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Agricultural eco-design scenarios based on AGRIBALYSE® residual organic fertiliser inventories

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Abstract

This work focuses on the assessment of the potential environmental benefits associated with the diversity of organic fertilisers available in the AGRIBALYSE database. Under the eco-design perspective, the shift from mineral to organic fertilisation regimes must not be over simplified, as fertilisation of each crop has an effect on the whole crop rotation. This work contrasts the environmental impacts of conventional crop rotations with equivalent eco-designed ones, featuring partial substitution of mineral by organic fertilisers at a level that the current yield is maintained. Two eco-design strategies involving AGRIBALYSE were devised. The first consists of retrofitting existing single crop processes by replacing conventional fertiliser inputs with newly available residual organic fertiliser processes. The second consists of eco-designing agricultural systems (i.e. technical itineraries representing crop rotations or crop sequences) by partially substituting mineral with newly available residues-based organic fertilisers. In both cases, it is necessary to adjust the fertiliser-related direct field emissions accordingly. In the second strategy, large amounts of organic fertilisers are input to replace mineral ones (tonnes vs. kg), and therefore overall impacts (i.e. impacts across impact categories) increase considerably, yet this effect is minimised when considering the alternative waste disposal pathways associated with the mineral fertilisation strategy (i.e. mineral fertilisation + disposal of the amount of organic residues necessary to deliver an equivalent level of fertilisation). The expanded functionality of a cropping system consuming organic waste-derived fertilisers (i.e. fertilisation + organic waste disposal) should be considered in comparative LCAs.

Keywords: agricultural life cycle assessment; organic fertilisation; fertilisation strategy; crop rotation

1 Introduction

Eco-design is a systematic process-improvement approach that considers environmental aspects in design and development, with the aim to mitigate adverse environmental impacts throughout the life cycle of a product (ISO, 2020). It relies on the life cycle approach to guide sustainability choices, focusing on the most relevant steps and impacts (hotspots), avoiding burden shifts, and can be used in, virtually, any sector (including agriculture). It is a process-improvement approach. Although focusing on environmental sustainability, eco-design must deal with economic constraints and opportunities to identify realistic improvement solutions. It can rely on full Life cycle assessment (LCA) tools or on simplified and more operational tools such as “checklists, guidelines, labels, production charts”. Those simplified tools must remain in line with LCA knowledge, and more broadly environmental science, to be considered in the eco-design framework.

The sustainable growth of the agricultural sector is now clearly identified as a major challenge to be addressed, especially if the global production system intends to be within Earth´s planetary boundaries (Campbell et al., 2017). Indeed, it accounts for about 20% of climate change impact, as it is the sector consuming the most water and whose practices have a strong effect on biodiversity, via both local/direct and indirect impacts (e.g., feed market). Increasingly aware of the sustainability challenges, and under the pressure of environmentally-conscious consumers, the agricultural sector and the food systems are now looking for technical and organisational solutions. The main axes to answer these sustainability challenges are currently quite consensual: sustainable production (with an important focus on agriculture), diet shifts, as well as reduction of food losses and waste generation (IPCC, 2019; Poore and Nemecek, 2018; Willett et al., 2019).

Agricultural eco-design has been explored from multiple points of view (e.g., technological, agronomical, sociological, environmental, economic, etc.) (Czyrnek-Delêtre et al., 2018; Hill, 2014). In France, public and private bodies are supporting further development of eco-design. For agriculture, French eco-design initiatives benefit from the AGRIBALYSE research programme, developed since 2009 by a partnership of public bodies (ministries, the French environmental agency ADEME), research institutions (INRA, CIRAD) and private institutes (technical institutes, consultancies and cooperatives). AGRIBALYSE developed and continuously improves a life cycle inventory (LCI) database for agriculture (www.agribalyse.fr) , which includes the main agricultural products and processes relevant to the French context (Colomb et al., 2015; Wilfart et al., 2016), as well as methodological guidance on direct field emission modelling (Koch and Salou, 2016). Both the database and its underlying methodology facilitate the broadcasting of environmental information and developing eco-design in the agriculture and food sector. In its first development period (2009-2013), the database mainly provided benchmark data (LCIs) for average and dominant agricultural production systems in France, based on national statistics, on a crop-by-crop basis. In the latest years, its focus has shifted to the modelling of systems with expected environmental benefits, to explore and highlight the potential of eco-design in farming systems. For instance, the database has been enriched with LCIs of organic farming systems (Nitschelm et al., 2020; van der Werf et al., 2018). Moreover, from 2019, the scope of the database expanded from farm gate to the consumer's plate (Asselin-Balençon et al., 2020), opening wider eco-design options, including all foodstuffs' stages. Finally, specific support for food companies has been developed by ADEME to engage in operation eco-design strategies (Colomb et al., 2018), as formalised via the GreenGo programme (ADEME, 2020).

Fertilisation is a key element in crop production, yet it is also a key driver for potential environmental impacts, affecting, among other impact categories, climate change, soil and water quality. On climate change, fertilisation (including fertiliser production and direct field emissions) may represent up to 40-50% of the total agricultural impact (Koch and Salou, 2016). Together with fuel consumption, it is one of the most relevant sources for potential impacts. To mitigate these impacts, some fertilisation improvement strategies may be employed, such as the inclusion of legumes in the crop rotations (providing natural N fixation in soils), using of precision/integrated agriculture (with a more accurate use of fertilisation inputs), and/or shifting towards organic fertilisation (thus avoiding the production of synthetic fertilisers) (Astudillo et al., 2015; Debaeke et al., 2017; Rothé et al., 2019; Schröder et al., 2018).

Under the eco-design perspective, the shift from mineral to organic fertilisation must not be over simplified: beyond the crop directly affected, it has an effect on the whole crop rotation, and, more broadly, on the farm system. Moreover, eco-design initiatives, including those based on participatory approaches (e.g., Rouault et al., 2020), must be grounded in sound agronomic considerations. Some trade-offs should also be identified, such as potential transfer of contaminants to the soil or yield reduction (Agegnehu et al., 2016; Houot et al., 2014; Noirot-Cosson et al., 2016; Odlare et al., 2011; Walsh et al., 2012). Finally, organic fertiliser availability is limited and variable according to the region.

LCA is increasingly used to estimate the environmental impacts associated with agricultural systems and their products. For instance, Web of Science (https://apps.webofknowledge.com/) shows a steady increase in annual publications featuring the keywords "LCA" and "Agriculture", from 36 works in 2010 to 87 in 2018. Moreover, the recommendations of the European Commission on Product Environmental Footprint – PEF (EC, 2018) include specific guidance for agricultural systems.

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Agricultural LCA depends on two key elements: agricultural background data and direct field emission models, both required to build agricultural LCIs. A recent project produced for AGRIBALYSE a set of LCIs representing a large number and variety of residual organic fertilisers and amendments (Avadí, 2020), i.e., products of agricultural interest resulting from organic waste treatments. Some treatments aim at dealing with the waste streams, and produce amendments and fertilisers as a secondary function. Others are primarily aimed at producing amendments and fertilisers. These types of treatment systems produce, respectively, residual organic amendments and fertilisers, and commercial organic amendments and fertilisers (Avadí, 2020). The availability of these organic amendments and fertilisers enables some aspects of eco-design, as it enables the *ex ante* modelling of cropping systems that partially or fully replace mineral fertilisers with organic ones, a key element of agricultural systems eco-design (Czyrnek-Delêtre et al., 2018; Grasselly et al., 2016).

In this work, we focus on the assessment of the potential environmental benefits associated with the diversity of organic fertilisers available for agriculture. We present eco-design scenarios based on fertilisation regime changes, aiming to highlight the relevance of the AGRIBALYSE database for agricultural systems eco-design —a long term ambition of the AGRIBALYSE programme (Colomb et al., 2018; van der Werf et al., 2018)— and the challenges associated with agricultural systems eco-design. We moreover identify the conditions under which a substitution of mineral fertilisers by organic ones is environmentally suitable, thus contributing to cleaner/sustainable production in agriculture. We do so by comparing the environmental impacts of conventional crop rotations with equivalent eco-designed ones (featuring partial substitution of mineral by organic fertilisers at a level that maintains yields). The proposed strategy follows a true “eco-design/redesign” paradigm rather than a “substitution-based” one, as defined in Hill (2014).

2 Material and methods

2.1 Inventory data improvement

Agricultural LCIs available in databases are usually built on a crop-by-crop basis. When practitioners use these inventories as background data in LCA studies, they either accept them as-is (for instance, as a proxy) or adapt them to fit the particular conditions of their study, most often by tweaking the inputs, yields and emissions depending on agricultural practices (Meron et al., 2020; Milà i Canals et al., 2011).

Before addressing eco-design of agricultural inventories, inventory data improvement/adaptation should be discussed, as it is a common practice. Two of such data improvement strategies were identified (Fig. 1).

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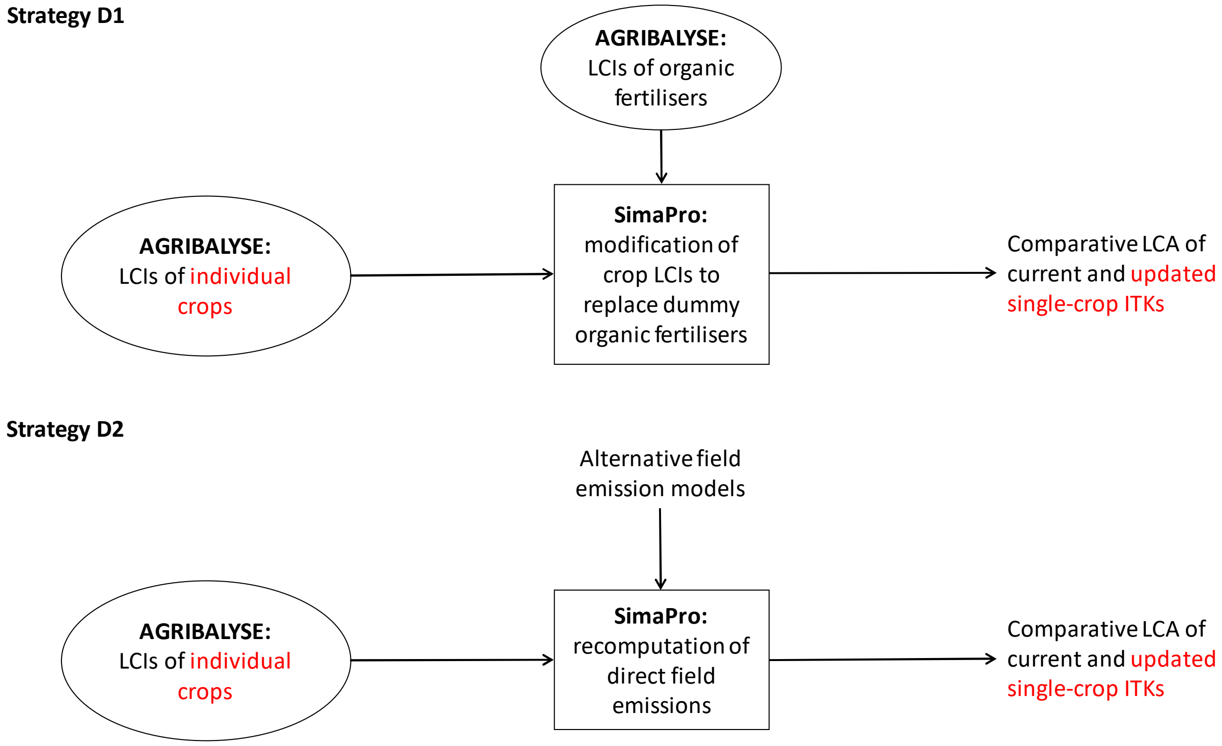

Fig. 1. Strategies for agricultural inventory data improvement with AGRIBALYSE (ITK: technical itinerary)

For instance, AGRIBALYSE users may attempt to modify existing single crop processes by replacing generic organic fertiliser inputs, currently modelled as **"dummy" or "empty" processes** (i.e. processes without associated impacts, which do not incur in resource consumption and generate no emissions; a usual modelling device in LCA practice), with newly available residual organic fertiliser processes, which do include treatment and storage impacts. This data improvement strategy (Strategy D1 in Fig. 1) was explored on three single crop inventories (as described in section 2.3). Strategy D1 updates existing agricultural processes modelled at the crop level. It is common among LCA practitioners to modify existing database processes to adapt them to specific situations. For instance, an aquaculture system may consume, via aquafeeds, a local crop which does not exist in a reference database. In that case an LCA practitioner would likely modify an existing similar crop to the specific local circumstances, in order to include its impacts into the overall assessment of the foreground aquaculture system (Bohnes et al., 2018). Agricultural systems are modelled in AGRIBALYSE as individual crops representing national and other average practices, yet intrinsically associated with French crop rotations (i.e., by means of allocating fertilisers and their associated emissions to the associated representative crop rotations). When replacing dummy processes with new processes, the direct field emissions do not require, in principle, any update. The required LCI modifications associated with Strategy D1 thus include 1) replacement of generic dummy organic fertiliser processes, expressed in terms of their nutrient content (N, P or K) with specific ones expressed per kg of product, and 2) calculation of adjusted organic fertiliser doses based on the total nutrient (N, P, K) contents of the specific organic fertilisers. The LCIs were modified in SimaPro, and comparative life cycle impact assessments were computed for both the original and the modified single crop LCIs.

Another data improvement approach that could be attempted by practitioners is to re-compute direct field emissions of existing agricultural processes by means of emission models different from those used by the LCI database (Strategy D2 in Fig. 1). This strategy was not explored here, as it is the subject of a separate article by our team (Avadí et al., submitted).

2.2 Strategies for agricultural eco-design with AGRIBALYSE

Two key strategies for agricultural eco-design involving AGRIBALYSE were devised (Fig. 2). Strategy E1, a basic eco-design approach, consists of modifying existing single crop processes by replacing mineral fertiliser inputs with processes representing organic fertiliser. Strategy E2, an advanced eco-design approach, consists of eco-designing agricultural systems —i.e. technical itineraries (ITKs) associated to crop rotations— by partially substituting mineral with selected newly available residual organic fertilisers.

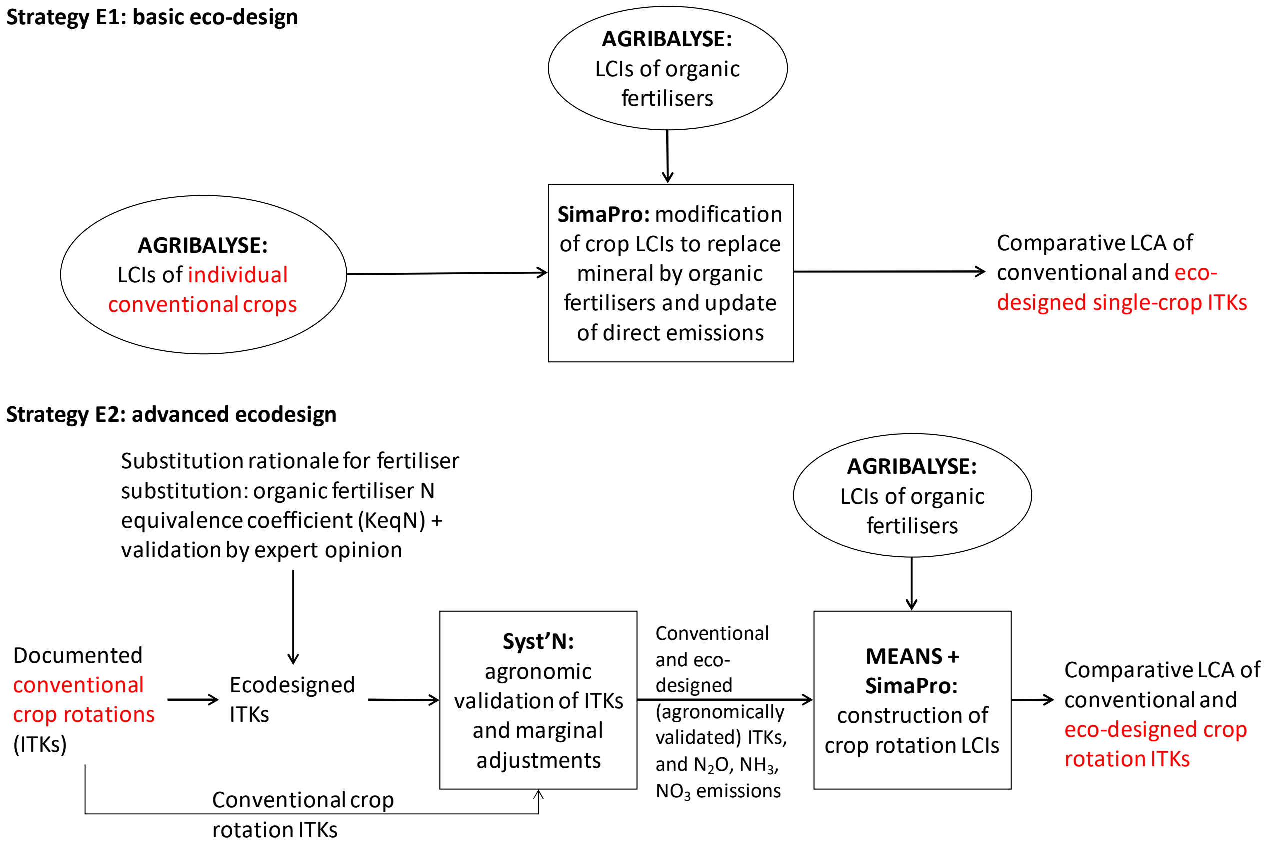

Fig. 2. Strategies for agricultural eco-design with AGRIBALYSE

Strategy E1 would imply eco-designing new single crop processes by replacing mineral fertilisers with organic ones, a rather complex endeavour that would imply recalculation of direct field emissions and could imply updating yields and allocation factors —because the underlying crop rotation would change, as conventional and organic crop rotations are different to optimise interactions among crops and due to the mineralisation dynamics of organic fertilisers (Meier et al., 2015; Notarnicola et al., 2017)—. Despite probably being the most likely approach to be attempted by LCA practitioners, we did not explore Strategy E1 because the underlying crop rotation is not described, and it is thus impossible to be soundly adjusted from an agronomical point of view. We thus preferred to focus on Strategy E2, which directly and transparently addresses modification of a whole crop rotation in response to eco-design needs.

Strategy E2 (eco-)designs new agricultural systems by partially replacing mineral fertilisers with organic ones. The redesign of whole crop rotations involves verification of the technical and economic soundness of the fertiliser substitutions, which may alter yields and demand management changes. We used the dynamic agricultural model Syst'N (Parnaudeau et al., 2012) to modify existing crop rotations, validate the technical feasibility of the new rotations, and update direct field emissions.

The replacement of mineral by organic fertilisation regimes in Strategy E2 was based on mineral N fertiliser equivalence coefficients (KeqN), as defined in COMIFER (2013) and informed by literature data (COMIFER, 2013; Constant, 2011). Both the conventional and the new dominantly organic fertilised (i.e. eco-designed) systems were represented in Syst'N and the resulting scenarios simulated over 3-4 rotation lengths, to cross check for agricultural coherence and estimate direct field emissions (which are integrated into the LCIs). The use of crop models to design and validate agricultural systems is one of the main reasons for the existence of such models, as technical elements such as crop sequences and fertiliser rates are among the most important aspects of agricultural systems' performance (Antle et al., 2017; Jones et al., 2017; McNunn et al., 2019). Once the ITKs were validated, the associated LCIs for both systems were constructed in the online multi-criteria sustainability assessment MEANS platform (Auberger et al., 2013; https://pfmeans.inra.fr/means/login.jsp) linked with SimaPro (PRé, 2012). Finally, comparative life cycle impact assessments were computed for both the original (called reference) and eco-designed crop rotation LCIs.

MEANS' life cycle assessment (LCA) component is heavily based on the AGRIBALYSE methodology (Koch and Salou, 2016) (e.g. choices and methods for direct field emissions estimation and allocation of fertilisers over the crop rotation) and data from AGRIBALYSE and ecoinvent (Wernet et al., 2016). It facilitates the creation of agricultural LCIs and the computation of environmental impacts via a back-office integration with SimaPro. Nonetheless, the direct emissions as computed in Syst'N were retained, as they were considered more accurate for the eco-designed ITKs (among other reasons, because Syst'N considers plant nutrient uptake and other key performance parameters).

2.3 Comparative LCA of cropping systems

LCA was conducted based on two functional units useful in agricultural system comparisons (Meier et al., 2015; Salou et al., 2016): 1 kg of product (only relevant for data improvement Strategy D1) and 1 ha of cultivation (relevant for both data improvement Strategy D1 and eco-design Strategy E2).

In the case of individual crops, the 1 ha of cultivation considered the AGRIBALYSE accounting period (harvest to harvest). In the case of crop rotations, the functional unit represents the cultivation of 1 ha over a period covering a full rotation length. All LCAs feature a cradle-to-farm gate scope. Individual crops and rotations were selected based on data availability and the intention to represent the variety of French agricultural production and contexts. The selection of crops was based on their representativeness of French agricultural production and practices.

For Strategy E2, we considered that for a comprehensive and fair comparison of alternative systems, the functional unit should be enlarged to include the disposal of organic waste —i.e. system expansion without substitution (Heijungs et al., 2021). Namely, the systems being compared are, in one hand an agricultural rotation using mostly mineral fertilisers **plus** the amount of organic waste equivalent to the organic fertilisers used in the alternative eco-designed system, and in the other hand an alternative eco-designed system where most of mineral fertilisers are replaced by organic fertilisers produced from organic waste. When agricultural systems include digestates as fertilising inputs, the allocation of impacts for the anaerobic digestion process ensures that only the impacts of producing digestate are included in the agricultural process. In the other hand, the eventual production of energy from biogas is not a constituency of the agricultural system or of the enlarged agricultural + waste management system, and thus should not be considered. We followed the dominating French LCA dogma that no impacts are allocated to manure production (Koch and Salou, 2016; Nitschelm et al., 2020).

Strategy E2 produced new LCIs representing, *a priori*, examples of agricultural systems eco-design (Andrianandraina, 2015; Czyrnek-Delêtre et al., 2018; Grasselly et al., 2016).

The impact assessment was based on the ILCD 2011 Midpoint+ v1.0.9 method (EC-JRC, 2012), which was the set of methods more closely aligned with the PEF at the time of calculation. ILCD 2011 includes a single score based on equal weighting for all impact categories. ILCD 2011 estimates toxicity impact categories with the consensus toxicity model USEtox (Fantke (Ed.) et al., 2017; Rosenbaum et al., 2008). The characterisation factor for climate change of "CO_2 in air" was changed from -1 to 0, because CO_2 absorbed by plants and reemitted in the short term was not considered to represent carbon sequestration in annual or short cycle crops. SimaPro v8.5 was used to calculate the impacts.

3 Results and discussion

3.1 Life cycle inventories

According with the last French survey on agricultural practices (AGRESTE, 2014), cereals and grasslands dominate the agricultural land use, with cereals occupying 34%, oily seed 8.7% and market vegetables 1.4%. In 2010, the top 12 crops by mass of production included soft wheat and rapeseed: out of 138 million t of produce, sugar beet represented 28%, soft wheat 25%, forage maize 14%, maize grain 11%, barley 6%, potato 5%, rapeseed 4%, sugarcane 2%, durum wheat 1%, triticale 1%, sunflower 1% and protein peas <1% (AGRESTE, 2014). Consequently, and to represent the variety of French agriculture, three conventional crop inventories were selected from AGRIBALYSE v2.0 to illustrate Strategy D1: “Soft wheat grain, conventional, national average, animal feed, at farm gate, production/FR U”, “Rapeseed, conventional, 9% moisture, national average, animal feed, at farm gate, production/FR U”, and “Tomato, average basket, conventional, soil based, non-heated greenhouse, at greenhouse/FR U”. The selected LCIs already feature organic fertilisers as inputs under the current AGRIBALYSE modelling, yet modelled as dummy processes that exclude their production impacts (the impacts of organic waste treatment), and which are declared in terms of their nutrient contents (e.g. “Organic or farm manure (empty process), as N/FR U”).

Organic fertilisers, modelled in AGRIBALYSE as empty processes and declared in terms of their nutrient contents, were replaced by newly available LCIs featuring the associated impacts of fertiliser production/storage, including animal effluents, treated sewage sludge, composts and digestates. These fertilisers, described in Avadí (2020) and updated in Galland et al. (2020), are representative of French practices. For instance, according with the National Observatory of Mineral and Organic Fertilisation, in 2017, 19.3 million t of animal effluents (dominated by cattle slurry, but including poultry manure), 1.8 million t of residual organic fertilisers (including digestates), and 123 000 t of commercial organic fertilisers (many of consist of enriched composts) were spread (ANPEA, 2018; Avadí, 2020). The fertilisers and associated emissions of these LCIs are summarised in Table 1.

Table 1. Main fertilisation and emission features of three scenarios of fertiliser process replacement in individual crops inventories representing national averages from AGRIBALYSE (Strategy D1)

		Soft wheat	Rapeseed	Tomato
Yield	kg/ha	7 100	3 243	159 100

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Mineral fertilisers				
Average N fertiliser	kg/ha (kg N/ha)	500.6 (175.0)	89.8 (29.2)	
Sulfonitrate	kg/ha (kg N/ha)		107.4 (27.9)	
Ammonium sulphate	kg/ha (kg N/ha)		66.5 (14.0)	
Urea (46% N)	kg/ha (kg N/ha)		7.0 (3.2)	
Ammonium nitrate (33.5% N)	kg/ha (kg N/ha)		113.1 (37.9)	
Solution 390 (30% N)	kg/ha (kg N/ha)		156.8 (49.4)	
Average P fertiliser	kg/ha (kg P_2O_5/ha)	53.8 (55.0)		
Monoammonium phosphate (10% N)	kg/ha			3.0
Single superphosphate	kg/ha (kg P_2O_5/ha)			18.0 (3.6)
Average K fertiliser	kg/ha (kg K_2O/ha)	71.5 (68.0)		
Potassium nitrate (13% N)	kg/ha (kg K_2O/ha)			48.0 (22.2)
Potassium sulphate	kg/ha (kg K_2O/ha)			6.0 (1.8)
Potassium dihydrogen orthophosphate	kg/ha			3.0
NPK 15-5-20	kg/ha			30.0
NPK 15-15-36	kg/ha			24.0
NPK 15-10-30	kg/ha			1500.0
NPK 18-6-26	kg/ha			330.0
NPK 4-8-8	kg/ha			1500.0
Organic fertilisers (originally modelled as "Organic or farm manure (empty process), as [nutrient]/FR U")				
Swine slurry	kg/ha (kg N/ha)	794.3 (2.8[a])	550.6 (1.9[a])	
Swine manure (with straw)	kg/ha (kg N/ha)		64.2 (0.5)	
Cattle slurry	kg/ha (kg N/ha)		383.4 (1.3)	
Cattle manure	kg/ha (kg N/ha)	1020.0 (5.6[a])	2 846.0 (15.5[a])	
Poultry droppings	kg/ha (kg N/ha)	72.9 (2.8[a])	307.3 (11.7[a])	
Poultry manure	kg/ha (kg N/ha)		110.7 (2.3)	
Liquid sludge	kg/ha (kg N/ha)		134.9 (0.2)	
Dewatered sludge	kg/ha (kg N/ha)		134.9 (1.2)	
Dried sludge	kg/ha (kg N/ha)		134.9 (5.4)	
Sugar beet vinasse	kg/ha (kg N/ha)		211.9 (4.5[a])	
Compost, of cattle manure	kg/ha (kg N/ha)		121.3 (0.8)	
Compost, of green waste	kg/ha (kg N/ha)		217.3 (1.7)	540.0 (4.2)
Vegethumus (organic amendment <3% N)	kg/ha (kg N/ha)			1653.0 (33.1)
Total N (organic N)	kg N/ha	186.2 (11.2)	208.6 (47.0)	396.3 (37.3)
Total P_2O_5	kg P_2O_5/ha	55.0		3.6
Total K_2O	kg K_2O /ha	68.0		24.0
Emissions associated to each crop				
Ammonia (NH_3)	kg/ha (kg N/ha)	12.4 (10.2)	19.7 (16.2)	28.3 (23.3)
Nitrogen oxides (NOx)	kg/ha (kg N/ha)	4.3 (2.0)	5.0 (2.3)	9.7 (4.5)
Dinitrogen monoxide (N_2O)	kg/ha (kg N/ha)	4.3 (2.7)	4.9 (3.1)	6.9 (4.4)
Carbon dioxide, from lime and urea (CO_2)	kg/ha	68.2	57.3	176.0
Nitrate (NO_3)	kg/ha (kg N/ha)	135.1 (30.5)	141.7 (32.0)	425.9 (96.2)

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Notes: [a] N quantities of organic fertilisers computed using AGRIBALYSE nutrient contents, otherwise computed using Galland et al. (2020) nutrient contents. Data on specific fertilising inputs were retrieved from MEANS InOut, because in AGRIBALYSE all fertilisers are reported exclusively in terms of their N, P and K contents. Nutrient quantities represent national means and not specific fertilisation strategies

To illustrate Strategy E2, three conventional rotations were chosen, namely A) a leek-carrot-barley-cauliflower rotation receiving livestock effluents and COAF, B) a maize-wheat-rapeseed-wheat rotation receiving livestock effluents, and C) a field crops-sugar beet rotation receiving sewage sludge and digestate; the first two taking place in Brittany (Bretagne) and the third in the Picardy (Picardie) region. The dominantly mineral fertilisation regime of these rotations were substituted, while preserving yields, with dominantly organic fertilisation regimes. The nutrient contents of selected used fertilisers are summarised in Table 2, while the full list with uncertainty data is available in Galland et al. (2020). The fertilisers and associated emissions for these rotations are defined in Table 3 (full ITKs are presented in the Supplementary Material).

Table 2. Nutrient contents of selected organic fertilisers

Organic fertilisers	**C/N**	**Dry matter (%)**	**Total N (g/kg)**	**NH$_4$-N (g/kg)**	**KeqN [a]**	**P$_2$O$_5$ (g/kg)**	**K$_2$O (g/kg)**	**C (g/kg)**	**IOMS [b]**
Swine slurry (Rotation A)	3.4	3.6	3.5	2.5	0.42	2.1	2.7	11.9	50.0
Swine slurry (Rotation B)	3.4	6.8	4.5	2.5	0.42	2.1	2.7	11.9	50.0
Cattle manure	19.0	19.9	4.8	0.9	0.16	2.3	5.9	90.1	65.0
Poultry manure	12.4	64.1	21.7	3.0	0.31	15.3	19.0	269.5	42.3
Digestate of green waste [c]	18.0	26.5	5.9	1.9	0.73	2.7	5.1	102.8	91.0
Dehydrated limed sewage sludge	9.5	25.0	9.3	1.0	0.35	8.5	0.9	85.7	45.0
Commercial organic fertiliser 7-6-8	4.0	85.0	73.0	2.5	0.60	50.0	75.0	280.0	33.0

Notes: [a] Coefficient of N fertiliser equivalence, representing the ratio between the amount of N provided by a mineral fertiliser of the ammonium nitrate type and the total amount of N provided by an organic fertiliser, which allows the same N absorption by the crop over its cycle (COMIFER, 2013). [b] Index of Organic Matter Stability, the proportion of organic matter that will likely contribute to the replenishment of C stocks in soil (Fuchs et al., 2014; Lashermes et al., 2009). [c] In Syst'N simulations, liquid fraction of phase-separated digestate (total N: 1.3 g/kg; NH$_4$-N: 0.8 g/kg) was used instead of raw digestate, considering an equivalent N fertiliser value. All values reported per kg WM (wet mass). Source: Galland et al. (2020). Detailed dataset of organic fertilisers characteristics available from Avadí and Paillat, (2020)

Table 3. Main features of three fertiliser substitution scenarios for crop rotations, representing actual technical itineraries (Strategy E2)

	Rotation A:	**Rotation B:**	**Rotation C:**
	(1) leek	(1) mustard (catch crop)	(1) mustard (catch crop)
	(2) carrot	(2) maize silage	(2) sugar beet
	(3) barley	(3) soft (winter) wheat	(3) soft (winter) wheat
	(4) (late) cauliflower	(4) rapeseed	(4) mustard (catch crop)
		(5) soft (winter) wheat	(5) (spring) barley
			(6) soft (winter) wheat

Fertilisation strategy		Conventional	Eco-design: "Organic"	Conventional	Eco-design: "Organic"	Conventional	Eco-design: "Organic"
Yield 1	t/ha	50	50	N/A	N/A	N/A	N/A
Yield 2	t/ha	50	50	15	15	85	85
Yield 3	t/ha	7.5	7.5	8	8	8	8
Yield 4	t/ha	15	15	3.5	3.5	N/A	N/A
Yield 5	t/ha			8	8	7	7
Yield 6	t/ha					8	8
Mineral fertilisers							
Ammonium nitrate (33.5% N)	kg/ha	1254		1313	418	955	478
NPK 18-46-0	kg/ha			111	111		
Solution 390 (30% N)	kg/ha					1000	333
Organic fertilisers (doses are presented per individual crop in the rotation)							
Commercial organic fertiliser 7-6-8*	t DM/ha		1.3 (1) 1.0 (2) 1.0 (4)				
Cattle manure	t WM/ha		51.5 (2) 4.4 (4)	40 (2)	40 (2)		
Swine slurry	m^3/ha		50.4 (3)		40 (3) 22 (4) 40 (5)		
Dewatered sludge	t/ha						18 (2)
Digestate of green waste	t/ha						11 (3) 13 (5) 11 (6)
Emissions							
Ammonia (NH_3)	kg/ha	0	10.9	4.9	24.3	14.6	14.6
Nitrogen oxides (NOx)	kg/ha	10.8	18.9	16.7	15.5	0.62	26
Dinitrogen monoxide (N_2O)	kg/ha	1.9	2.4	1.3	1.3	1.4	1.3
Carbon dioxide, from lime and urea (CO_2)	kg/ha	0	0		0	196.2	65.4
Nitrate (NO_3)	kg/ha	757.3	956.6	1010	1045	230.3	248

Notes: *Organic fertiliser based on manure compost enriched with rendered animal products and press cakes (Avadí, 2020).

3.2 Life cycle impact assessment

A comparison of the relative impacts of mineral and organic fertilisers, per t of product, is beyond the scope of this work. Such comparisons are available in the literature (e.g. Hasler et al., 2015; Hospido et al., 2010; Quirós et al., 2015; Skowrońska and Filipek, 2014) including on French fertilisers (e.g. Avadí, 2020; Déchaux and Pradel, 2016).

The impacts of all individual crops inventories considered in Strategy D1 (Table 1) after the substitution of dummy organic fertiliser processes with new processes featuring production impacts are practically identical, both per kg product and per ha. It implies that the contribution of organic fertilisers' production is marginal. Single scores increased 0.5% for soft wheat, 1.7% for rapeseed and 0.7% for tomato. In the case of rapeseed, which features relatively higher inputs of organic fertilisers, for certain impact categories such as climate change, ionizing radiation, terrestrial eutrophication and resource depletion (biotic, abiotic and water), the relative change exceeds 10%. The main reason behind these small variations is the fact that organic fertilisers with high associated impacts (e.g. treated sludge) are input in small amounts (in the order of hundreds of kg, as shown in Table 1), because the modelled processes represent **national averages** and thus combine (as a weighted mean) a variety of organic fertilisation practices.

For Strategy E2, the amounts of organic waste required to deliver the necessary organic fertilisation in the alternative eco-designed “organic” rotations, as well as their most common disposal pathways, are detailed in Table 4. These rotations are not fully organic, as they include some mineral fertilisation, but rather organic fertiliser-dominated. According to a recent review (Loyon, 2017), about 11% of animal effluents are treated in France, thus we retained storage + spreading (Loyon, 2018) as the alternative pathway for this waste stream. As of today, the vast majority of liquid and dewatered sewage sludge are either spread in soils (76% of liquid and 36% of dewatered), composted (14% and 37%) or incinerated (3% and 23%) (Pradel, 2019) , thus we retained storage + spreading as the alternative pathway. No specific data on green waste and biowaste was available, other than the indication than in the last ten years around 30% of municipal solid waste was incinerated (ADEME, 2018), 20% of biodegradable municipal waste is landfilled (ETC/SCP, 2013) and about 10% of green waste is collected —separately from municipal solid waste— and valorised via shredding and use as mulch, composting or anaerobic digestion (FranceAgriMer, 2015). We, therefore, retained landfilling and incineration as alternative pathways.

Table 4. Organic waste streams and business as usual disposal pathways associated with the organic fertiliser consumption of organic rotations

		Rotation A		Rotation B		Rotation C		Alternative disposal pathway
Fertilisers	Units	Organic fertilisers	Organic waste	Organic fertilisers	Organic waste	Organic fertilisers	Organic waste	
Commercial organic fertiliser 7-6-8	t/ha	3.3	manure: 0.38 wool residues: 0.11					storage + spreading
Cattle manure	t/ha	56	56	40	40			storage + spreading
Swine slurry	m^3/ha	50	50	102	102			storage + spreading
Dewatered sludge	t/ha					18	raw sludge: 225	storage + spreading
Digestate of green waste	t/ha					36	green waste: 53	landfilling or incineration

In Strategy E2, large amounts of organic fertilisers (tens of t/ha) are input to replace mineral ones (hundreds of kg/ha) (Table 3), and therefore overall impacts increase considerably (Fig. 3), yet this effect is minimised when considering the alternative waste disposal pathways associated with the mineral fertilisation strategy (system expansion). Nonetheless, the choice of not allocating impacts to the production of animal effluents, rather consensual amongst the French LCA community, plays a role in limiting the impacts of these materials as inputs to agriculture. In contrast, the FAO initiative Livestock Environmental Assessment and Performance (LEAP) Partnership (FAO, 2018) suggests allocating impacts to manure (based on heat energy content or economic fertiliser value), because it is a useful co-product as energy feedstock or fertiliser.

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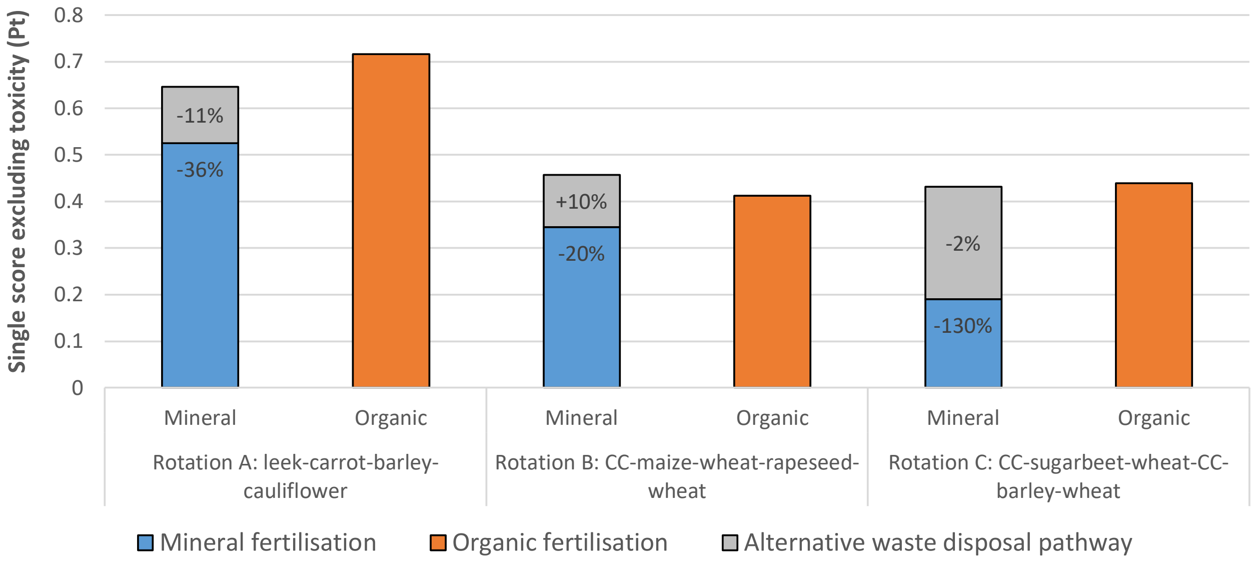

Fig. 3. Relative single scores for three rotations (mineral vs. organic fertilisation), per ha. Percentages represent the overall variation in impacts for the Mineral fertilisation with respect to the Organic fertilisation with and without considering the alternative waste disposal pathways, as represented by the single score (excluding toxicity impact categories, as they tend to dominate due to limitations in the underlying models)

These important differences (if the alternative waste disposal pathways associated with the mineral fertilisation strategy are not considered) are driven by the replacement of mineral fertilisers by animal effluents in Rotation A and Rotation B, and by dewatered sewage sludge and digestate in Rotation C (Fig. 4). In Rotation C, the large increase (>400%) in climate change with respect to the mineral fertilisation is due to the input of 18 t of dewatered sewage sludge, which required the treatment of 12.5 t of raw liquid sludge per t of dewatered sludge (based on their relative DM content), where the direct methane emissions during stocking of liquid sludge are in the order of 2.19 kg CH_4/t (Avadí, 2020; Pradel, 2016; Richard and Pradel, 2014). These organic waste treatment impacts are not considered in the AGRIBALYSE dummy processes representing organic fertilisers. This dramatic increase is reduced to 1% when the alternative waste disposal pathways associated with the mineral fertilisation strategy is included. When the cumulative impacts of the sewage sludge treatment (storage and thickening of liquid sludge) are removed, impacts drop considerably for most impact categories, and still more when all impacts of sludge treatment are removed (Fig. 4c, representing the current situation in AGRIBALYSE processes), yet such impacts should always be considered and its exclusion is presented only to highlight their importance.

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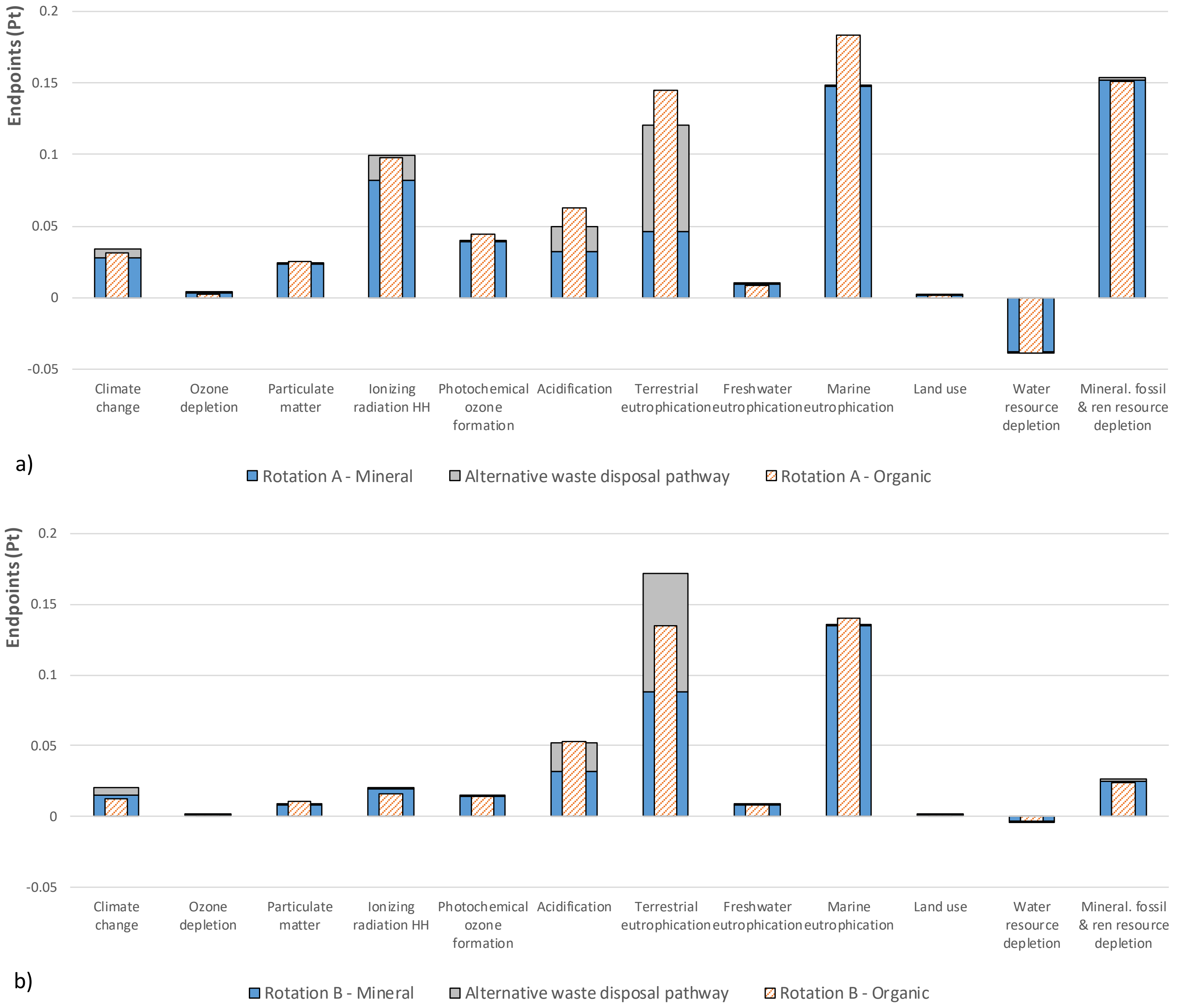

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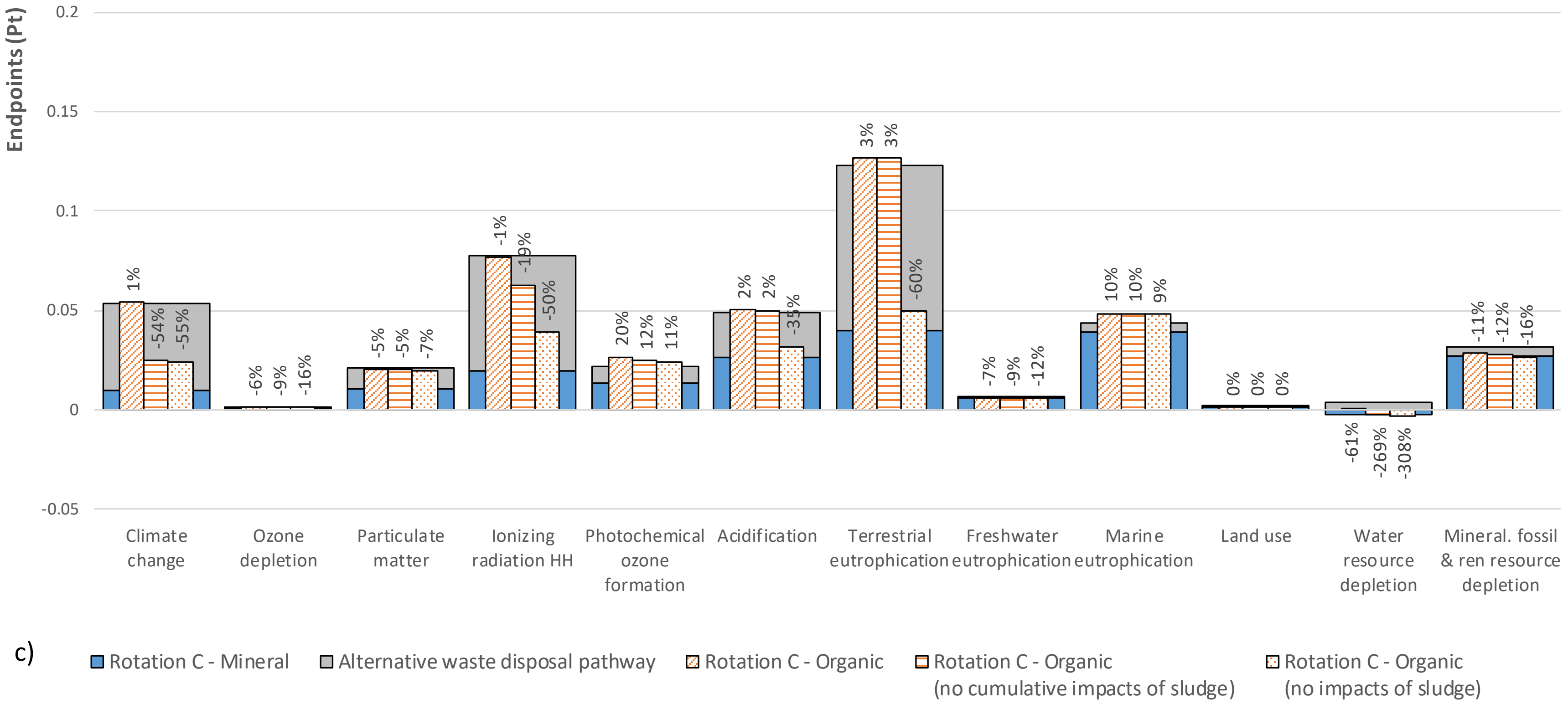

Fig. 4. Relative endpoints for three rotations (mineral vs. organic fertilisation), a) Rotation A: leek-carrot-barley-cauliflower, b) Rotation B: catch crop-maize-wheat-rapeseed-wheat and c) Rotation C: catch crop-sugar beet-wheat-catch crop-barley-wheat. Percentages in c) represent the overall variation in impacts per impact category, highlighting the contribution to impacts of including organic waste processing, with respect to the mineral fertilisation scenario including the alternative waste disposal pathway

A contribution analysis of Rotation C (Fig. 5), excluding the alternative waste disposal pathways, shows that the key contributors to impacts are mineral fertilisers and soil works for the mineral fertilisation strategy and the provision of organic fertilisers (including treated sewage sludge, which features high cumulative impacts) for the organic fertilisation strategy. If the cumulative impacts of treating sludge are not considered (e.g. if dewatered sludge is considered as a waste stream with zero impact, or if dewatering impacts are allocated to the wastewater treatment system), the impacts are dominated by the anaerobic digestion process.

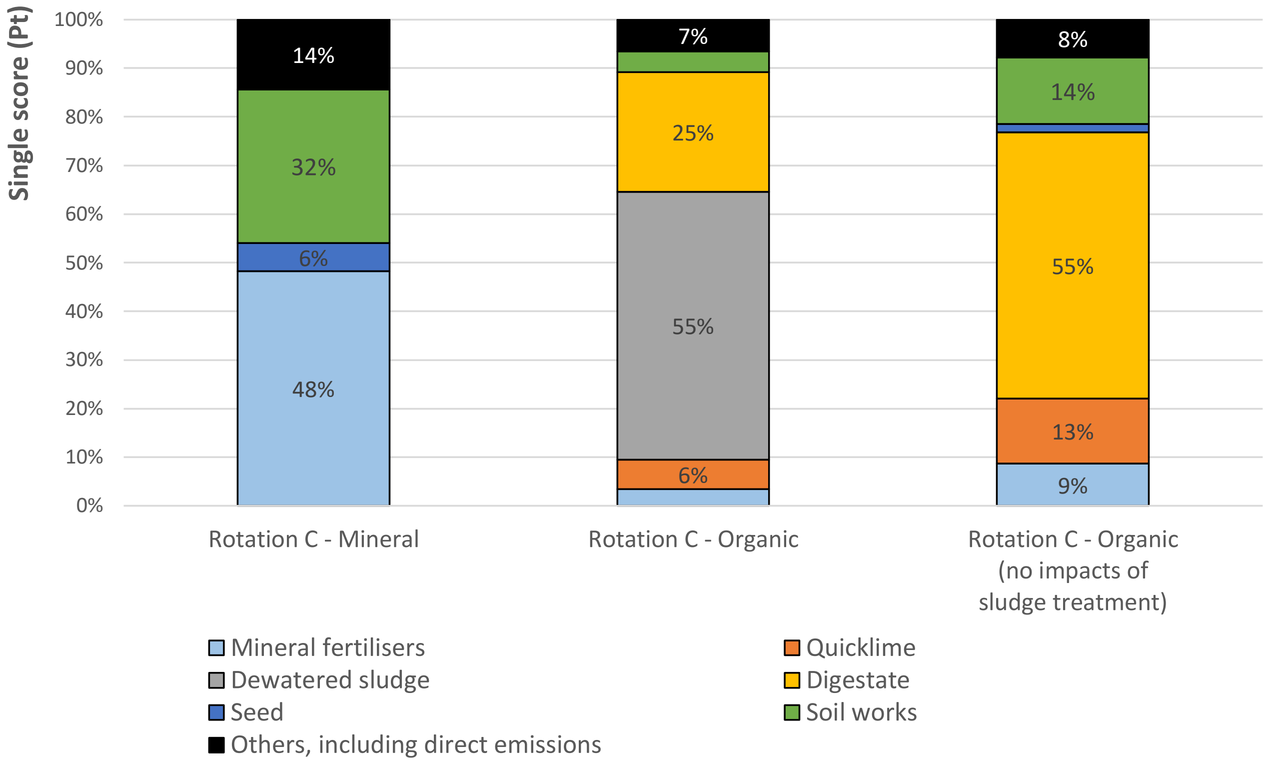

Fig. 5. Contribution analysis of Rotation C: catch crop-sugar beet-wheat-catch crop-barley-wheat

3.3 Feasibility and environmental impacts of improved agricultural inventories and eco-designed "organic" cropping systems

In principle, the substitution of mineral fertilisers by organic ones reduces environmental impacts when the nutrient contents of organic fertilisers are known (so that fertiliser doses can be accurately calculated), and when the avoided impacts of alternative organic waste disposal pathways are considered. In countries where the latter is not mandatory or enforced, the alternative disposal pathway would be modelled as simply dumping of organic waste in the environment, with large associated emissions (nutrient leaching, methane generation, etc.).

Many LCA practitioners model such substitutions by deducting the impacts of producing and spreading mineral fertilisers, especially those using DTU Environment's substance flow-based LCA model EASEWASTE/EASETECH (Clavreul et al., 2014; Kirkeby et al., 2006), which favours the inclusion of avoided flows. This approach has been followed also by non DTU-related practitioners (e.g. Brockmann et al., 2014; Lombardi et al., 2015; Saer et al., 2013). Potential shortcomings of and recommendations on substitution have been widely discussed in the literature (Hanserud et al., 2018; Pradel and Déchaux, 2016; Vadenbo et al., 2017). In our opinion, the practice of system expansion (without substitution) is more informative, as it widens the functions of the modelled system, which in the case of agricultural recycling of organic waste, includes fertilisation of crops and disposal of organic waste. Several practitioners have followed this approach (e.g. Corbala-Robles et al., 2018; Martínez-Blanco et al., 2009; Mattila et al., 2012; Nakatani, 2014; Suh and Rousseaux, 2002).

Strategy D2, as described in Avadí et al. (submitted), would modify direct field emissions, sometimes significantly, depending on the emissions modelling methods used. It is more difficult to justify, especially if the underlying crop rotation (relevant for various direct field emission models) is unknown. We do not recommend it under such conditions. Strategy E1, which would constitute a basic eco-design approach, is neither recommended if the underlying crop rotation is unknown. We insist that such a single crop-based fertiliser substitution would reduce the credibility of the agricultural inventory as representative of a real-world system.

The elaborated data improvement Strategy D1 and eco-design Strategy E2 are not comparable, as they respond to two different sets of LCA needs. Strategy D1 is a very simplified approach to adapt existing single crop inventories to specific situations, be it by replacing dummy organic fertiliser processes with more complete ones (as in our example) or to replace at the crop level mineral fertilisers with organic ones (Strategy E1). For the latter purpose, careful analysis of the impacts of a fertilisation regime change on yields and emissions (including recalculation), as well as of the fertiliser replacement rationale, should be performed. AGRIBALYSE is a key source of cropping systems inventories, useful for agricultural eco-design initiatives. It should nonetheless be kept in mind that processes representing national averages, such as those in AGRIBALYSE and other reference databases such as ecoinvent (Wernet et al., 2016), World Food LCA Database (Nemecek et al., 2020) and Agri-footprint (Blonk Consultants, 2019), do not represent actual ITKs of crops, but a weighted mean of various practices.

Strategy E2 is more complex, and an advanced approach to eco-designing crop rotations by partially replacing mineral fertilisers with organic ones. Such an endeavour demands the use of a dynamic crop model to validate the agronomical soundness of the eco-designed system (i.e. the sequence of crops and associated fertilisation needs), as well as to recalculate the direct field emissions associated with the reformulated fertilisation regime. As it has been shown at the regional/territorial scale (Nitschelm et al., 2018), crop models allow to take account of more specificity and variability in system assessments with LCA.

These complexities should be considered not only by LCA practitioners, but also by other decision-makers engaged in cleaner production in agriculture.

4 Conclusion

The described strategies illustrate the two most common approaches that LCA practitioners would follow to adapt existing agricultural LCIs, at the single crop or crop rotation levels, to particular agricultural situations featuring organic fertilisation. If single crop inventories representing national averages are modified, it is unlikely that the additional impacts of organic waste treatment would significantly contribute to the crop’s production impacts. If crop rotations are to be eco-designed by replacing conventional fertilisation strategies with a dominantly organic fertilisation one, it is recommended to use an agricultural model to validate the new rotation, because substitution of fertilisers is a rather complex endeavour demanding careful calculation of equivalences and interactions among crops. The inclusion of impacts of treating organic waste may have a considerable contribution to impacts, due to energy-intensive processes (e.g. sludge dewatering) and the large amounts of material that would need to be spread to replace mineral fertilisation. Moreover, the expanded functionality of a cropping system consuming organic waste-derived fertilisers (i.e. fertilisation + organic waste disposal) should be considered in comparative LCA.

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All these refinements in agricultural LCA modelling contribute to a cleaner agricultural production, as they in principle enable more accurate comparisons of alternative agricultural systems, especially at the rotation level.

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Figure captions

Fig. 1. Strategies for agricultural inventory data improvement with AGRIBALYSE

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Fig. 2. Strategies for agricultural eco-design with AGRIBALYSE

Fig. 3. Relative single scores for three rotations (mineral vs. organic fertilisation), per ha. Percentages represent the overall variation in impacts for the Mineral fertilisation with respect to the Organic fertilisation with and without considering the alternative waste disposal pathways, as represented by the single score (excluding toxicity impact categories

Fig. 4. Relative endpoints for three rotations (mineral vs. organic fertilisation), a) Rotation A: leek-carrot-barley-cauliflower, b) Rotation B: catch crop-maize-wheat-rapeseed-wheat and c) Rotation C: catch crop-sugar beet-wheat-catch crop-barley-wheat. Percentages in c) represent the overall variation in impacts per impact category, highlighting the contribution to impacts of including organic waste processing, with respect to the mineral fertilisation scenario including the alternative waste disposal pathway

Fig. 5. Contribution analysis of Rotation C: catch crop-sugar beet-wheat-catch crop-barley-wheat