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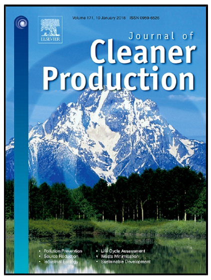

Effectiveness criteria for customised agricultural life cycle assessment tools

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Effectiveness criteria for customised agricultural life cycle assessment tools

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ABSTRACT

Greater use of life cycle assessment (LCA) by agents of change will be needed to inform environmental improvements in agriculture, but the complexity of LCA can be a barrier. More accessible LCA tools customised for agriculture are emerging, but their effectiveness has not been considered. The aim of the work was to understand how tool features influence effectiveness and to propose criteria for effectiveness, for informing the design and evaluation of tools. We define 'customised' tools as those that focus on the life cycle phases and aspects of most relevance for the particular sector (in this case agriculture), and that parameterise practice variables to enable evaluation of practice alternatives. A theoretical framework for the role of tools in agricultural practice change was first used to define the desired objectives of LCA tools: i) to engage agricultural agents of change with LCA by catering to their needs, being accessible and manageable to use, ii) to generate information that users can interpret for informing environmental improvements, and iii) generate information that can align with the wider decision making context. A desktop review of 14 LCA customised agriculture tools identified the features that influence these objectives: tool purpose, mode of access, ease of use, results presentation, degree of practice parameterisation, capacity for regionalised analysis, system scope, impact categories assessed, and alignment with other assessment frameworks. From this, a set of effectiveness criteria for customised LCA tools was developed. A few criteria from amongst this set will be challenges for

future tool development: the balance between analysis capacity and ease of use, enabling regionalised analysis, and the presentation of results in a way that aids interpretation for informing environmental improvements.

1. Introduction

Environmental sustainability is a challenge for agriculture, because it is a major contributor to global environmental impacts, notably degradation of land, deletion of freshwater, pollution from nutrients and pesticides, and greenhouse gas emissions (Godfray et al., 2010; Rockström et al., 2009; Tilman, 2011). The agricultural phase of food production makes a significant contribution to global environmental impacts, and thus agricultural practice change is a key lever for environmental improvement (Keating *et al.*, 2010). Environmental improvement in agriculture refers to changes that reduce dependence on natural resources (fossil fuels, water, land and minerals) and avoid emissions of pollutants to the environment (nutrients, chemical substances, heavy metals, etc.). Environmental life cycle assessment (LCA) is a key method for informing environmental improvements, because it quantifies sources of impacts across the product life cycle for a range of environmental impacts so that environmental improvements can be identified and prioritised (Hellweg and Milà i Canals, 2014; Rebitzer et al., 2004). It has been proven to be relevant for informing practice change in agriculture (Ali et al., 2015; Hass et al., 2001; Kulak et al., 2016; Renaud-Gentie, 2015).

LCA can be complex and time-consuming and standard practice has been to use LCA software designed to manage this complexity. This poses a barrier for its use by agricultural agents of change who may not be able to justify the complex use or cost of LCA software or services. Agricultural agents of change are those responsible for identifying and making decisions about environmental improvements, and include farmers, extension advisors, agricultural researchers, government policy makers, agri-food companies, etc. This challenge has been noted for product supply chains broadly (Baitz et al., 2013; Knight and Jenkins, 2009; O'Rourke, 2014; Rossi et al., 2016), and also for agriculture (van der Werf et al., 2014). “The mainstream application of LCA requires simplification and standardisation to enable consistent and easy use in practice" (Hellweg and Milà i Canals, 2014). Better access to LCA-derived information is known to be a determinant for practice change (Prokopy et al., 2008)

A response has been the development of tools that simplify, streamline or customise LCA to make it more accessible. Those described as 'simplified' tools can generate a partial LCA for screening purposes (Bala *et al.*, 2010), provide a more accessible user interface for LCA software (Arzoumanidis et al., 2017; Rossi et al., 2016), or easier ways of collecting and compiling input data (Bellon-Maurel et al., 2014). Here we are interested in tools that 'customise' the LCA process by focusing on the life cycle phases and aspects that are most relevant or significant to a particular sector (in this case agriculture), and that parameterise practice variables to evaluate alternatives. We chose to focus on 'customised' tools because they tend to be more targeted towards informing environmental improvements. Informing environmental improvements refers to the process of providing relevant facts and information that can guide decisions about practice change.

Customised agricultural LCA tools potentially provide better access to LCA information by providing a simpler, lower-cost method. The targeted assessment possible through customisation can also make it more rapid and site-specific than is possible with conventional LCA software. A potential risk however, as for tools in general, is for them to be underutilised or ineffective through mismatch between the way tools function and the way users make decisions (Cerf et al., 2012). Given the considerable investment required for their development, there is a need to understand how tool design influences effectiveness, so that future investment is money well spent.

There has been very limited discussion in the academic literature about what makes LCA tools effective. Lewis et al (2013) made observations about the effectiveness of GHG accounting tools for informing mitigation opportunities in arable cropping, but beyond this there is currently little guidance for evaluating effectiveness to inform their further development.

The aim of this research was to understand how the features of customised agricultural LCA tools influence their effectiveness for informing environmental improvements, and to propose a set of effectiveness criteria. These criteria are useful for informing the design and evaluation of tools. For brevity the term 'LCA tools' used throughout refers to customised agricultural LCA tools.

2. Materials and methods

We started with a theoretical framework that defines the objectives of LCA tools for informing agricultural practice change. We then reviewed a sample of existing customised agricultural LCA tools to understand the features that influence the achievement of these objectives, and to propose criteria for effectiveness.

2.1 Theoretical framework for defining the objectives of tools

To understand how LCA tools may inform environmental improvements in agricultural, we drew on past research about the role of information and decision support tools in agricultural decision making and practice change adoption. Kuehne et al. (2017) provide a very useful framework of the factors influencing practice adoption in agriculture, which comprehensively synthesizes the existing body of literature on the topic. This framework shows that information and knowledge, such as that generated by LCA tools, are only one of numerous influencing factors, and that the link between acquiring the information and implementing change is rarely direct. Therefore it is inappropriate to judge the effectiveness of an LCA tool based on whether its use led to implementation of environmental improvements. Instead, it is more appropriate to consider a tool's effectiveness in terms of its specific role of providing knowledge that feeds into a decision-making process.

We propose that to generate knowledge that informs environmental improvements in agricutlure, tools need to be effective in how they engage agricultural agents of change, how they generate information, and how that information aligns with the wider decision making context. By engagement we mean the initial matching of the tool's purpose to the user's needs, followed by access to the tool, and then the actual use of the tool. Based on this framework, we propose three desired objectives for agricultural LCA tools that frame our review:

- to engage agricultural agents of change by catering to their needs, being accessible and manageable to use;
- to generate information that users can interpret for informing environmental improvements; and
- to generate information that can align with the wider decision making context.

2.2 Review of customised agriculture LCA tools

A sample of existing LCA tools customised for agriculture were reviewed to understand how they achieve the desired objectives identified in the previous step, and how their features may influence their effectiveness. These observations provided the evidence for proposing effectiveness criteria.

A search of academic literature and the internet identified 14 LCA tools customised for a range of agricultural sectors (Table 1). Carbon calculators (greenhouse gas accounting / carbon footprinting tools), of which there are many (for reviews see Colomb et al. (2013), Whittaker et al. (2013), and Lewis et al. (2013) and Peter et al.(2017)), were not included, as we were interested in LCA tools that inform a range of environmental improvements, not just climate change mitigation. However, carbon calculators that allow alternative practices to be evaluated were considered in relation to their functionality (i.e. Cool Farm Tool, Carbon Navigator, CCAFS-MOT and PalmGHG). Streamlined or simplified LCA tools not specifically customised for agriculture, such as those reviewed by Arzoumanidis et al. (2017) (Bilan Product, CCaLC, eVerdEE), were also not included.

The features of the 14 selected LCA tools were reviewed in terms of how they influence the desired objectives, i.e.: i) which features influence how tools engage users? (i.e., meeting needs of users, access and use) ii) which features help the users interpret the LCA results? and iii) which features influence how the results align with the decision making context? The information required to answer these questions was found either in the supporting documents (instruction manuals or method documents) or within the tools themselves. For each of the identified features, we then used our observation from the review to propose the outcomes that should be achieved by LCA tools for them to be effective, i.e., effectiveness criteria.

One of the features reviewed was the degree of parameterization, which was determined by counting the number of agricultural practice parameters that can be defined and modified in the tool. By practices we mean individual processes occurring as part of an agricultural systems such as machinery operations, fertilizer application, manure spreading, etc. Practice parameters define what is done, how it is done, what inputs are used, in what quantities and of what composition.

3 Results and discussion

The results from our review of the 14 LCA tools are detailed in Table 1. It characterizes the various features of the tools, according to the objectives they influence. The sections that follow describe our rationale for why and how these features influence effectiveness, and the criteria we propose for gauging effectiveness against the desired objectives. An overall summary of the desired objectives, influencing features and resulting effectiveness criteria is provided in Table 2.

3.1 Tool features that influence user engagement

3.1.1 Purposes and target-users

For most of the reviewed tools, the target users are non-LCA practitioners and their purposes are to generate information that can prompt consideration of environmental improvement opportunities, including (Table 1):

- increasing awareness about environmental impacts, by generating life cycle impact assessment (LCIA) results and/or contributional analyses for showing the sources of impacts;
- benchmarking environmental performance to highlight broad improvement potential, by generating LCIA results relative to industry ranges or standards;
- enabling the evaluation and comparison of alternative practices to inform improvement opportunities in more detail.

For a few of the reviewed tools, the target users are researchers and LCA practitioners, and the main purpose is to generate an inventory of inputs / outputs for subsequent use in LCA software or for building databases (ALCIG, MEANS).

Some of the reviewed tools cater to more than one purpose and user. The CaneLCA tool generates an inventory of inputs / outputs for export to conventional LCA software, suited to LCA practitioners and researchers, as well as the final LCA results suited to agricultural users. The EDEN and SENCE tools, while initially designed for agricultural advisors or farmers, have also been used by researchers. The CAP'2ER provides an online version for farmers that generates diagnostic information for awareness, and a MSExcel version for advisors that allows more detailed comparisons. Therefore, tools do not need to be confined to specific target users or purpose, and catering to multiple uses and users may increase the use of the tool and its influence. Furthermore, producing information for a range of contexts caters to the fact that decision-making involves various stakeholders with different information needs (Cerf and Meynard, 2006).

Effectiveness criteria are that a tool's purpose(s) matches the needs of target user(s), and where appropriate, caters for multiple purposes and users by generating outputs in multiple forms.

3.1.2 Mode of access

Mode of access influences how easily users can access LCA tools, and ranges from fully independent operation, requiring the use of LCA software, or requiring analysis by a third party (Table 1).

Fully independent operation means the user can conduct an analysis in one step without the use of LCA software or involvement of a LCA specialist, and 10 of the 14 reviewed tools allow for this. They can be either 'off-line' as a file installed on the user's computer (MSExcel or MSAccess), or 'online' as a web-based interface that may link to a database on a server. We expect that offline and online access would provide similar degrees of engagement, but the differences were not specifically examined.

LCA tools that require the use of LCA software involve a two-step process of first generating an inventory of inputs and outputs with the tool, then feeding this into conventional LCA software to generate the final LCIA results (as in the MEANS platform and ALCIG). They are suited to users with LCA software skills.

LCA tools that require analysis by a third party require the user to provide raw data to a consultant or researcher who then conducts the analysis and generates a report. They are suited to those who have the resources to engage consultants or researchers, such as food companies.

Effectiveness criteria related to mode of access depend greatly on the potential user. However, a general criterion would be that the mode of access does not inhibit the use of the tool by target user(s).

3.1.3 Ease of use

We used the amount of data required by a tool as an indicator for ease of use. Many of the reviewed tools aim to keep data entry to a minimum (10-20 items of data) (Table 1), and take a few hours to complete. In contrast, those tools that enable practice alternatives to be evaluated have higher data requirements: EDEN (50), CaneLCA (37) and MEANS (56), and the assessment takes longer (4-5 hours). This time requirement may be barrier to use by users. For example, for farmers who have to engage an advisor to assist with the analysis, the cost may be too high if the analysis takes too long to complete.

The desire for LCA tools to be manageable to use in order to engage users is at odds with the higher level of data required to conduct a detailed assessment (Lewis et al., 2013), which is discussed in further 3.2.2. Tools with higher data requirements offer greater scope for analysis (more data in – more analysis out), but may be less appealing to use. Tools with fewer data requirements are easier to use, but the scope of analysis for informing environmental improvements is limited (limited data in – limited analysis out). Baumgartner et al (2016) noted the need to balance these objectives in their development of the FarmLife tool.

Effectiveness criteria for ease of use are that the time required to use the tool is within the means of the target user(s), and that there is an appropriate balance between ease of use and the desired analysis capacity.

The right balance between level of detail and ease of use will depend on the needs of the user. Some users may be motivated to provide more data because they value the more detailed analysis that will result, whereas others may value a quick assessment. Possible ways of achieving a balance observed from the review, are to i) focus data requirements on those aspects that are most significant, ii) request data in a form that is readily available to users, minimises the amount of pre-calculation, and that aligns with other record keeping requirements, iii) enable alternative modes of data input, and iv) invest in the development of innovative user interfaces. Furthermore, involving target users and communication specialists in the tool development process can greatly inform tool design for ease of use (Baumgartner et al., 2016; Le Gal et al., 2011). In the future it may be possible use evolving traceability and farm data management systems to upload data into the tools directly, as proposed by Bellon-Maurel et al. (2014).

3.2 Tool features that influence results interpretation for informing environmental improvements

3.2.1 Results presentation

The following aspects of result presentation can influence how users interpret the outputs from LCA tools: the LCA stage at which results are reported; the reporting of a contributional analysis; and the reporting of relative performance indicators (Table 1).

The reviewed tools generate and report results at different stages (analysis points) in the LCA – inventory of inputs and outputs, life cycle inventory (LCI), life cycle impact assessment (LCIA) results, and weighted LCIA results (see notes under Table 1 for definitions). All the reviewed tools generate an inventory of inputs / outputs as a part of the analysis process, but only three (MEANS, ALCIG and CaneLCA) report the inventory as an output. The principal output from all reviewed tools is the life cycle impact assessment (LCIA) results, presented as a set of mid-point impact indicators (Table 1), often in the form of one or more graphs. Two of the reviewed tools

(AgBalance and MEANS) undertake or allow subsequent weighting and aggregation, or end-point impact assessment to generate a single score (see notes under Table 1 for definitions).

There is debate about the relative merits of multiple mid-point indicators versus a single weighted score (Kägi et al., 2016). The value of a single score is that it condenses the complexity of the multiple impact indicators. The downside is that transparency about the nature of impacts is lost. In relation to interpretation, one perspective is that professional decision makers are used to making decisions based on multiple considerations and do not need weighting and aggregation (Baitz *et al.*, 2013). Another is that for users with little prior-exposure to LCA, multiple indicators may be daunting (Ridoutt and Pfister, 2013). The preferred approach for effective interpretation by tool users is not known, and this is an area for future research. Whichever way, results need to be transparent enough for the user to see the link between contributing activities and impacts.

All the reviewed tools report a contributional analysis, a well-established means of showing the contributing activities (hot-spots) to prompt consideration of impact mitigation opportunities. Sources of impacts are commonly grouped into broad categories related to the farming inputs (eg., tractor operations, machinery production, fertiliser production, direct emissions, etc.). However, for results interpretation that informs environmental improvements, it may be useful to group according to the relevant practices (Renaud-Gentie, 2015). How best to categorise contributional analyses to facilitate effective interpretation is another aspect for further research.

LCIA results presented as absolute values, which is how most of the reviewed tools present results, is useful for reporting, certification or labelling purposes, but may be less useful for interpreting environmental improvements. In contrast, some of the reviewed tools report LCIA results relative to a point of reference (on a percentage scale), and so are performance indicators. Points of reference can be the range for the sector (as per FarmLife Report and CaneLCA), a performance standard (AgBalance), or sector targets (Carbon Navigator tools). Relative results can facilitate interpretation of the results because people are motivated by the normative information that shows how they compare to peers (Baitz et al., 2013; Baumgartner et al., 2016), and the positivity of improving environmental performance rather than the negativity of reducing impact indicators (Baumgartner et al., 2016). Furthermore, relative results allow multiple impact indicators to be presented on the one graph with common percentage scale, making the presentation of results more streamlined. Generating results relative to sector data may require having a database from which to generate reference values, and then interpretation of what sub-set of the database is sensible for comparison. This may not always be feasible. An alternative is for the absolute results to be generated in a way that allows them to be used within peer review processes within the sector.

Effectiveness criteria for results presentation are that i) results are transparent enough for the user to see the link between contributing activities and impacts, ii) contributional analysis is categorised with sufficient resolution for the identification of important sources of impacts, and iii) results are or can be presented relative to sector performance values or other point of reference.

3.2.2 Parameterisation of practice parameters to compare practices

All the reviewed tools generate 'diagnostic' information for awareness-raising (extent of environmental impacts, relative performance, and contributional analysis of sources of impacts) as discussed in the previous section. This can help identify possible areas for improvement, but for informing the best ways to make improvements the ability to compare alternative practices is needed.

Comparing alternative practices requires the parameterisation of practice variables so they can be modified (Basset-Mens *et al.*, 2007). An example from the CaneLCA tool is to derive fuel use for machinery operations from tractor operating parameters (specific fuel use of the tractor, speed, field efficiency, number of operations, etc.) which are validated against the user's records of actual fuel use. Fuel use efficiency can then be explored by modifying the practice parameters. This means that customised LCA tools effectively become a simple systems model for predicting the implications of changed practices, which is less easily achieved using conventional LCA software. The value of LCA software is in managing the analysis complexity of product life cycles that are made up of many life cycle phases, and less so for modelling changes to practices that occur within the individual phases (Goglio et al., 2017). Some parameterisation is possible in LCA software and databases (Cooper *et al.*, 2012), but there is usually not enough transparency in the results to easily see the effects of modifying parameters.

All reviewed tools have some degree of parameterisation for comparing practices (Table 1). Ten of the 14 reviewed tools have 8-18 modifiable parameters, which means they can assess a moderate range of pre-defined practice alternatives. Whereas, three of the tools have 37-56 parameters (CaneLCA, EDEN and MEANS) and can assess a much wider scope of alternatives.

There are some limitations in the capacity of LCA tools to effectively evaluate alternative practices. Firstly, it is limited to known practice alternatives (such as shifting towards already defined 'best-practice' standards) because the algorithms and factors for performing the analysis are pre-defined in the tools. Alternatives that have not been foreseen cannot be evaluated without extending the scope of the in-built calculations and factors. So it is difficult for LCA tools to inform very innovative changes to agricultural practices and systems.

A second limitation relates to uncertainty. Effective comparative assessment requires the uncertainty of the results to be known, to discern differences that are outside the uncertainty ranges (Mattila et al., 2012). Uncertainty is rarely calculated in LCA tools, because of the difficulty in integrating uncertainty simulation models in MSExcel. The review did not provide any guidance on how best to enable uncertainty analysis, so it was not possible to propose any effectiveness criteria for this aspect. It is instead noted as a limitation and area for further research.

An effectiveness criterion for evaluating practice alternatives, is that the degree of parameterisation is sufficient to enable evaluation of the practice changes being considered by a sector, without adversely compromising ease of use.

3.2.3 Regionalised analysis

Regionalisation is the consideration of the site- or region-specific conditions when generating inventories and characterising impacts, and the parameterisation in LCA tools makes this possible. Capacity for regionalised analysis is a valuable feature particularly for eutrophication potential, toxicity potential, and water scarcity, which are greatly influenced by local conditions (climate, soil, water availability) (van der Werf *et al.*, 2009).

Regionalised inventories are possible by modelling different production parameters (practices, technologies, inputs etc.). This has been demonstrated in applications of the EDEN, CaneLCA and Greenhouse tomato tool to evaluate different production typologies in different locations (Renouf et al., in review; Torellas et al., 2013; van der Werf et al., 2009). Some LCA tools are also parameterised to enable estimation of region-specific emission factors for nutrients (nitrogen and phosphorus), sediment, pesticides, metals etc. The FarmLife tool contains sub-modules for estimating nitrogen, phosphorus and heavy metal losses based on the SALCA methods, which account for site-specific conditions (Herndl *et al.*, 2015). CropLCA calculates nitrate leaching and soil phosphorus loss with consideration of local conditions using SQCB and USLE methods, respectively (Goglio et al., 2017). The CCAFS-MOT tool uses country-specific emission factors (Feliciano *et al.*, 2017). A farm nitrogen budget was incorporated into the EDEN tool to improve the site-specific estimation of emissions of nitrogen species (van der Werf *et al.*, 2009). The ability to generate region- or site-emission factors is a valuable attribute of customised LCA tools and could occur through incorporation of material balances, and simple fate models within tools, or by drawing on the outputs from agronomic simulation models.

Regionalisation of impact characterisation can also be facilitated in LCA tools because the foreground (on-farm) components of the inventory can be more easily distinguished from the background (off-farm) components, and region-specific versus globally-generic impact characterisation factors applied, respectively. This is more difficult using conventional LCA software because one set of generic characterisation factors is applied to both. Factors and methods for regionally-specific impact assessment are emerging (Antón et al., 2014), but their actual use in LCA studies is limited as factors are not currently available for all areas and impact categories.

An effectiveness criterion is that LCA tools support regionalised inventory development and impact assessment, by providing the option to apply site- or region-specific emission factors and characterisation factors, where possible.

3.2.4 Impact categories assessed

Tool customisation also involves focusing on a sub-set of relevant or significant impact categories to reduce the complexity of the outputs. The reviewed LCA tools (not including the carbon footprint tools) report between three and eight categories (see Table 1), compared with the 14 or so available using LCA software. There is little consistency in the impact categories assessed, except that all report climate change, non-renewable energy use and eutrophication potential. Consideration can be given to aspects with positive significance as well as those with negative significance, because highlighting strengths as well as challenges makes the reported results less confronting to users (Baumgartner *et al.*, 2016). For example, biodiversity indicators are assessed in the EDEN and CAP'2ER tools to highlight the potential positive aspects of livestock production (Kanyarushoki *et al.*, 2016).

Assessing a wide range of mid-point impact indicators increases the complexity of the reported results, which may adversely affect the effectiveness of results interpretation by the user. The review did not provide any guidance on how best to balance a wide representation of impact categories against ease of results interpretation. So we instead default to the general best practice guidance for LCA, which is consider the significance of impacts when choosing impact categories (ISO, 2006).

Therefore the effectiveness criterion for this aspect is that the environmental impact categories assessed are those of most significance for the system being assessed.

3.3 Tool features that influence alignment with wider decision making context

3.3.1 System scope

Most of the tools reviewed focus on the agricultural phase up to the farm gate (cradle to farm gate), but three extend the analysis up to the factory gate. The advantage of focusing on the farm phase is that greater parameterisation of agricultural practices for evaluating alternatives tends to be possible (Table 1). The downside is that the whole of life cycle perspective is lost, making it difficult to consider the influence of changed agricultural practices on downstream processes. For example, in sugarcane growing, changed management of residues in the field influences the amount of biomass that is available as fuel in the sugar mills. In viticulture changed practices may effect grape quality and downstream wine production processes. Furthermore, it is of value to know the significance of changed agricultural practices on the environmental performance of the end-product, relative to improvements in other parts of the supply chain.

Solutions could be the inclusion of modules for key downstream processes (as in PalmGHG) but with parameterisation and detail remaining focused on the agricultural phase, or for the inventory of inputs / outputs generated by the tools to be exportable to conventional LCA software for full product life cycle assessment (as in MEANS and CaneLCA).

An effectiveness criterion is that, if the system scope of the tool is focused on a partial system scope ('cradle to farm gate'), the tool enables the results to feed into full product LCA.

3.3.2 Alignment with other assessment frameworks

Whether generated by LCA software or customised LCA tools, environmental impacts information does not alone inform decision making towards environmental improvements. It is considered alongside other aspects, such as profitability, product quality, social issues etc. So LCA tools may be more effective if their outputs can align with other assessment frameworks. Our review identified a number of ways this can occur. The first is for it to occur within the one tool, as is the case for the AgBalance tool, which generates environmental, social and economic indicators, and the Carbon Navigator tools which perform a combined assessment of global warming mitigation potential and economic savings. A second way is for the outputs from the LCA tools to align with those from tools that assess other aspects, so outputs can be reported alongside each other. This has been demonstrated in an application of the CaneLCA tool, in which the environmental information generated by the tool was interpreted alongside farm profitability information generated by an separate economic tool (Poggio et al., 2018). A third way is for the outputs of LCA tools to align with decision support frameworks that use multi-criteria assessment to weigh the pros and cons of alternative agronomic practices across a wide range of indicators (Bockstaller *et al.*, 2009).

An effectiveness criterion is that environmental information generated can be interpreted alongside the outputs from other relevant assessment frameworks.

4 Conclusions

From a review of 14 customised agricultural LCA tools we identified features that influence their effectiveness for informing environmental improvements. Our evaluation of effectiveness was framed by the following desired objectives for LCA tools, which were derived from their known role in agricultural practice change: i) to engage agricultural agents of change by catering to their needs, being accessible and manageable to use, ii) to generate information that users can interpret for informing environmental improvements, and iii) to employ methods that align with the user's decision making context. The tool features that influence how to achieve these objectives were found to relate to: tool purpose, mode of access, ease of use, results presentation, degree of practice parameterisation, capacity for regionalised analysis, system scope, impact categories assessed, and alignment with other assessment frameworks. For each of these features effectiveness criteria were proposed (Table 2).

The proposed set of effectiveness criteria can be used to guide the development of future LCA tools and to evaluate their effectiveness, for example in user surveys. A number of criteria from within this set are challenges for future tool development, and warrant further investigation. The first is the ability to strike a balance between analysis capacity and ease of use. We identified that the desire for LCA tools to be easy to use in order to engage users can be at odds with the higher level of data required to compare alternative practices and inform improvements. Some possible ways for achieving a balance were identified for consideration in tool development. The second is the enabling of regionalised analysis to generate more representative estimates of direct emissions and impact characterisation. Customised LCA tools are particularly suited to this, because they can be parameterised to model emissions and impacts based on regional- or site-specific conditions. This will be an important area of future tool development through the incorporation of simplified emissions estimation models. The third is the effective presentation of LCA results in a way that aids interpretation by users for informing environmental improvements. The most effective mode of presentation is not well known, in terms of whether to present results as multiple mid-point indicators or weighted single score results, and how best to categorise contributional analysis to facilitate the exploration of practice alternatives.

Some limitations of customised LCA tools for informing environmental improvement are that they may not be well suited to evaluating very innovative changes to agricultural practices and systems, and uncertainty analysis needed to discern real environmental improvements cannot be easily accommodated.

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Table 1: Features of the reviewed customised agricultural LCA tools

		Tool features that influence engagement of users									Tool features that influence results interpretation †							Features that influence alignment with decision making context‡
		Purpose					Access			Ease of use	Para-meters	Results presentation					Impact categories[j]	System scope
												LCA stage reported						
Tool name	Sector	Generating inputs / outputs inventory	Building shared database	Awareness raising	Benchmarking performance	Comparing agricultural practices	Independent	Requires LCA software	Assisted by third party	Number of practice parameters / data entry requirements[a]		Inventory of inputs and outputs[b]	Life cycle inventory (LCI)[c]	Life cycle impact assessment (LCIA)[d] at mid-point[e]	End-point[f] or weighted[g] LCIA	Relative performance indicators[h]	Contributional analysis[i]	Environment impact categories assessed	Up to which gate?
AgBalance[1]	Multiple			X	X				X	NA			X	X	X	X	CC, NRE, EUT, ACID, ETOX, BIO, MIN	factory
PalmGHG[2]	Oil palm			X	X		X			8			X			X	CC	factory
SENCE[3]	Multiple			X	X	X	X			11			X			X	CC, NRE, EUT, ACID, ETOX, HTOX, LU, WATER	factory
CCAFS-MOT[4]	Multiple			X		X	X			10			X			X	CC	farm
CoolFarm Tool[5]	Crops & livestock			X		X	X			11			X			X	CC, BIO, WATER	farm
CropLCA[6]	Crops	X					X			11			X		X	X	CC, NRE, EUT, ACID	farm
FarmLife[7]	Multiple			X	X				X	13			X		X	X	not specified	farm
ALCIG[8]	Multiple	X						X	X	14	X	X					ALL	farm
CAP'2ER[9]	Livestock			X	X		X			16			X			X	CC, NRE, EUT, ACID, BIO	farm
Greenhouse eFoodPrint[10]	Various			X			X			17			X			X	CC, NRE, EUT, ACID, PCO, ABD, WATER	farm
Carbon Navigator[11]	Livestock			X	X	X	X			18			X		X	X	CC	farm
CaneLCA[12]	Sugar-cane	X		X	X	X	X			37	X		X		X	X	CC, NRE, EUT, ETOX, WATER	farm
EDEN[13]	Dairy	X		X	X	X	X			50			X			X	CC, NRE, EUT, ACID, ETOX, LU, BIO	farm
MEANS Platform[14]	Multiple	X	X			X		X		56	X	X	X	X		X	ALL	farm

Notes:

† Capacity for regionalised assessment was also identified as an influencing feature, but was not itemised here for brevity. Tools with some degree of regionalisation capacity are FarmLife, CropLCA, CCAFD-MOT and EDEN.

‡ Alignment with other assessment frameworks was also identified as an influencing feature, but not itemised here for brevity. Tools that have demonstrated this capacity are AgBalance, Carbon Navigator and CaneLCA.

Details of the reviewed tools:

1. AgBalance, developed by Bayer Chemicals (Schoeneboom et al., 2012) It calculates LCA results, and benchmarks against reference production protocols and industry performance, to enable reporting to supply chains.
2. PalmGHG Calculator (Version 2), developed by consultants and CIRAD, France (Bessou et al., 2014) for the Roundtable on Sustainable Palm Oil (RSPO) quantifies the carbon footprint of palm oil products, consistent with RSPO's certification program.
3. SENCE, developed by ESU as part of the Harmonized Environmental Sustainability in the European food and drink chain project (Ramos *et al.*, 2016). It generates an Environmental Information Document.
4. Climate Change, Agriculture and Food Security (CCAFS) Mitigation Option Tool (CCAFS-MOT) developed by the University of Aberdeen (Feliciano *et al.*, 2017), It generates and compare greenhouse gas emissions for a range of mitigation scenarios.
5. CoolFarmTool (Hillier *et al.*, 2011), originally developed by Unilever and researchers at the University of Aberdeen and the Sustainable Food Lab, and now distributed by the Cool Farm Alliance (https://coolfarmtool.org/). Three separate online tools evaluate greenhouse gas emissions, biodiversity score and water (in development).
6. CropLCA (Goglio et al., 2017) is a modular LCA tool, coded in the open-source program R, and designed for LCA practitioners.
7. FarmLife-Report, developed by Agroscope (Herndl *et al.*, 2015) generates LCA results using the SALCA database and presents them relative to industry ranges to highlight possible areas of action.
8. Agricultural Life Cycle Inventory Generator (ALCIG), developed by Quantis, US (https://alcig.quantis-software.com/). It is a data collection spreadsheet completed by the user and sent to a consultant for generation of the life cycle inventory. As an example, ALCIG is used to generate LCI for Nestle's EcodEX eco-design tool (Schenker et al., 2016).
9. Calcul Automatisé des Performances Environnementales en Elevage de Ruminants (CAP'2ER), developed by the French Livestock Institute (Moreau *et al.*, 2016). Both standalone (for farmers) and online (for extension advisors) tools.
10. A tool developed for greenhouse horticulture by the Research and Technology for Food and Agriculture (IRTA), and Wageningen UR, as part of the Euphoros project (Torellas *et al.*, 2013). This tool was integrated into the similar eFoodPrint online tool which just calculates greenhouse gas emissions (Torres et al., 2017).
11. The Beef and Dairy Carbon Navigator tools, developed by the Irish Food Board (Bord Bia) and Agriculture and Food Development Authority (Teagasc) (Murphy *et al.*, 2013). They allow the user to see what on-farm changes can be made to achieve the industries greenhouse gas emissions targets, alongside the farm profitability implications.
12. The Sugarcane Eco-efficiency Calculator (CaneLCA), developed by the University of Queensland for the Australian sugar industry (Renouf et al., 2014). It generates and compares LCA results for different scenarios.
13. Evaluation de la Durabilité des Exploitations (EDEN), developed by INRA and the Chambre d'Agriculture de Bretagne, France (van der Werf *et al.*, 2009). It generates and compares LCA results for different scenarios.
14. MEANS software platform, developed by INRA, France (www.inra.fr/means) (Auberger et al., 2015) comprises two tools: InOut and Simapro. InOut collects information about farming system and practices to generate an input/output inventory, which is then transferred to the Simapro LCA software. MEANS allows assessment of the main crop and animal production systems in France. (In relation to the number of practice parameters, 35 are for plant production systems and 21 for livestock systems).

Definitions

a. Practice parameters define what is done, how it is done, what input are used, in what quantities and of what composition. The value represents the number of parameters that can be defined and modified in the tool. For infrastructure, individual components and design choices were not counted individually.

b. Input / output inventory is an inventory of the materials and energy inputs to a particular process, and the emissions and wastes that are outputs from the process.

c. Life cycle inventory (LCI) is an inventory of the resulting environmental exchanges between the environment and the product system, which is generated from the input / output inventory and aggregated over the life cycle of the product system.

d. Life cycle impact assessment (LCIA) results, expressed as absolute values, are environmental impact indicators that are generated by multiplying the LCI data by impact characterisation factors.

e. Mid-point indicators represent a single environmental problem at a mid-point along the impact pathway (for example, greenhouse gas emissions as a proxy for climate change)

f. End-point indicators aim to represent environmental impacts further along the impact pathway at the actual impact (for example, effects on human health, resource scarcity, etc.)

g. Weighted LCIA results are generated by multiplying the LCIA results by a weighting factor for each impact category (representing their relative significance).

h. Relative performance indicators express the LCIA results as relative values, relative to some reference, for instance a sector range or target, to represent relative performance.

i. Contributional analysis presents a breakdown of the LCIA results to show the sources of the impacts.

j. Environmental impact categories in order from most to least commonly reported: CC= climate change (8), NRE=non-renewable energy use (8), EUT=eutrophication potential (7), ACID=acidification potential (5), ETOX=eco-toxicity potential (4), MIN=mineral depletion (3), WATER=consumptive water use (3), LU=land use (3), BIO=biodiversity (1), HTOX=human toxicity (1), and PCO=photo-chemical oxidant formation (1); SOC=social (1); ECON=economic (1), ALL = the inventory generated is exported to LCA software, so all impact categories can be assessed. NA= information not available.

Table 2: Objectives, features and effectiveness criteria for agricultural LCA tools

Desired objectives	Tool features that influence objectives	Effectiveness criteria
Engage agricultural agents of change by catering to their needs, being accessible and manageable to use	Tool's purpose	Tool's purpose(s) matches the needs of target user(s) Tool caters for multiple purposes and users by generating outputs in multiple forms
	Mode of access	Mode of access does not inhibit the use of the tool by target user(s)
	Ease of use	Time required to use the tool is within the means of target user(s) There is an appropriate balance between ease of use and the desired analysis capacity
Generate information that the user can interpret for informing environmental improvements	Results presentation	Results are transparent enough for the user to see the link between contributing activities and impacts Contributional analysis is categorised with sufficient resolution for the identification of important sources of impacts Results are or can be presented relative to sector performance values or other point of reference
	Degree of practice parameterisation to enable comparison of practices	The degree of parameterisation is sufficient to enable evaluation of the practice changes being considered by a sector, without adversely compromising ease of use
	Capacity for regionalised analysis	Tools support regionalised inventory development and impact assessment, by providing the option to apply site- or region-specific emission factors and characterisation factors where possible
	Impact categories assessed	Environmental impact categories assessment are those of most significance for the system being assessed
Generate information that can align with the wider decision making context	System scope	If the system scope of the tool is focused on a partial system scope ('cradle to farm gate'), the tool enables the results to feed into full product LCA
	Alignment with other assessment frameworks	The environmental information generated can be interpreted alongside the outputs from other relevant assessment frameworks

Highlights

Customised agricultural LCA tools make LCA more accessible to agents of change

Effectiveness criteria proposed for guiding development and evaluating effectiveness

Key criterion and challenge is the balance between analysis capacity with ease of use

Capacity for regionalisation of inventories and impact assessment is a valuable feature

Further research needed on how results presentation influences interpretation