Research article

Contribution of LCA to decision making: A scenario analysis in territorial agricultural production systems

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The corrections made in this section will be reviewed and approved by a journal production editor.

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Abstract

Territorial Life Cycle Assessment (TLCA) appears a promising method to support informed decision making of local actors in territorial agricultural production systems (TAPS), by assessing environmental impacts of agricultural activities and potential strategies. The objectives of this study were to i) adapt TLCA methodology to integrated environmental assessment of TAPS and ii) evaluate TLCA's contribution to supporting informed decision making by assessing scenarios of change in TAPS. A TLCA of the agricultural sector was performed for a territory in the Aube department in France, including main crops and animal production types from raw material extraction to the first stage of processing. Exchanges of agricultural products and by-products among agricultural subsectors were considered by allocating impacts, which prevented double-counting them. Two contrasting scenarios were assessed with TLCA – development of on-farm biogas production and reintroduction of sheep grazing – and compared to the current situation. Results were expressed per unit area (ha), per unit biomass produced (kg) and per percentage contribution to total impacts of the territory before and after processing (at and beyond the farm gate, respectively). The main contributors (cereal and oilseed crops) did not have the highest impact at the farm scale (per ha and per kg), which highlights that contribution to total impacts of the territory is a relevant addition to the impacts per functional unit. Consideration of exchanges showed that TLCA can be used to assess effects of material interactions (biomass flows) between sectors. Scenario results showed no significant differences in impacts, except for higher water resource depletion for the biogas scenario, because most differences between scenarios were smaller than uncertainties in the input data. Other challenges were identified, such as the need to evaluate consequences of changes beyond the territory gate when performing TLCA of scenarios or the utility of characterizing the network of biomass flows in more detail. In conclusion, the methodological framework that was developed successfully identified environmental hotspots and reflected environmental impacts of material interactions between actors. Finally, it can estimate environmental impacts of future strategies, as long as uncertainty is reduced; thus, it shows potential as a decision-support tool.

Keywords: Territorial LCA; Environmental assessment; Agricultural production; Scenario analysis

1 Introduction

Agricultural production is at the crossroads of multiple strategies of development towards an emerging issue: the bioeconomy (Wohlfahrt et al., 2019). Several actors wish to explore the potential to develop new agro-industrial sectors, such as biofuel production or green chemistry (Gauvrit and Mora, 2010), and a growing number of countries implement policies that encourage including agricultural biomass in energy production systems. The growing interest in agricultural products in industrial sectors may lead to competition between new and traditional uses (e.g. food, feed) of agricultural products.

In the current context, in which agriculture has substantial environmental impacts (Foley et al., 2011), changes to agricultural production systems should consider environmental issues. Thus, growing competition among uses of agricultural products and requirements of sustainable agriculture raise the need to support informed decision making by estimating multiple environmental impacts of agricultural production and potential strategies.

Resource management, including agricultural production, is shaped by the territorial context in which it occurs (Cerceau et al., 2018). The term "territory" refers to a system that combines a group of actors and the geographical space that they use, develop and manage (Moine, 2006). We define territorial agricultural production systems (TAPS) as the agricultural sector embedded in a specific geographical space, where agricultural activities are managed by local actors whose visions influence their decisions. Similar systems have been studied under the term "agrarian systems", mostly by historians and researchers in agricultural economics (Cochet, 2011). The geographical scales of territories can vary greatly (Loiseau et al., 2012). The present study focused on a relatively large territory (>300 000 ha), which is relevant for environmental impact assessment and decision making, since it generally corresponds to the scales of impacts and impact management, except for very local impacts (e.g. noise) and global impacts (e.g. climate change) (Nitschelm, 2016).

Few environmental assessment tools can be applied to territories (Loiseau et al., 2012). Among them, life cycle assessment (LCA) is both a "life cycle" approach and a framework that allows for multi-criteria environmental assessment of goods provided by, in this case, agricultural systems (van der Werf et al., 2011). The method has been used substantially in the agri-food sector (Brentrup et al., 2001; Charles et al., 2006; de Vries and de Boer, 2010; Chauhan et al., 2011; Perrin et al., 2014).

For several years, authors have recommended extending the product-oriented perspective scope of LCA (Yi et al., 2007 ; Guinée et al., 2011). Payraudeau and van der Werf (2005) stated that LCA is suitable for assessing environmental impacts of a farming region. Loiseau et al. (2013) adapted the LCA framework to assess land-planning impacts on a territory by developing territorial LCA (TLCA), which includes i) goal and scope definition, ii) activity inventory and iii) impact assessment and interpretation and addresses a variety of methodological bottlenecks. First, the multifunctional nature of territories must be considered. TAPS sustain functions such as land management (e.g. protection of nature), economic activities (e.g. provision of employment and income) and food production (Cairol et al., 2009). Baumgartner et al. (2011) addressed this issue by using multiple functional units (each of which represents one function of the studied system, and to which the inputs and outputs are related (ISO, 2006)). Loiseau et al. (2013) went further by defining a territory and its associated land-planning scenario as the LCA reference flow and then selecting appropriate functions related to them. Researchers increasingly claim that agricultural LCAs require multiple functional units, since results may depend on the function chosen (Salou et al., 2017). Boundary selection is also an issue because a territory can be held responsible for environmental impacts generated through production, consumption or both (i.e. total responsibility (Loiseau et al., 2013)). Considering total responsibility can lead to double counting, for instance when some of a territory's production is consumed within the same territory.

More recently, Nitschelm et al. (2016) developed a spatialized TLCA method to address the loss of spatial characteristics in TLCA (van der Werf et al., 2011). Several authors have demonstrated how TLCA can help identify environmental hotspots and facilitate decision making for sustainable development at the territorial scale (Mazzi et al., 2017; Roibás et al., 2017; Jouini et al., 2019), often by combining LCA with other methods (e.g. including LCA in an environmental management system (Mazzi et al., 2017); combining TLCA and a participatory approach (Jouini et al., 2019)).

Loiseau et al. (2018) highlighted the lack of a consistent definition of TLCA and defined two approaches: type A, which focuses on a specific sector anchored in a territory, and type B, which focuses on all production and consumption activities in a territory. In the agricultural sector, some authors performed type A TLCA studies, encompassing several agricultural activities at the territorial scale (Bartl et al., 2012; Nitschelm et al., 2016; Jouini et al., 2019). Their scopes stop at the farm gate, which is common in agricultural LCAs. However, interactions among farms generate emergent properties of farming territories that need to be considered (Payraudeau and van der Werf, 2005). These interactions can be exchanges of services, products or equipment. Increasing the scale allows impacts of interactions among farms on the environment to be studied, but this approach remains lacking in agricultural TLCA literature.

In addition to identifying environmental burdens, LCA is suitable for assessing environmental outcomes of future scenarios, which is an important feature to facilitate decision making (Björklund, 2012). At the regional scale, some studies have used LCA to assess future scenarios of agricultural production, focusing on a single sector (e.g. dairy production (Acosta-Alba et al., 2012), crop production (Bartl et al., 2012)).

Due to its ability to quantify a wide range of environmental impacts and assess environmental outcomes of scenarios, developing TLCA further appears to be a promising option to support local actors' decision making in TAPS and informed policy making at a national scale. However, the literature currently does not provide a method for agricultural TLCA that encompasses all agricultural activities embedded in a territory and that extends beyond the farm gate to consider interactions among farms and their impacts on the environment. Considering biomass flows among agricultural subsectors would also help to avoid double counting. Furthermore, TLCA's potential to support informed decision making by assessing contrasting scenarios of resource management within a TAPS has not been sufficiently explored. Therefore, the objectives of this study were to i) adapt TLCA methodology to integrated environmental assessment of TAPS and ii) evaluate TLCA's contribution to supporting informed decision making by assessing scenarios of change in TAPS, especially in the context of competition among uses of agricultural products, which requires actors to agree on how to use their local resources. A type A TLCA of the agricultural sector, including interactions among farms and the first processing stage of agricultural products, was performed for a territory in the Aube department in France. Two contrasting scenarios were then built in collaboration with the actors and assessed with TLCA: development of on-farm biogas production and reintroduction of grazing sheep.

2 Materials and methods

2.1 Description of the territory

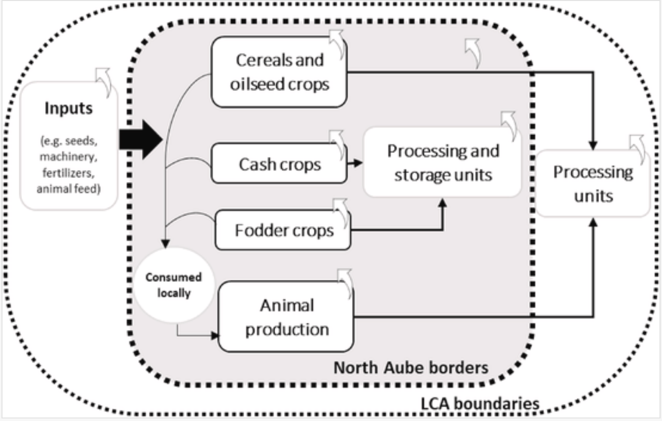
This study focuses on the north of the Aube department (hereafter, "North Aube"), a contiguous area of 380 000 ha located 100 km southeast of Paris. The spatial limits of this TAPS correspond to those of the PDO "Brie de Meaux" cheese in the Aube department. In 2017, agricultural land covered 177 068 ha and was dominated by arable cropping, mostly soft winter wheat (29.7%), spring barley (18.4%), sugar beet (13.2%), rapeseed (10.7%) and winter barley (6.8%) (ASP, 2019; AGRESTE, 2020). Livestock production was less common (183 of 1911 farms) (INSEE, 2018). Some farms have diversified into bioenergy by producing first-generation biofuels and biogas. The agro-industry of North Aube is well developed, with a sugar refinery, dehydration plants, cereal traders, vegetable processors and nearby production of hemp fiber. Many farming systems are facing sustainability challenges, either agronomic (e.g. loss of soil organic matter, rapeseed pest infestations) or organizational (e.g. livestock reduction due to the 70 km distance to a large slaughterhouse). In addition, increasing social tension around the use of non-food biomass (e.g. dehydrated alfalfa, pressed sugar beet pulp, straw) with the development of the biogas sector, which competes with traditional feed use by the livestock sector, requires local actors to make collective decisions about the use of these products.

2.2 Goal and scope definition

The goal of this attributional TLCA was to inform decision makers about current environmental outcomes of their TAPS and consequences of possible dynamics. The scope of the TLCA encompassed life cycles of agricultural products from raw material extraction to storage (for grain crops) or to the first stage of processing. Background processes ("upstream" off-farm processes, i.e. production of inputs) were included (Fig. 1). The study included all crops that covered at least 1% of the agricultural land, which represented more than 90% of the agricultural land. Crop production data were extracted from the national geographic information system at the plot scale for 2017 (Appendix A in the supplementary material) (ASP, 2019). Spring pea and silage maize were included, even though they covered less than 1% of agricultural land, because they represent an important feedstock for biogas plants and/or sheep production. Thus, local data about farmers' practices for these crops needed to be obtained to construct reliable scenarios. For the same reason, intermediate crops (i.e. crops grown between two main crops) were included since they represent a large share of biogas feedstock, and some were used as grazing areas for sheep. Similarly, the most important types of animal production were included: dairy and beef cattle, sheep, pigs, broilers and layers. Products with similar characteristics were grouped into production groups to make the results at the farm gate easier to visualize and understand. Crops were grouped into cereal and oilseed crops (i.e. cereals, grain maize and rapeseed), cash crops (i.e. sugar beet, potato and hemp) and fodder crops (i.e. alfalfa, permanent grassland, forage spring pea and silage maize). Meat from dairy cattle and beef cattle was grouped into cattle for beef, and that from broilers and layers was grouped into chicken for meat.

alt-text: Fig. 1

Fig. 1



Scope and system boundaries of the territorial life cycle assessment (LCA), which extended beyond the borders of North Aube, since background processes and processing activities that occurred outside the borders were included. White arrows represent emissions associated with each stage of production. Black arrows represent transport.

One processing activity was chosen based on the main destination of the product (Table 1). All grain was assumed to be temporarily stored, rapeseed crushed into oil and meal, sugar beet used for sugar extraction, hemp scutched to extract fiber, alfalfa dehydrated, grassland and silage maize ensiled, all animals produced for meat slaughtered and all milk processed into cheese. Potatoes, spring peas and eggs were assumed to be exported without processing or storage. Production of biogas for injection into the natural gas network was also represented, although it has yet to become a major processing activity for any biomass in the territory. It is likely to develop in the TAPS, however, and thus was the focus of one of the future scenarios. The temporal scope was one year.

When it was necessary to distribute environmental impacts between two or more final products, two types of allocation were performed (Fig. 2, Table 1):

i) When a single production type produced two or more co-products, either at the farm gate or after processing (e.g. milk and meat from dairy cattle; sugar, sugar beet pulp and molasses after sugar extraction), impacts were divided between the co-products using economic allocation (i.e. the proportion of each co-product's revenue in the total revenue of the system; Ardente and Cellura, 2012). We prioritized use of local data to estimate allocation factors (i.e. selling prices) and relied on average French reference data when no local data were available (details in Appendix B).

ii) Some agricultural products, whether processed or not, were partly consumed locally within North Aube as animal feed or biogas plant feedstock (e.g. sugar beet pulp (Fig. 2, Table 1)). In this case, the product could have more than one destination. We assumed that agricultural products used as biogas feedstock and fodder came from North Aube if these products were also produced locally. When an agricultural product had more than one destination, impacts were divided between the final products using mass allocation to avoid double counting. Estimates of the allocation factors (i.e. amounts used locally) were obtained by combining data for detailed animal rations and biogas feedstock from interviews and expert opinion regarding the number of livestock head and biogas plants in North Aube. Since the territory did not produce enough maize silage to feed biogas plants and livestock, maize silage was not double counted or allocated between destinations. We assumed that 100% of local maize was consumed locally and that additional amounts came from outside the territory. When intermediate crops were used for biogas feedstock or fodder, their impacts were allocated to biogas or animal production, respectively. When they were not, their impacts were allocated to the following main crop. Benefits of nitrate capture were still allocated to the main crop when intermediate crops were harvested.

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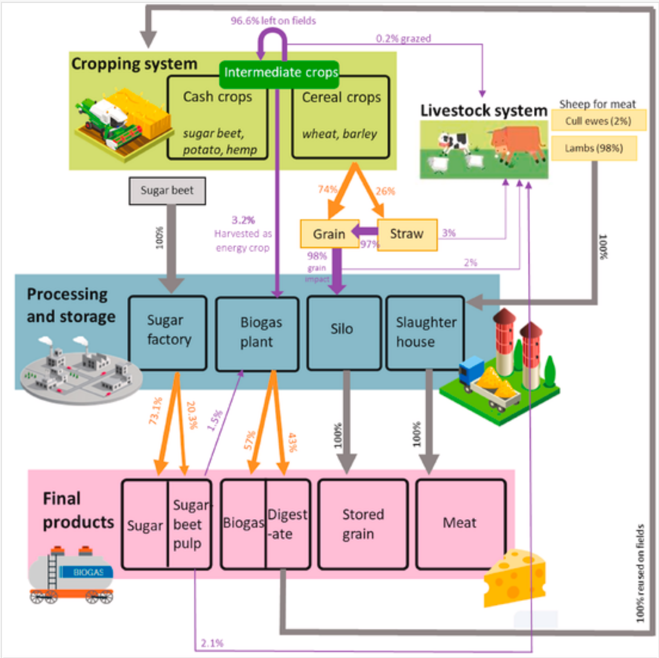
Fig. 2



Some of the allocations performed in the territorial life cycle assessment. Orange arrows represent economic allocations between co-products. Purple arrows represent mass allocations when part of local production was used in another agricultural system in the territory. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

alt-text: Table 1

Table 1

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Destinations of agricultural products and impact allocations of the final products. Economic allocation was used for co-products, while mass allocation was used to avoid double counting.

Product	Destination		Final product/impact allocated to	Allocation
Winter wheat grain	Silo	98%	Stored grain	Mass
	Local livestock	2%	Pigs (99.7%), Beef cattle (0.3%)	Mass
Winter wheat straw	Left on fields	95.3%	Stored grain	Mass
	Local livestock	4.7%	Dairy cattle (75%), Beef cattle (23.3%), Sheep (1.7%)	Mass
Spring barley grain	Silo	98%	Stored grain	Mass
	Local livestock	2%	Pigs (70.2%), Sheep (15.5%), Beef cattle (14.3%)	Mass
Spring barley straw	Left on fields	99.8%	Stored grain	Mass
	Local livestock	0.2%	Sheep (92.6%), Beef cattle (7.4%)	Mass
Winter barley grain	Silo	100%	Stored grain	Mass
Rapeseed	Crushing factory	100%	Meal (68.3%), Oil (31.7%)	Economic
Maize grain	Silo	46%	Stored grain	Mass
	Local livestock	54%	Pigs (90%), Dairy cattle (8.2%), Beef cattle (1%), Sheep (0.8%)	Mass
Sugar beet	Sugar factory	100%	Sugar (73.1%), Sugar beet pulp (20.3%), Molasses (6.6%)	Economic
Potato	Export	100%	Potatoes	None
Hemp	Scutching factory	100%	Hemp products	None
Alfalfa	Dehydration plant	98.6%	Dehydrated alfalfa	Mass

	Local livestock	1.4%	Beef cattle (71.2%), Dairy cattle (18.8%), Sheep (10%)	Mass
Permanent grassland	Ensiled	52.5%	Grass silage	Mass
	Local livestock	47.5%	Beef cattle (51%), Sheep (49%)	Mass
Maize silage	Biogas plant	none	Biogas (57%), Digestate (43%)	Economic
	Local livestock	none	Dairy cattle (89%), Beef cattle (11%)	Mass
Spring pea	Export	100%	Spring pea	None
Intermediate crops	Local livestock	0.2%	Sheep	Mass
	Biogas plant	3.2%	Biogas (57%), Digestate (43%)	mass (between destinations) and economic (between final products)
	Left on fields	96.6%	Crops at risk of nitrate leaching	Mass
Sugar beet pulp	Biogas plant	1.5%	Biogas (57%), Digestate (43%)	mass (between destinations) and economic (between final products)
	Local livestock	2.1%	Dairy cattle (75.3%), Beef cattle (20.8%), Sheep (3.9%)	Mass
	Exported	96.4%	Sugar beet pulp	Mass
Digestate	Applied on fields	100%	Intermediate crops (73.4%), Silage maize (22%), Sugar beet (4.6%)	Mass
Milk	Cheese factory	100%	Cheese (97%), Liquid whey (3%)	Economic
Meat from dairy cattle and beef cattle	Slaughterhouse	100%	Beef	None
Sheep meat	Slaughterhouse	100%	Sheep meat	None
Pork	Slaughterhouse	100%	Pork	None
Meat from broilers and layers	Slaughterhouse	100%	Chicken meat	None
Eggs	Exported	100%	Eggs	None

The functional units selected to report the environmental impacts were unit area (ha of agricultural land) and biomass produced (i.e. kg of product; kg dry matter for forages) to reflect the territory's multifunctionality (i.e. land management and production, respectively). For animal production, impacts per ha included all on- and off-farm agricultural land necessary to produce animal forage and feed (even outside the territory) in addition to that covered by buildings.

2.3 Life cycle inventories

2.3.1 Local data collection

Experts and representatives from crop and livestock value chains were interviewed to describe the diversity of the agricultural production and provide contacts. Subsequently, 18 face-to-face interviews were conducted with farmers in 2019. In total, specific data on 37 types of agricultural production were collected. Surveys contained specific closed-ended questions that focused on detailed farming practices for a given product (Appendix C). Another section of the survey was used to describe the farm and collect data on biomass flows in North Aube. These data were used to define mass allocation factors for product destinations.

When practices for a given production type varied among farmers or when a crop covered a large area (i.e. cereal crops and sugar beet), data were collected from several farmers to obtain a more representative sample (Appendix D). Data for each of the other production types came from only one farmer, and their representativeness was verified based on local expertise.

2.3.2 Life cycle inventory construction

Life cycle inventories (LCIs) were constructed using MEANS-InOut software (Auberger et al., 2018), which estimates emissions at each stage of the production process using models for foreground processes (i.e. on-field emissions and/or direct resource use). The models chosen followed the French LCA methodology AGRIBALYSE (Koch and Salou, 2016) (Appendix E). The background processes came from the AGRIBALYSE database v1.3 (Colomb et al., 2015) and ecoinvent database v3.4 (Frischknecht et al., 2005).

When several datasets were available for a given production type, a weighted-average LCI was constructed based on the representativity of the practices according to expert opinion (Fig. 3, details in Appendix D). Due to large differences in management, separate LCIs were constructed for intermediate crops used as feedstock or fodder and those returned to the soil. For storage and processing stages, LCIs from the ecoinvent database v3.4 were used. Transport from farms to processing and storage units was included. The final impacts of products were the sum of impacts of production and the first storage/processing stage.

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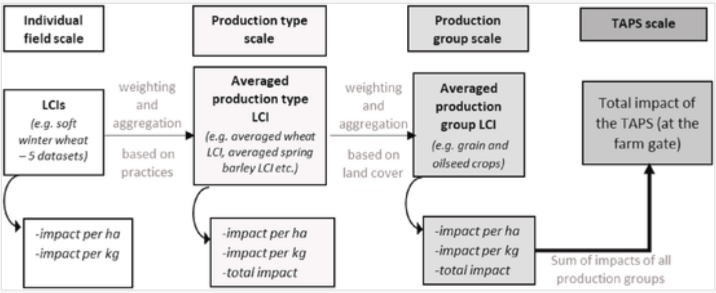
Fig. 3



Calculating impact from the individual field scale to the territorial scale. Total impacts of the territorial agricultural production system (TAPS) were calculated by multiplying the impact per unit of crop and livestock product by the total amount produced. All weighting details are available in Appendix D. LCI: life cycle inventory.

2.4 Life cycle impact assessment

LCIs were imported into SimaPro v8.5 (Pré Consultants, Amersfoort, Netherlands) to calculate six impacts: water resource depletion (m^3 water eq), depletion of abiotic resources (MJ), land competition (m^2year), global warming potential over a 100-year horizon (kg CO_2 eq), acidification potential (kg SO_2 eq) and eutrophication potential (kg $PO_4{}^{3-}$ eq). The characterization models used were ILCD 2011 (water resource depletion) (Chomkhamsri et al., 2011), CML-IA baseline (abiotic resource depletion, acidification potential and eutrophication potential), CML non-baseline (land competition) and IPCC (global warming potential) (Frischknecht et al., 2007).

First, impacts were calculated at the farm gate. Once processing and local consumption of agricultural products were included, total impacts of the TAPS were estimated, from input production to the first processing gate. These impacts were then scaled up to the production-group and territorial scales as a function of land cover (crop production) or number of head (animal production) (Fig. 3, details in Appendix D).

2.5 Uncertainty analysis

When constructing the LCIs, each input variable (survey, process and transport data) was assessed qualitatively using a “pedigree matrix” that consists of five data-quality indicators (reliability, completeness, temporal correlation, geographical correlation and further technological correlation) (Weidema and Wesnaes, 1996). These indicators are then aggregated into a standard deviation of uncertainty in each variable. In SimaPro, a 95% confidence interval of total impact was estimated for each impact category using Monte-Carlo simulation by running 5000 iterations with all input variables that had pedigree-matrix scores drawn randomly from their distributions.

2.6 Scenario development and assessment

Two exploratory scenarios were designed for assessment with TLCA. The baseline scenario was the current situation of agricultural production in the territory (hereafter, “current situation”). One exploratory scenario focused on developing on-farm biogas production (i.e. “biogas scenario”), while the other focused on reintroducing grazing sheep into the territory (i.e. “sheep scenario”). They were created with local actors. Both scenarios represent potential strategies for managing agricultural biomass in North Aube. Moreover, they help address the issues related to the growing tensions around non-food biomass, lack of local organic matter and the relative lack of livestock.

The temporal horizon was set to 10 years. A realistic estimate of the potential development of biogas and sheep was defined with experts. Then, the biomass required for new biogas feedstock or sheep fodder was quantified (details in Appendix F). Impacts of the feedstock or fodder were allocated to their new destination using mass allocation (Table 2). It was assumed that all required biomass was local; thus, when local production of biogas feedstock or sheep fodder (i.e. silage maize and grassland) was not sufficient, land-use change was assumed, with the area of the crop required replacing rapeseed. Rapeseed was chosen because its production has already decreased in the territory and local actors stated that it will continue to decrease due to large pest problems. New organic matter from biogas plant digestate or sheep manure was quantified and applied on local fields (Appendix G). Scenario impacts were calculated using the same method as that used in the current situation. TLCA results of the scenario were compared to those of the current situation to estimate environmental consequences of these new strategies.

alt-text: Table 2

Table 2

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Allocations of products to local livestock, biogas or other uses in the current situation, biogas scenario and sheep scenario. In the current situation, since the territory did not produce enough maize silage to feed biogas plants and livestock, maize silage was not allocated between destinations. We assumed that 100% of local maize was consumed locally and that additional amounts came from outside the territory. Silage maize area increases by 5363 ha in the biogas scenario and 313 ha in the sheep scenario. Grass silage area increases by 1219 ha in the sheep scenario.

Product	Allocation in scenarios								
	Current situation			Biogas scenario			Sheep scenario		
	Alloc. to local livestock	Alloc. to biogas	Other uses	Livestock	Biogas	Other	Livestock	Biogas	Other
Grain	2.0%		98.0%	Same as the current situation			4.0%		96.0%
Straw	3.0%		97.0%	3.0%	8.0%	89.0%	3.5%		96.5%
Intermediate crops	0.2%	3.2%	96.6%	0.2%	24.0%	75.8%	1.8%	3.2%	95.0%
Sugar beet pulp	2.1%	1.5%	96.4%	2.1%	27.5%	70.4%	2.3%	1.5%	96.2%
Grass (silage and grazed)	47.5%		52.5%	47.5%	50.0%	2.5%	100%		
Alfalfa	1.4%		98.6%	Same as the current situation			1.8%		98.2%
Maize silage	No allocation			7.0%	93.0%		44.0%	56.0%	
Spring pea			100%	Same as the current situation			94%		6%

2.7 Current situation

North Aube currently has three operational biogas plants that produce biogas for the national network (A. Croenne, Aube Chamber of Agriculture, pers. comm.). Biogas feedstock was estimated from an interview with a local farmer who produced biogas (Appendix F). Digestate was assumed to be spread on biogas-dedicated crops (i.e. silage maize and intermediate crops for biogas production) and on sugar beet (Appendix G). There are three flocks of grazing sheep with a total of 1100 suckler ewes in North Aube (F. Desné, Aube Chamber of Agriculture, pers. comm.). Ewes spend 80% of the year outside, grazing intermediate crops and grassland. They are returned to barns before lambing until lambs are weaned. Lambs are fattened indoors (Appendix F). Since one LCI of certain crop fields (i.e. sugar beet, rapeseed) already included application of sheep manure and had been averaged with other LCIs of the same crop, no additional replacement of mineral fertilizers with sheep manure was assumed.

2.8 Biogas scenario

Actors mentioned in each interview that many more biogas plants will be constructed in the territory. Assuming that the development path would resemble that in Brittany, a French administrative region where biogas production is already well developed (AILE, 2020), we estimated that 40 biogas plants, including the three already existing, would feed the gas network within 10 years. Each year, these 40 plants would use 453 920 Mg of biomass and produce 55 296 000 m^3 of biogas and 453 920 Mg of digestate.

The feedstock was assumed to consist of sugar beet pulp, food industry co-products, intermediate crops (sorghum), maize silage and cereal straw. It was designed according to the local biogas plant model, except that cereal straw was included. The area of intermediate crops devoted to energy production increased from 2000 to 15 533 ha. To produce the amount of maize silage required, 5363 ha of rapeseed in the current situation was converted to silage maize. Digestate was applied on silage maize, sorghum and sugar beet (Appendix G).

2.9 Sheep scenario

In this scenario, the number of grazing sheep was increased ten-fold, to 11 000 ewes. These new flocks were assumed to operate in the same way as those observed in the current situation. Lamb feeding practices were changed so that all feedstock (except vitamins) would be produced locally. Overall, 11 000 suckler ewes and their lambs were assumed to consume/use 49 793 Mg of biomass $year^{-1}$ (i.e. grazed intermediate crops, grazed grassland, grass silage, sugar beet pulp, maize silage, cereal straw alfalfa hay, spring pea and barley grain). Overall, 1532 ha of rapeseed in the current situation was converted to 1219 ha of grassland and 313 ha of silage maize to produce the amounts of grass and maize silage required. The additional 6640 Mg of sheep manure was applied on sugar beet (Appendix G).

3 Results

3.1 Impacts of production groups at the farm gate in the current situation

Impacts of production groups at the farm gate varied per ha of agricultural land, per kg of product and for the entire TAPS (Fig. 4; detailed results in Appendix H). Cereal and oilseed crops, which cover more than 60% of the agricultural land, contributed 60–70% of North Aube's total impact in all impact categories except water resource depletion, even though they did not have the highest impact per ha of land or per kg of product. The second main contributor was cash crops (ca. 18% of the agricultural land), which contributed 12–23% of North Aube's total impact in all categories except water resource depletion, for which it was by far the main contributor (96%). Cash crops usually had relatively low impacts from a productivity perspective (per kg) but not from a land-management perspective (per ha). Animal production often had the highest impacts per kg and per ha but contributed little (<8%) to North Aube's total impact due to its modest scope.

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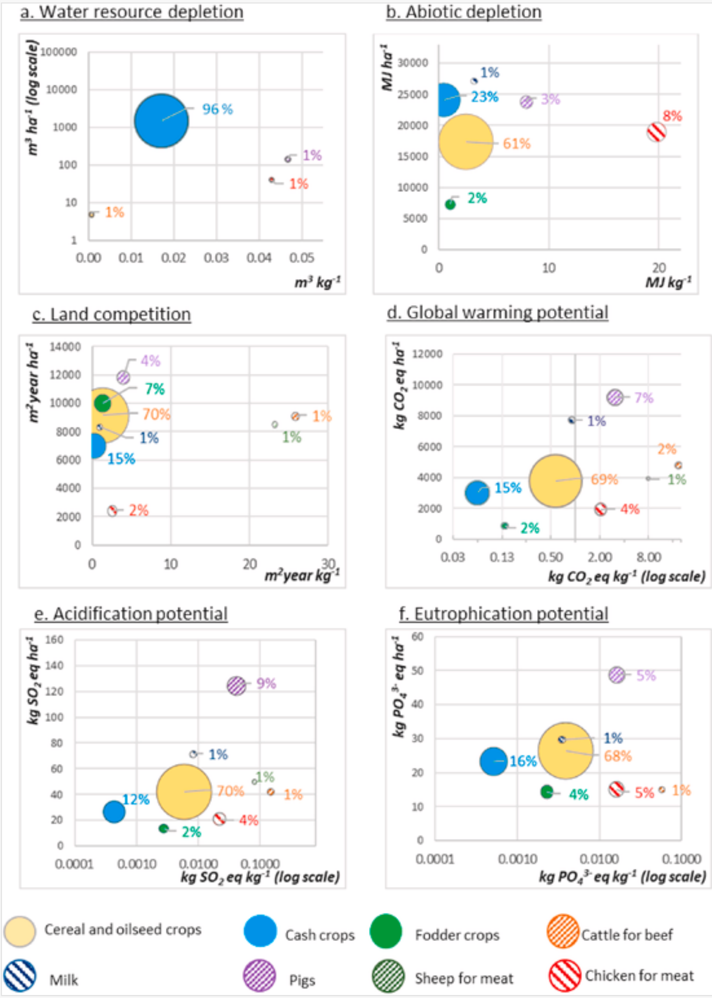
Fig. 4



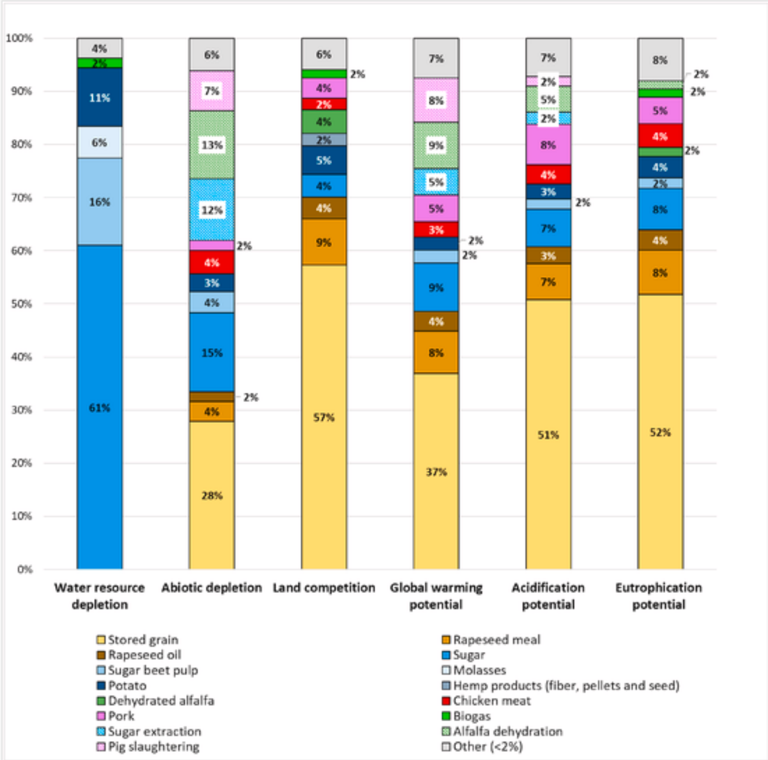
Impacts at the farm gate of the main agricultural production groups in North Aube per ha of agricultural land (y-axis) and per kg of production (x-axis), shown as a percentage of each group's contribution to the total impact in the territory (circle area). Groups that contributed less than 1% of total impact are not shown.

3.2 Impacts of final products and processing in the current situation

Among final products, stored grain (wheat, barley and maize) contributed the most (31–57%) to all impact categories except water resource depletion (Fig. 5). Storage itself accounted for less than 2% of total impact. Rapeseed oil and meal contributed 7–13% of all impact categories except water resource depletion. Sugar beet products (sugar, sugar beet pulp and molasses) contributed 4–9% of all impact categories except water resource depletion (83%). Sugar extraction contributed 13% of abiotic resource depletion, 5% of global warming potential and 2% of acidification potential. Alfalfa cultivation contributed less than 2% of all impact categories except land competition (4%) and eutrophication potential (2%). Alfalfa dehydration, however, contributed more to abiotic resource depletion (13%) and global warming potential (9%). Among all animal products, pork and chicken meat were the only ones that contributed more than 2% of North Aube's impact. Pig and broiler production contributed respectively 5% and 4% of eutrophication potential, 8% and 4% of acidification potential and 5% and 3% of global warming potential. Pig slaughtering contributed 9% each of abiotic resource depletion and global warming potential. Finally, biogas production contributed 2% each of water resource depletion, land competition and eutrophication potential.

alt-text: Fig. 5

Fig. 5



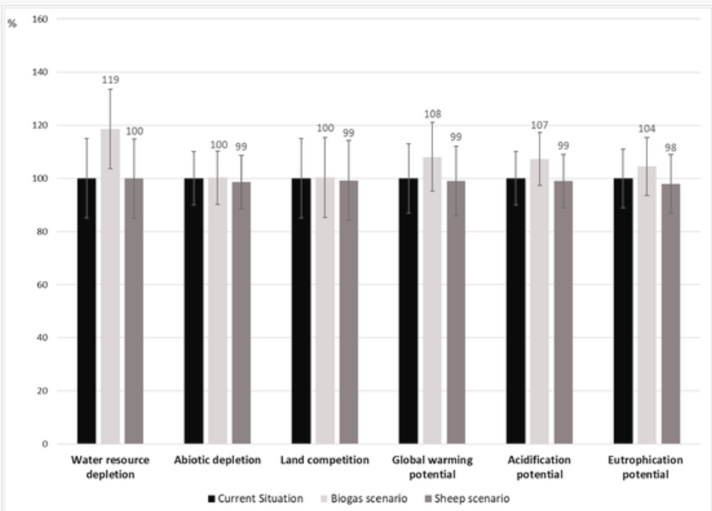
Relative contribution of each final agricultural product (solid bars) or processing activity (hashed bars) to total territorial impact. Products and processing activities that contributed less than 2% are grouped into “Other”.

3.3 Uncertainty analysis

According to Monte-Carlo simulations estimated total impacts were likely to vary by ±15% for land use and water resource depletion, ±13% for global warming potential, ±11% for eutrophication potential and ±10% for abiotic resource depletion and acidification potential (Fig. 6).

alt-text: Fig. 6

Fig. 6



Impacts (in percentage) of the biogas and sheep scenarios relative of those of the current situation. Error bars indicate 95% confidence intervals based on uncertainty in input data (pedigree matrix) estimated from 5000 Monte-Carlo iterations.

3.4 Impacts of the biogas and sheep scenarios

In the biogas scenario, water resource depletion, global warming potential acidification potential and eutrophication potential of the territory increased by 19%, 8%, 7% and 4% compared to those in the current situation (ignoring potential replacement of natural gas) (Fig. 6), but due to uncertainty in input data, only the increase in water resource depletion was statistically significant. To some extent, increased impacts were due to direct emissions from biogas production itself (42% of global warming potential, 7% of acidification potential and 3% of eutrophication potential of biogas production). Feedstock contributed 60–99% of total impacts of biogas production. The large increase in the area of intermediate crops devoted to energy production contributed greatly to this scenario's higher impacts. Because practices for intermediate crops, especially fertilization, differ depending on the crops' destination, intermediate crops had higher impacts per kg dry matter when they were grown for energy than when they were left on fields, for water resource depletion (+41%), abiotic depletion (+37%), global warming potential (+90%), acidification potential (+98%) and eutrophication potential (+40%). Thus, increasing the area devoted to energy production also increased the territory's environmental impacts. Regarding agricultural practices, fields fertilized with digestate required less mineral fertilizer, which decreased abiotic resource depletion and global warming potential, but involved higher PO43- eq. emissions. Silage maize contributed the most to water resource depletion in the biogas scenario () since its area increased greatly to produce enough biomass, and the local reference for “energy maize” cultivation is irrigated.

In the sheep scenario, impacts of the territory decreased by no more than 2% (Fig. 6). Thus, increasing the sheep herd from 1100 ewes to 11 000 ewes in 10 years would have a negligible environmental impact at the scale of the TAPS. We decided not to test reintroducing even more sheep, since this ten-fold increase is already considered to be ambitious.

4 Discussion

4.1 Data selection and system boundaries for environmental assessment of TAPS

4.1.1 System boundaries

In this study, TAPS boundaries were defined upstream with local actors. However, including processing activities in agricultural TLCA raised an issue: whether TAPS′ geographical borders should correspond to the LCA's boundaries, since several processing activities occur outside North Aube. Loiseau et al. (2013) recommend stopping LCAs at the geographical borders because local actors have no influence on what happens beyond them. In this study, the first processing stage was included whether it occurred in the TAPS or not. By stopping at the geographical borders, only certain processing activities would have been included, which would have introduced bias into the comparison of impacts among products. In a prospective approach, stopping at the geographical borders when estimating impacts of scenarios risks confusing mitigation of impacts with displacement of impacts. However, a relevant addition to this study would have been to distinguish impacts inside the TAPS borders from those outside. Ultimately, LCA and TAPS boundaries do not have to overlap perfectly when the scope goes beyond the farm gate. The importance lies in adapting the scope to the challenges that local actors address.

4.1.2 Data collection

Data collection is a crucial part of TLCA since the data must be representative of the TAPS. Two types of data were collected in this study. First, regional and national databases were used to collect information on land cover, background processes and industrial processes. These databases are constructed with large samples of data, but when TAPS boundaries do not overlap perfectly with administrative borders, extracting relevant data from these databases can be an issue. In addition, they often lack information about farming practices, which is necessary to construct representative LCIs. Thus, we preferred using the second type of data (interview data) to describe farming practices. Interview data were compared to data provided by the Aube department's Chamber of Agriculture (Vegelia, unpublished) to ensure their representativity. It is necessary to compare multiple sources of data to improve data quality (Jouini et al., 2019). Unfortunately, the data were not always representative. For instance, the large contribution of cash crop cultivation to water resource depletion, due mainly to irrigation of sugar beet, may have been due to sampling bias. One of the three farmers interviewed to build the average LCI of sugar beet irrigated massively. Without more data on the percentage of irrigated land and on irrigation practices in North Aube, it is difficult to assess the validity of this result. Similarly, one of the sugar beet LCIs and one of the rapeseed LCIs included sheep manure application. Since the percentage of local fields actually fertilized with sheep manure was not considered when the LCIs were weighted and averaged, the TLCA likely overestimated this percentage, which compromises the accuracy of the results.

To perform TLCA, using these two types of data was relevant. To improve local data collection and extrapolation of the results, a farm typology based on production or practice indicators would have been useful (Avadi et al., 2016). Jouini et al. (2019) built a typology based on local actors' understanding of agricultural systems using territorial participatory assessment, which truly reflects local actors’ visions of their territory and empowers them by involving them early in the TLCA process.

4.2 Adapting TLCA for integrated environmental assessment

4.2.1 Material interactions

In this study, exchanges of agricultural products and by-products among farms were considered. Doing so showed that TLCA, via allocation, can be used to assess effects of material interactions (i.e. biomass flows) among subsectors. Indeed, these interactions must be included in TLCA to reflect TAPS dynamics more completely. Moreover, many effective solutions to decrease environmental impacts of production focus on collaborative strategies and on closing loops of material flows (e.g. use of by-products; Simboli et al., 2015). In a prospective approach, these interactions need to be included in TLCA to provide actors with better environmental assessment of collaborative strategies that they may consider. However, the allocation assumptions in this TLCA simplified real-life processes. More detailed data would improve the accuracy of these results. For instance, it was not possible to estimate what percentage of animal feedstock was produced locally, so we assumed that all of it was. In addition, other interactions could be considered, such as equipment sharing.

To improve TLCA, characterizing biomass flow networks better thus seems an important step of data collection, for instance by interviewing local experts. These networks can then be represented better using methods such as material flow analysis (MFA). MFA has been combined with LCA for waste management and urban development (e.g., De Meester et al., 2019; Westin et al., 2019), but combining it with agricultural LCA at the territorial scale remains to be explored.

Immaterial interactions (e.g. social parameters that influence decision making) were not considered in this study, although they influence territories' dynamics greatly (Lamine et al., 2019). Including social processes requires a transdisciplinary approach. One option is to combine TLCA with agent-based models (i.e. computer simulations of actors' roles and behavior), which provide understanding of consequences of actors' actions in the social network (Fernandez-Mena et al., 2016). Combining these methods is challenging because it requires complex tools, analysis and models (Fernandez-Mena et al., 2016), but it seems essential for developing more realistic scenarios.

4.2.2 Scales of impact assessment

TLCA is an excellent way to identify environmental hotspots in TAPS, thus providing a starting point for setting priorities when designing strategies for the future. TLCA can assess environmental impacts at multiple scales (from field to TAPS scales); these scales represent interdependent levels of organization (Cochet, 2011), and results at a larger scale can be interpreted only with those at a smaller scale. For instance, looking at impacts at the production-group scale without comparing them to impacts at the crop scale complicates interpretation. This study highlighted that expressing the contribution of each production group to the total impact of the TAPS is important. The main contributors to North Aube's total impact (i.e. cereal and oilseed crops) do not have the highest impact at the farm scale (i.e. per ha and per kg). Conversely, animal systems have the highest impacts per ha and per kg but contribute little to the total impact since they are less common. Observing contribution of the systems to the total impact was especially relevant for final products. For instance, although alfalfa covered only 4% of agricultural land, alfalfa dehydration contributed disproportionately to total abiotic resource depletion (13%) and global warming potential (9%) because dehydration plants burn mostly coal. However, alfalfa is the production type with the lowest impact at the farm gate. Since alfalfa is the only nitrogen-fixing crop cultivated at a large scale in North Aube, it is important to maintain, and new strategies should be considered to process it. Ultimately, environmental impacts of TAPS must be assessed at multiple scales. Indeed, this shifting-scale property is one great advantage of TLCA for supporting decision making, since results can either be summarized at the territorial scale or detailed at smaller scales, thus addressing a wider audience (Carof et al., 2013).

4.3 Scenario assessment: challenges to overcome

TLCA has potential as a scenario assessment tool. First, the results show that TLCA can model changes in production (e.g. increase/decrease of one production type), biomass flow (e.g. redirection of local biomass to sustain new production types) and practices (e.g. replacing mineral fertilizers with digestate/manure). In addition, the multi-indicator and multi-scale nature of TLCA provides detailed results, and its transparency allows one to determine how results were obtained (e.g. contribution analysis). Thus, it serves as a strong basis for dialogue with local actors (Lazarevic et al., 2012), although non-specialists may have difficulty interpreting results (Renouf et al., 2018). However, this study highlights important limits of TLCA and obstacles to overcome to assess scenarios successfully for local actors.

4.3.1 Data uncertainties

The main challenge identified in this study is that nearly all changes in impacts between the current situation and the scenarios lay below the 10–15% uncertainty level. The sheep scenario, which added 10 000 ewes to the TAPS, differed in impact from the current situation by only 0–2%. In the biogas scenario, 40 biogas plants would use a huge amount of biomass. It appears that installing 37 more biogas plants would not change significantly environmental impacts of the TAPS, except for water resource depletion. These results emphasize the need to decrease uncertainties to obtain more conclusive results, or to build and assess more extreme scenarios. This is clearly a disadvantage of using TLCA to help local actors, because most of the scenarios that they may want to test would lie below the uncertainty level. In addition, TLCA is time-consuming, so it is necessary to agree on a few relevant scenarios to explore, which requires deep communication between research actors and local actors throughout the process.

In this study, uncertainties arise mainly from the representativity of the farm sample and from the quality of interview data. Although results usually matched literature references well (Brentrup et al., 2001; Charles et al., 2006; de Vries and de Boer 2010; Niero et al., 2015; Hijazi et al., 2016), results for eutrophication potential seemed relatively high for wheat and barley cultivation, perhaps because these crops receive the phosphorus fertilization for the entire crop rotation. Representing the entire rotation in the study would help confirm or refute this hypothesis. Uncertainty in LCA calculation models is also an issue. For instance, N_2O emissions in the model we used (IPCC, 2006; Tier 1) are assumed to be a linear function of nitrogen fertilizer application alone, even though many factors influence them (e.g. nitrogen form, farming practices, soil and climate characteristics). These simple models prevent comparison of farming practices (Perrin et al., 2014), such as the no-tillage that many farmers in North Aube practice on cereal and oilseed crops. In addition, relevant impact categories for comparing these practices (e.g. impact on biodiversity or soil quality) were not selected due to the current limitations of their characterization methods in LCA (Garrigues et al., 2012).

4.3.2 Consequences overlooked

Q2 This study did not consider consequences of changes beyond North Aube's borders sufficiently. For instance, the biogas scenario ignored the potential to replace natural gas with biogas, because natural gas is not used much in agricultural activities of this territory. Considering natural gas replacement in the biogas scenario may decrease the scenario's environmental impacts, since 1 kWh of biogas emits 90% less CO_2 than 1 kWh of natural gas (Quantis, 2020). Similarly, sugar beet pulp was one of the main biogas feedstock components in the biogas scenario. Currently, most of it is dehydrated and exported as animal feed, but this second processing stage was not considered in our study, whose boundaries stopped at the first processing stage. Including dehydration would penalize the current situation and sheep scenario more than the biogas scenario, since much pulp in the latter scenario is sent to biogas plants instead of being dehydrated. However, the decreased availability of sugar beet pulp for livestock systems outside of North Aube might lead to indirect land-use change to produce animal feed. LCA studies have shown that producing biogas from by-products traditionally used for livestock emits less greenhouse gases than fossil fuels per unit of energy, but that when the biogas production system is expanded (i.e. when consequences outside the system are included), the impacts of additional production of feed crops decreases these savings in emissions greatly (Tufvesson et al., 2013). To improve our understanding of consequences, it seems essential to perform consequential LCA (Ekvall and Weidema, 2004), which would better represent processes modified by changes at the local scale.

5 Conclusion

A methodological framework for integrated environmental assessment of TAPS using TLCA was developed and tested on the territory of North Aube. The method was able to assess environmental outcomes of all agricultural activities, including processing, and outcomes of material interactions among agricultural subsectors. Moreover, TLCA was applied to assess two scenarios: biogas development and sheep grazing. The main results showed no large differences in impacts for either scenario compared to the current situation, except for higher water resource depletion for the biogas scenario. Efforts must be made to decrease uncertainties in input data to assess scenario impacts effectively. Scenarios should be designed with local actors to help them learn what can be assessed and to select a reasonable number of scenarios to assess. Finally, to include economic and social assessment, TLCA could be combined other relevant approaches, such as agent-based models that include socioeconomic parameters. Recommendations from this study are to prefer local data to describe farming practices, compare multiple data sources and characterize biomass flows during data collection. Then, when performing attributional TLCA, allocation should be used to describe these flows. Results should be assessed at the farm and territorial scales to discuss them with local actors. Ultimately, consequential TLCA should be performed to investigate strategies that actors identified from an environmental perspective. Doing so requires deep communication among all actors, and combining TLCA with other approaches appears challenging. However, it could lead to the development of contextualized strategies for more sustainable TAPS.

Credit author statement

Noélie Borghino: Conceptualization, Methodology, Investigation, Writing – original draft. Michael Corson: Methodology, Resources, Writing – review & editing, Laure Nitschelm: Resources, Writing – review & editing, Aurélie Wilfart: Resources, Writing – review & editing, Julie Fleuet: Investigation, Writing – review & editing, Marc Moraine: Resources, Writing – review & editing, Tor Arvid Breland: Resources, Writing – review & editing, Philippe Lescoat: Conceptualization, Resources, Writing – review & editing, Funding acquisition, Olivier Godinot: Conceptualization, Methodology, Resources, Writing – review & editing, Supervision

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112288.

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Highlights

- Territorial LCA of the agricultural sector was performed for a territory.
- Environmental hotspots were identified.
- Environmental effects of material interactions between farms were assessed.
- Two scenario were evaluated with TLCA: biogas development and sheep reintroduction.
- Scenario results showed no large differences in impacts.

Appendix A Supplementary data

The following is the Supplementary data to this article:

Multimedia Component 1

Multimedia component 1

alt-text: Multimedia component 1

Queries and Answers

Q1

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