, g CO/h, g NO_X/h).

For all of them, the modelling was carried out introducing the equation reported below (Eq. 1) dependent on torque (M; Nm), engine speed (s; rpm) and engine-specific coefficients (Jahns et al., 1990; Lindgren, 2008). Torque and engine speed were gathered from the measurements, while the 9 coefficients adopted were calculated referred to the equation modelling the semi-static condition and were identified using the minimisation of the error related to variance. FC and EM were quantified per second, following the sensibility of CAN-bus, and afterwards were quantified for all working times. The equation was validated through data obtained during measurements completed with the same tractor.

$$FC = c_1 \cdot s + c_2 \cdot s^2 + c_3 \cdot s^3 + M \cdot (c_4 \cdot s + c_5 \cdot s^2 + c_6 \cdot s^3) + M^2 \cdot (c_7 \cdot s + c_8 \cdot s^2 + c_9 \cdot s^3) \qquad (1)$$

where *FC* is fuel consumption, volume time $^{-1}$; $c_1..c_9$ are engine-specific coefficients, dimensionless; *s* is engine speed, routes time-^{1}; *M* is torque, force length.

FC and EM were also expressed as specific values (brake specific fuel consumption, bsfc, g/kWh; specific emissions, EM_{spec}, g/kWh) in order to be widely comparable.

3. Results and Discussion

Data processing involved a first geographical and spatial analysis of the fields and then the model application for fuel consumption and exhaust gases emissions.

Consequently, the worked fields were analysed in their shape. The available GPS coordinates were used to identify the tractor spatial position and to distinguish the field shape and working states that describe the tractor working activity. This distinction permits to have data and results related to at least three working states, as also shown in Figure 5:

(i) effective work on field (moving forward while working, with a straight direction);

(ii) turns at the headlands (turning position);

(iii) stationary (no change in position, mainly with idling conditions).

In each state, characterised therefore by similar but not equal working features, the measured fuel consumption and exhaust gases were identified to have a series of values referred to the same grouping of states. According to the plan definition of each field and each operation, working features such as working speed, engine speed, torque, engine load, differed.

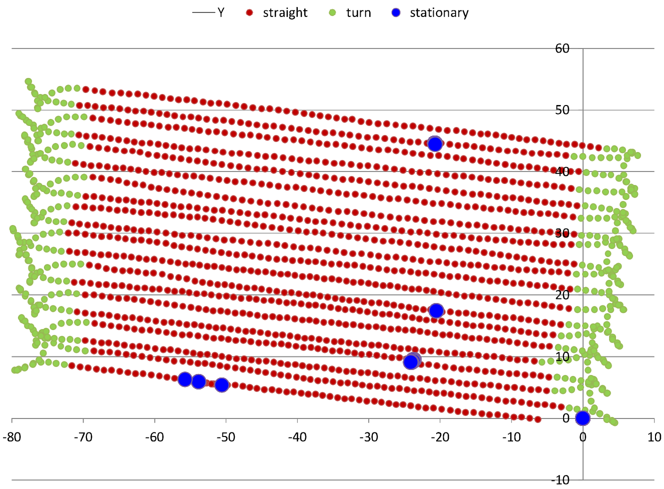

Figure 5. Working states on a field obtained thanks to the processing of the tractor GPS coordinates. Red represents the effective work, green is the turn on headlands and blue is stationary position with no-work ongoing.

Offsetting the positions, both CAN-bus and engine exhaust gases emissions from the analyser could be related to the same temporal position. All results from the measurement, monitoring and from the consequent modelling were also linked to the spatial position of the GPS and, therefore, were attributed to each working state.

With a complete data collection from a tractor in which the combinations concerning power (i.e. product of torque and engine speed) are established, other field operations - even with much different absorbed engine power - can be retraced because the engine features that describe the operation are already mapped. In more details, once the tractor-specific combinations are available, assessments related to fuel consumption and exhaust gases emissions can be obtained thanks to the modelling. Therefore, FC and EM from any operation carried out with the same tractor can be calculated.

A very interesting possibility concerns also the monitoring of exhaust gases emissions that, being measured on field during the operation, represent a step forward in defining the normative emissive limits. Attributing emissions to working states showed that, commonly, considerable and consistent differences emerge along the operation. Especially, with stationary-idling conditions and transient conditions, exhaust emissions of NO_X, CO and CO_2 increased a lot, and they represented up to 15% of the total working time. Measuring data on field it might result more difficult to respect the emissive limits, mainly because they are defined in steady-state conditions and not on field; therefore, although in the steady-state measurements engine exhaust emissions comply with the law, on field there exist more variability. For example, also during turns at headlands the measured engine emissions resulted higher than during the effective work.

From the results, it emerges the huge potential of this technology (CAN-bus + GPS + gas analyser) for environmental sustainability and for the reduction of inputs use. The possibility of linking any collected data and of performing big data processing permits to understand the behaviour of agricultural machinery along any operation. According to the goal, an optimisation of fuel consumption can be reached, mainly by understanding what are the engine conditions that determine the best fuel use and by adopting them. Moreover, any engine feature such as engine speed, engine load, torque, power, etc. can be monitored on a time interval that depends on the sensitivity of the adopted instrumentation and can be used for specific research requirements.

4. Conclusions

In this study was shown that the reliability of inventories carried out with local variables is very important, since the inventory data can deeply affect the downstream results of the study. Primary data are always more reliable than secondary data but their most important side effect is that they can be difficult, time consuming and expensive to get. However, with the spreading of modern technologies on agricultural tractors and modern machinery in general, the collection of primary data regarding mechanisation of field operations is getting easier. First, because the technological improvements are available on any modern tractor and secondly because data can be collected without any specific manpower utilisation, since an assembled software can store them while the tractor is working on field; then those primary data must be processed. Due the ease in measurements with CAN-bus, GPS, emissions analysers and analysis software, inventories for environmental impact assessments can be fulfilled with high reliability. In particular, engine-specific equations able to describe fuel consumption and exhaust gases emissions depending on torque and engine speed and any relevant available information can be developed for the studied tractor.

With such a big amount of available data, a huge potential for tractors analysis can be hypothesised. As shown in the study it is possible, among others, to measure data on field with specific equipment and to assume that the engine's behaviour is the same for other operations, although the operations themselves can differ. In fact, the implement coupled with the tractor – within the same engine features - does not affect the variables concerning the engine behaviour. Accordingly, after having measured tractor data on field and after having analysed and developed specific coefficients for fuel and emissions quantification, different operations can be built, and detailed and reliable inventories can be realised, distinguishing engine by engine.

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