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Exploring challenges and opportunities of an agricultural territory using Life Cycle Assessment.

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Abstract

Biomass of agricultural origin (BAO) has many uses and results from human activities in a specific context. Its management should consider the associated environmental impacts. Life Cycle Assessment (LCA) is a standardized environmental impacts evaluation method. Recent studies have emphasised its relevance at territory scale, as it generally corresponds to the scales of impacts and impact management. In this context, this study performed territorial LCA on North Aube agricultural territory. LCA was performed on main production sectors, from inputs production to first processing industry gate. Production's impacts were expressed per ha, per kg and in proportion of impact carried by each product relatively to the total territory's impact. Results show the major contribution of grain and cash crops (82-95% of each impact category), mainly due to on-farm emissions and mineral fertilizer use. To a smaller extent, pig and broiler production carry a part of the territory's impact. Results emphasized that processing should not be neglected. Two scenarios considering biomass use change were designed and assessed in order to validate territorial LCA as a relevant tool for prospective approaches. To improve the applicability of the method with regards to scenarios assessment, consequential LCA should be performed. In addition, further studies should use complementary indicators.

Keywords: Life Cycle Assessment – Territory – Scenarios – Agricultural biomass

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List of abbreviations

AD: Abiotic (fossil fuels) depletion
AP: Acidification potential
BAO: Biomass of agricultural origin
CH4: methane
CO2: Carbon dioxide
EU: Eutrophication potential
Eq: equivalent
GWP: Global warming potential
Ha: hectare
ISO: International Organization for Standardization
Kg: kilogram
KWh: kilowatt-hour
LC: Land competition
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
LEI: Low External Input
MJ: megajoule
N: nitrogen
NH3: ammonia
N2O: nitrous oxide
PJ: petajoule
PO4---: phosphate
SO2: sulphur dioxide
WRD: Water resource depletion

1 Introduction and literature review

All human economic activities consume natural resources and emit polluting substances into the environment. Dwindling of non-renewable resources and climate change are two trends that demonstrate that current demand from the economic system is higher than natural resources availability and sink capacities of ecosystems. (van der Werf et al. 2011)

In a sustainable development perspective, there is a need to adapt economic systems in order to better preserve the natural environment. Among these systems, agriculture (and the entire food system) is one of the main challenges. Indeed, expansion of agricultural area and intensification led to enhanced resources depletion and pollutant emissions. Agriculture is currently responsible for a large share of environmental degradation (e.g energy, water and land use, eutrophication, acidification, climate change**…** (Foley et al. 2011)**)** due to biomass production. There is an urgent need for effective methods for assessing environmental impacts (van der Werf et al. 2011) that could help develop innovative strategies for sustainable agricultural production. This should occur through cooperation of researchers and food systems actors.

1.1 Why should research focus on facilitating actors' decision making over agricultural biomass management?

Biomass of agricultural origin (BAO) includes both animal and plants, food and non-food, and products and by-products. It results from human activities in a specific context. Its management should consider environmental and energetic footprint of the ways it is produced and valorized. (Chatzimpiros 2011, Tritz 2013) In recent years interest was renewed for BAO's non-food uses. Some see in BAO the potential for new agro-industrial sectors to develop, such as biofuels production or green chemistry (Gauvrit and Mora 2010), and a growing number of countries implement policies that encourage the integration of biomass in energy or industrial production systems

BAO appears to be at the crossroads of multiple strategies. Each new use of biomass consists of a redirection of previous functions (Cerceau 2017). This raises the issue of potential competition between food and non-food uses of BAO. Such competition raise the need for to assess current BAO management strategies and their associated impacts, as well to study effects of evolving strategies to help actors designing the future of their territories.

1.2 At which scale should BOA production and management be evaluated?

According to Cerceau et al. (2018), the use of biomass must be considered in a territorial focus, since resource management is shaped by the territorial context in which it occurs. Especially for environmental impacts assessment, Nitschelm et al. (2016b) argue that territory scale is a good choice since, except for very local impacts such as noise and global impacts such as climate change, the scale of the territory generally corresponds to the scales of impacts and impact management.

As defined by Moine (2006), a territory is a geographically contiguous area within which human activities are ongoing. Those activities are managed by local actors whose vision of the territory influences their decisions. Thus, a territory is a place where actors gather around common questions (environmental, economic, and social) and make decisions (Payraudeau and van der Werf 2005). In agricultural territories, which are territories in which most land uses or economic activities are based on agriculture (Payraudeau and van der Werf 2005, Nitschelm et al. 2016b), actors focus on questions such as the trade-off between production and environment.

The term "territory" (rather than “region”) is commonly used in Francophone research. In this study the term territory is employed to refer to the study zone.

1.3 Which methodology to use for the evaluation of agriculture impacts at territorial scale?

There are many methods that exist to evaluate the environmental burdens associated with agricultural production (van der Werf and Petit 2002). Among them, Life Cycle Assessment (LCA) provides a multi-criteria, multi-scale and multi-functional perspective.

"LCA assesses the environmental impact of a product, service or system in relation to a particular function by considering all stages of its life cycle" (Jolliet et al. 2010) i.e. from the acquisition of raw materials, to its production, use and end of life (waste disposal, recycling). (van der Werf et al. 2011)

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 (Loiseau 2014, van der Werf et al. 2011). There are two types of LCA (Finnveden et al. 2009): i) attributional LCA, to describe a system and its environmental impacts ii) consequential LCA, to describe how the environmentally relevant flows can be expected to change as a result of actions taken in the system (Rebitzer et al. 2004).

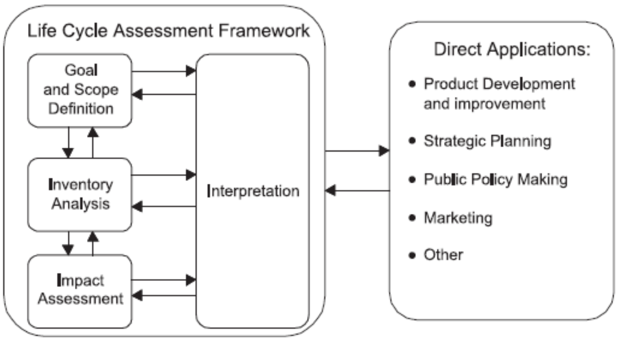

Figure 1- Phases and Application of Life Cycle Assessment.
(Rebitzer et al. 2004)

The method is standardized and based on international consensus. In accordance with ISO (International Organization for Standardization) standards (2006a, 2006b), LCA's methodological framework includes four steps (Fig. 1), (i) definition of the goal and scope of the study, including the functional unit to which are reported the impacts (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA) and (iv) interpretation of results. The different steps of the method are detailed in Appendix 1.

Few studies performed LCA at a territory scale to assess impacts of specific human activities (Loiseau et al. 2013). Therefore, territorial LCA is not standardized.

Loiseau et al. (2013) identified several methodological bottlenecks that should be addressed to perform territorial LCA. First, the multifunctional nature of territories must be considered. Thus, defining only one functional unit is a challenge. The main function of agricultural territories can be argued to be land management, financial or food production. Baumgartner et al. (2011) addressed this point by allocating multiple functional units simultaneously to a farming system. Boundary selection is also an issue identified by Loiseau et al. (2013). For environmental impacts, a territory can be held responsible for impacts generated through production, consumption or both. Considering the territory as responsible for both production and consumption impacts can lead to double counting, for instance, when some agricultural production is used within the territory for local consumption.

In agricultural LCAs, most of the time the system stops at the farm gate (de Vries and de Boer 2010). However, Payraudeau and van der Werf (2005) state that interactions between farms are emerging properties of farming territories and need to be considered. For example, these interactions can be exchanges of services, products, shared equipment or waste treatment. Indeed, shifting scale allows for study of positive or negative impacts of interactions between farms on the environment. LCA gate must then be expanded beyond the farm level. Finally, data collection is also problematic because it is necessary to ensure that the data collected are representative of the territory. This highlights the importance of investigating a representative sample.

Ultimately, territorial LCA is still a very recent field of research. More attempts of territorial LCA are necessary to identify which challenges can be avoided and how, as well as to identify the best options for scope definition and uses of studies results.

1.4 Presentation of the BOAT Project

This thesis is part of the BOAT project (*gestion des Biomasses d'Origine Agricole dans les Territoires* / Agricultural biomass management in territories), coordinated by AgroParisTech. The project is funded by ADEME (French Environment and Energy Management Agency) and brings together several partners: Université Technologique de Troyes, IRSTEA Grenoble, Université de Grenoble, Agrocampus Ouest, Lasalle Beauvais and Université Paris Diderot.

BOAT’s overall goal is to build a methodology for holistic territorial diagnosis to facilitate decision making of local actors to build sustainable agricultural territories. The project aims to study production and use of BAO at the territory scale to further improve its management with regards to environmental, energetic and socio-economic challenges. Two contrasting regions fall under the scope of the project (Biovallée in Drôme and North Aube), this study focused on the Aube study zone. Olivier Godinot, associate professor at Agrocampus Ouest is in charge of territorial environemental impact assesment using Life Cycle Assesment (LCA) methodology.

1.5 Research question and objectives

As discussed, environmental impact mitigation and BAO management are two major sources of interest in agricultural territories. This study was performed in that context. It arises from the need to identify current environmental impacts of the agricultural sector and to describe the evolution of these impacts if different BAO management strategies are adopted in the future.

This study is both result and methodology oriented. It has the objectives to bring elements for further improvement of territorial LCA as well as identifying which opportunities for agricultural sustainability are revealed when performing LCA on a territory, using the example of North Aube. In a second time, this study aims at supporting North Aube actor’s decision making with regards to the future of their territory, as well as evaluating territorial LCA as part of a prospective approach.

The research questions of this study are:

- What challenges are currently faced by the Aube territory, in terms of environmental impact mitigation and BAO use, to developing agriculture that performs well environmentally?
- What would be environmental results of developing scenarios related to potential future BAO management strategies?
- How can territorial LCA support a prospective approach to build sustainable agricultural territories?

2 Materials and Methods

The methodology used consisted of 6 steps (Fig 2).

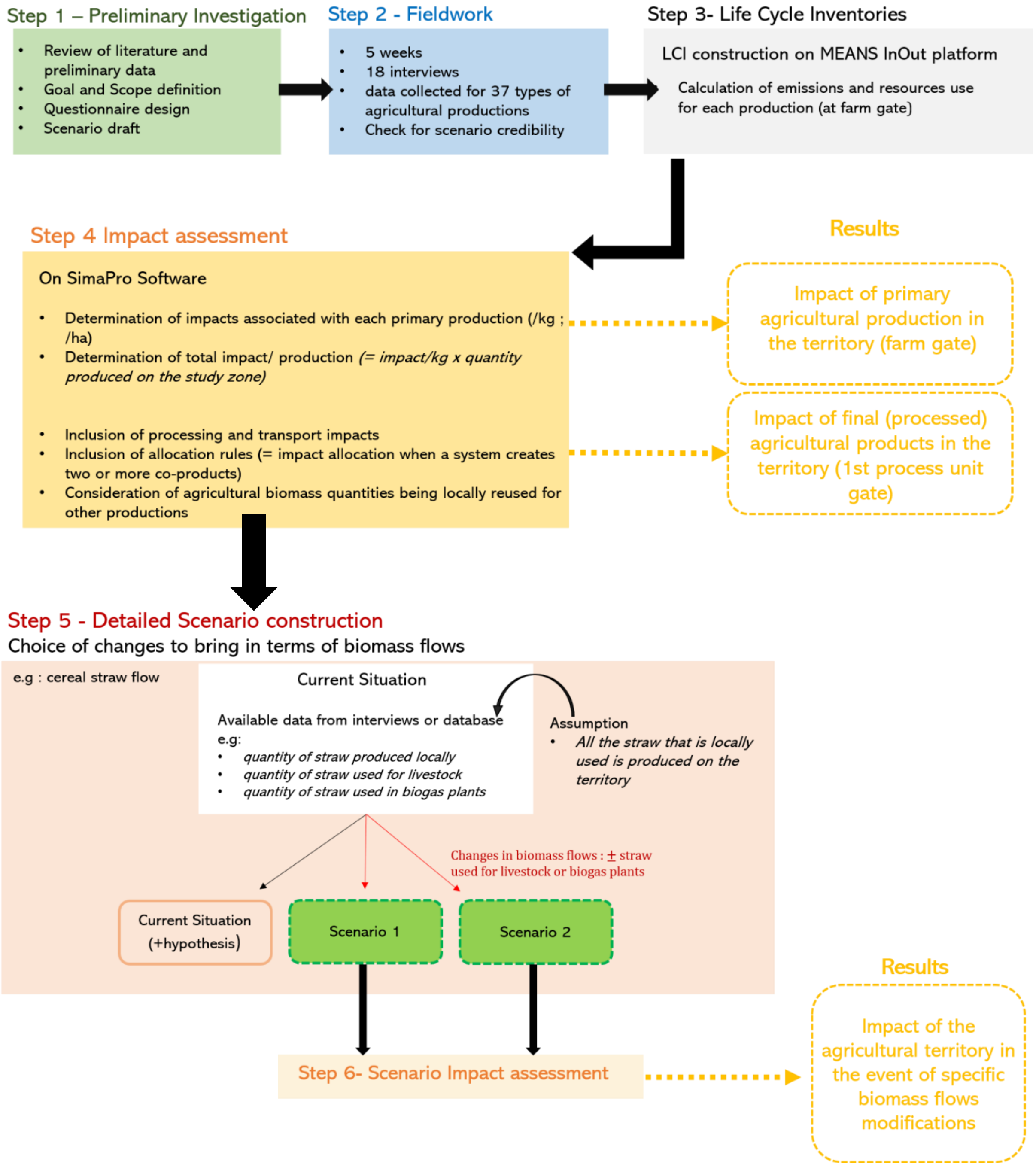

Figure 2- Method map of this study

2.1 Presentation of the territory under study

Data reported in the following section were extracted from the agricultural atlas of the French region Grand Est (DRAAF Grand Est 2016), statistics from the Ministry of Agriculture (AGRESTE 2019) and from exploratory interviews carried out previously for the BOAT project.

The French department of Aube is located in north eastern France. It has 300 000 inhabitants, one third of whom live in rural areas. The agricultural sector occupies 63% of the department's area (ca. 380 000 ha). Two production types dominate land occupation: viticulture for champagne production and arable cropping. Specialization in arable cropping led to a high mean farm size, which is still increasing (average of 126ha in 2000, 143ha in 2010 – vineyard excluded) as well as a decrease in farm numbers (-20% between 2000 and 2010). Livestock production appears limited (only 750 farms out of 1762) and is decreasing (-30% of pasture area and -50% of livestock from 2000-2010). Aube is also the French department that produces the most hemp. A few farms have diversified to energy production through biogas production from livestock waste, intermediate crops or sugar beet by-products

The spatial limits of this study are not the exact geographical borders of the department. Instead, the study focused on the northern part of the department (shaded in black on Fig. 3). These limits were decided by projects partners and are common to all studies in Aube in the BOAT project. Vineyards are almost absent in this area. Agricultural land of the study zone consists of 177068ha covered mostly by soft winter wheat (29.7%), spring barley (18.4%), sugar beet (13.2%), rapeseed (10.7%) and winter barley (6.8%) (Fig. 4).

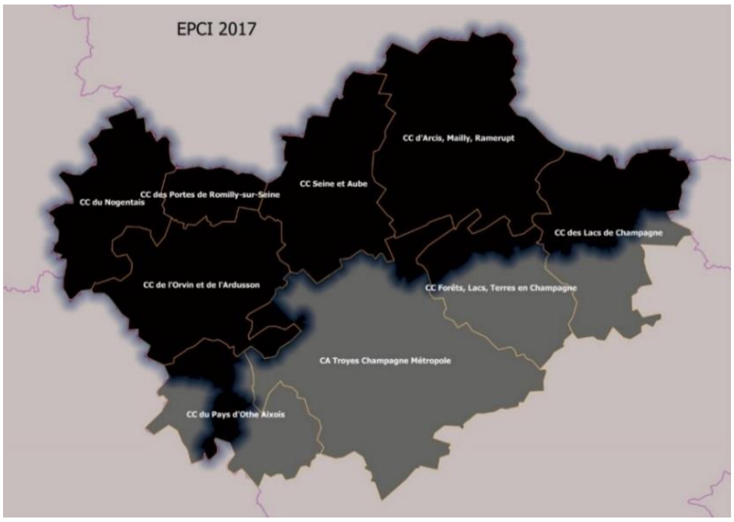

Figure 3 - Spatial limits of the territory under study: North Aube (in dark)
(IRSTEA, internal communication)

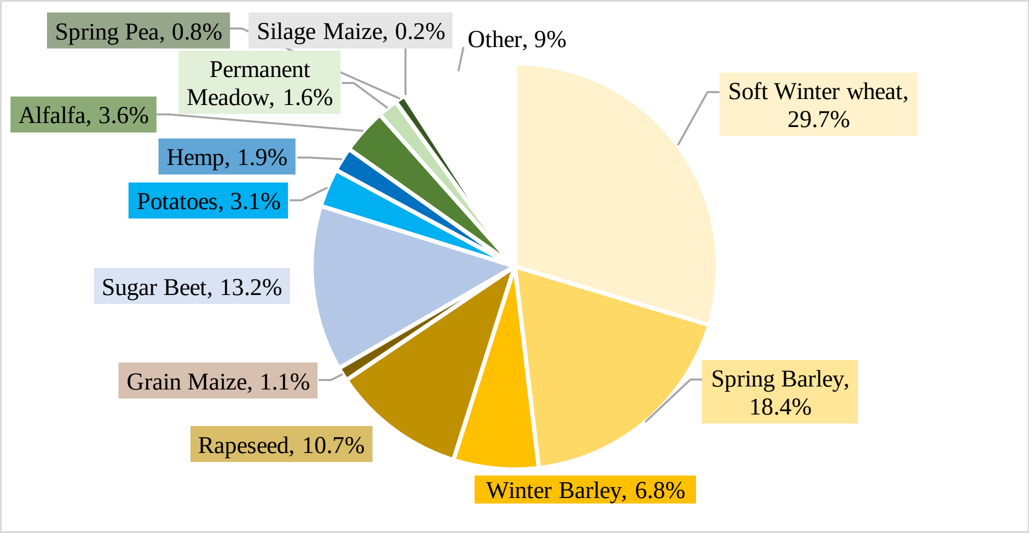

Figure 4 - Land cover in North Aube (Registre parcellaire Graphique (*plot record*), 2017. processed by IRSTEA LESSEM)

2.2 Goal, Scope and System boundaries definition

The goal of this study is to perform attributional LCA at territory scale to assess environmental impacts of North Aube's agricultural activities using several criteria. This study was intended for actors in the BOAT project and in the agricultural territory. Results of this study may be used in the future to develop a vision of a local and sustainable agricultural territory. Therefore, this study also demonstrate how LCA could facilitate decision making at the territory scale through impact assessment of scenarios.

The LCA's scope of this study (Fig. 5), encompassed product life cycles from raw material extraction to storage (for grain crops) or to the first stage of processing, whether it occurs within the territory's or not. Indirect impacts related to input production were included. The study included the main crops produced (i.e those that cover more than 1% of the region's agricultural land). Fig.5 presents all types of production selected to carry out the territorial LCA. Crops were gathered in categories: grain crops (cereals, grain maize and rapeseed), cash crops (sugar beet, potatoes, hemp) and fodders (alfalfa, meadows, spring peas and silage maize). A total of 90% of the agricultural land cover was included (Fig. 4), as well as all animal production activities. The one processing type that corresponds to the main destination of a given agricultural product was associated with that product. When some of the product could be used in the territory, in biogas plant or as livestock feedstock for instance, the product could have multiple destinations. For grain crops, storage in silos was chosen as the LCA gate, since existing data didn't highlight a main processing type (milling or raw export for instance). Fig.5 presents the processing chosen for each product.

In addition, some marginal types of production (e.g silage maize, spring peas, grazing sheep) were included in the study since they were necessary to construct scenarios. Finally, because biogas production lay at the core of one of the scenarios, biogas extraction from agricultural products or residues was also included in the study when biogas is sold to the national gas network. Biogas production was not included when biogas was used to cogenerate heat and electricity on the farm, even it happens in the territory, since this type of process was not used to develop scenario.

2.3 Impact categories and functional unit

The following impact categories were selected: water resource depletion (WRD), depletion of abiotic resources (fossil fuels) (AD), land competition (LC), global warming potential (GWP), acidification potential (AP) and eutrophication potential (EU) (Table 1). They correspond to the most frequently used impact categories for agricultural LCA. (*eg* Charles et al. 2006, Williams et al. 2006, Basset-Mens et al. 2009)

Table 1 - impact categories selected and their characterization methods

Impact Categories	Unit	Characterization method
Water resource depletion	m3 water eq	ILCD 2011
Abiotic depletion (fossils fuels)	MJ	CML-IA baseline
Land competition	m^2year	CML non baseline
Global warming potential (horizon 100 years	kg CO_2 eq	IPCC
Acidification potential	kg SO_2 eq	CML-IA baseline
Eutrophication potential	kg PO_4^{--} eq	CML-IA baseline

Finally, environmental impacts were expressed both as impact per ha and per kg to better reflect the agricultural territory's multifunctionality (i.e production and land management, respectively, following the example of Baumgartner et al. (2011) and recommendations of Salou et al (2017)).

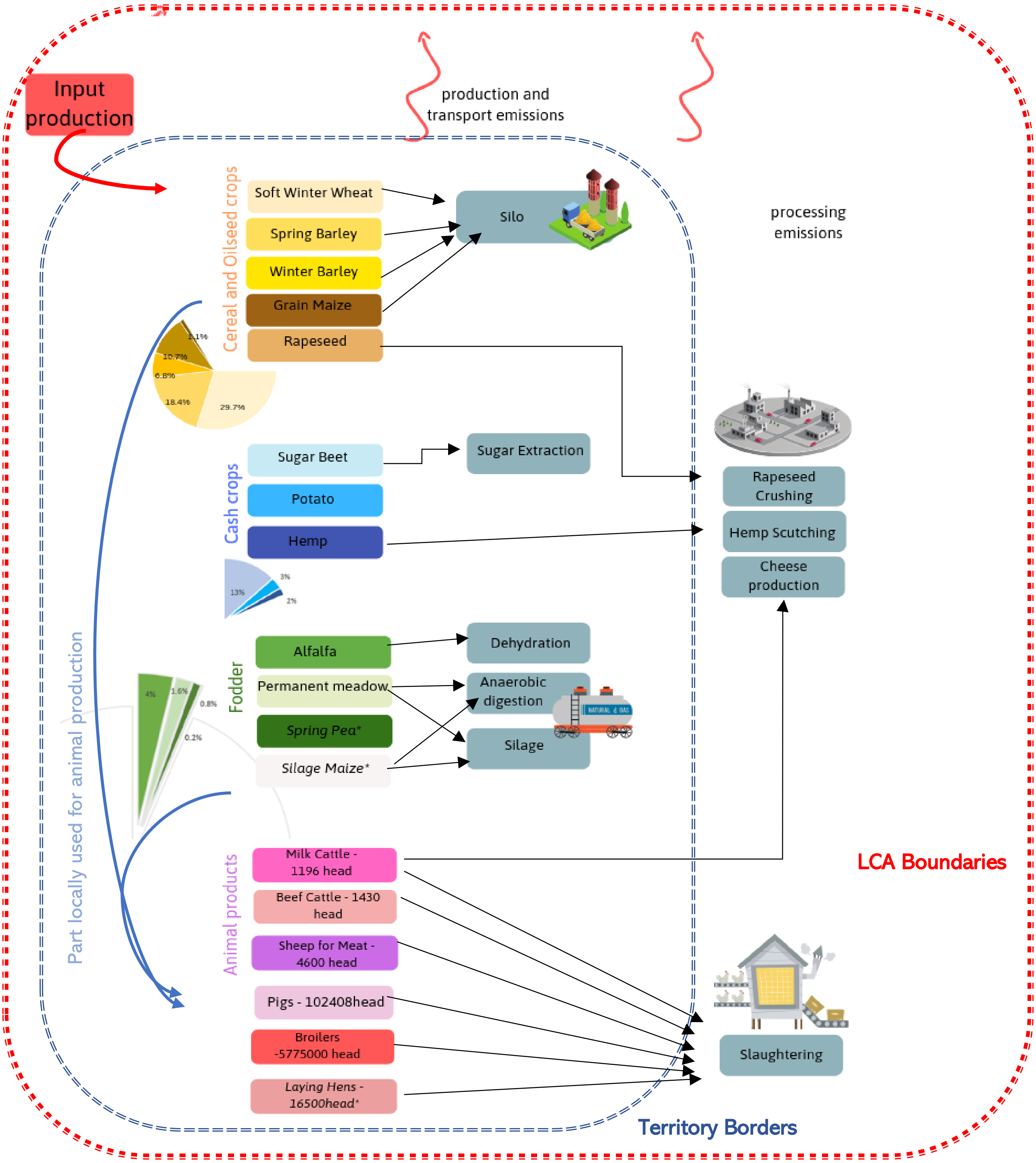

Figure 5 - Scope and system boundaries of the study. LCA boundaries are not the territory's borders, since background process (input factories) are included, as well as processes that occur outside the borders of North Aube. An asterisk associated with silage maize and peas means that the product is not representative of the land cover (<1%*)* but was included because it was needed to develop scenarios. Processing was chosen as follow : all grain is stored temporarily, rapeseed is crushed to make oil and meal, sugar beet is used for sugar extraction, hemp is scutched to extract fiber, alfalfa is dehydrated, meadow and silage maize are ensiled, all animals are slaughtered, and milk is transformed into cheese. Potatoes, spring peas and eggs are not transformed.

2.4 Preliminary investigation and fieldwork planning

Before field work, a literature review, scenario draft and survey construction were performed (Fig.2).

2.4.1 Identification of production types to explore and data gaps

The agricultural territory had been described using available public databases (Registre parcellaire Graphique 2017- plot record and Recensement General Agricole 2010 (RGA) – agricultural census). These databases provide indicators such as the area occupied by each crop and the number of farms. They were processed by the IRSTEA-LESSEM team to extract data related to our study zone's boundaries. This overview of the territory provided a sound basis for identifying types of production to be investigated. It also helped in identifying data gaps. For instance, the most recent public animal production data were collected in 2010. Since data shows that livestock production is rapidly decreasing in the study zone, it was important to work with more recent data on livestock holdings. Statistics on practices are also lacking in databases. It was assumed that no-till farming was an important practice in our study zone, but no data are available at our scale of study. Thus, this assumption had to be checked during field work. The data gaps were filled through interviews with relevant actors when possible (e.g. employees the Chamber of Agriculture). Sources of each relevant data point are summarized in Appendix 2, 3 and 4.

2.4.2 Scenario draft

Prior to fieldwork, a few explorative scenarios were drafted. Identification of these scenarios has been done by analyzing notes from preliminary interviews with important actors of each sector. In total, five drafts were presented to local actors to gather their perspectives, in order to select and model those which seemed the most credible to them and/or representative of a desired future. Although these scenarios were not built in a participatory approach with local actors, as strongly recommended by Reed et al. (2013), they were built based on the knowledge available on the local context and discussions with local actors. They can be defined as "cornerstone" scenarios, which are used to assess a potential direction of future development or to provide at least some information about an alternative path, and usually serve as a basis for further research (Personen et al. 2000). Participatory prospective is the next step of the BOAT project.

2.4.3 Surveys construction

Surveys were constructed in two parts. The first part contained specific closed-ended questions, focused on a particular product and used to collect all data necessary to construct an LCI (see full questionnaire in Appendix 5). Precise data were collected on soil management practices, fertilizer and pesticides use, machinery, irrigation, energy, infrastructure and for animal production, detailed feed and forage intake. Since some of the processing units are located in the study zone, a second type of questionnaire was developed for actors involved in product processing. It also aimed to collect information on resources used and emissions during processing, but in much less detail.

The second part of the questionnaire was containing both closed and open-ended questions. This part aimed to describe the farm (e.g. land size, crop rotation, number of employees…) and to collect data on biomass flows in the territory (e.g. exchange of matter, retailer, client). In addition, scenarios were subjected to the stakeholder's judgement in this part of the questionnaire.

2.5 Data Collection: Fieldwork

In total, 18 face-to-face interviews were conducted with farmers in five weeks and specific data on 37 types of agricultural productions and practices were collected. Among these types of production, the crops that covered the most area (winter wheat, spring and winter barley, rapeseed, sugar beet) had replicates in order to obtain a more representative sample. Time constraints prevented meeting all processing actors. Data were collected locally through interviews at two types of biogas plant and silos and. Local data on a sugar factory and dehydration plant were found on the factories' websites.

2.6 Data Analysis

This section describes LCI construction and LCIA of the current situation in North Aube (Fig 2.). Details are provided on the method used to proceed from farm gate LCIs to territorial LCA.

2.6.1 LCI construction

LCI were built on the MEANS InOut platform (developed by the MEANS team from the SAS research unit, INRA/Agrocampus Ouest, Rennes, as a common tool for multicriteria analysis). This platform makes it possible to list all inputs and operations necessary to produce an agricultural product. The platform calculates emissions at each step of the production process using calculation models that follow the AGRIBALYSE methodology (Koch and Salou 2016) and allows users to export the LCI as a file describing all inputs and emissions to another program used to calculate associated impacts. Foreground processes (on-field emissions and/or direct resource use (e.g. water and land)) are differentiated from background processes ("upstream" off-farm process (e.g. production of inputs)).

When a single system provides two or more co-products (e.g grain/straw from grain cropping, milk/meat from dairy cattle), impacts were divided between the coproducts using economic allocation. Economic allocation associate an allocation factor with each coproduct, calculated as the proportion of the revenue of the product in the total revenue of the system: $Pi = \frac{ni.xi}{\sum_i ni.xi}$ (Ardente et al. 2012). Examples of economic allocations are available in Fig.7. Allocation rules for each coproduct are given in Appendix 4.

2.6.2 Impact Assessment: from primary production to the territory's impact

LCIs were imported into SimaPro to calculate associated impacts. SimaPro is a commercial LCA software that includes a database of LCIs (ecoinvent V3.4), and also provides characterization models used to calculate each impact. (Frischknecht et al. 2007). SimaPro calculates indirect emissions and resource use for each input listed in the LCI. Then, by combining indirect and direct emissions and resource use, it calculates total impact per functional unit.

2.6.2.1 Primary agricultural production Impact

First, impacts were calculated for each unprocessed type of production. When several LCIs were available for a same type of production, a new weighted average LCI was constructed in SimaPro. Then, impacts were extrapolated to total production by multiplying impact.kg^{-1} by the total amount produced for each category. Thus, the total impact of the primary agricultural production in the territory was obtained (Fig.6.).

2.6.2.2 Final product impacts

Final product impact corresponds to production and first processing/storage impact. To assess the impact of the processing stage, pre-existing LCIs of the chosen processing/storage unit were used, from the ecoinvent database.

Transport from farms to processing units was included. To estimate the mean distance that each product was transported, distances from center of each territory's municipality to the processing unit were calculated and averaged using online mapping services. For storage, it was assumed that grain is stored in the closest silo. Thus, transport distance was estimated by halving the mean distance between two silos. A temporary storage of three months was estimated.

2.6.2.3 Agricultural territory impact: avoiding double counting

Some products studied are used locally to produce other agricultural goods. To avoid counting the impacts of these products twice, mass allocation was used to account for the part that was used locally. (Fig.7) It is considered that all products used as feedstock came from the territory and that interview data about livestock and biogas feedstock were valid for all farms. The types of productions concerned were grain, straw, intermediate crops, sugar beet pulp, alfalfa, meadows, silage maize and spring pea. For instance, it was assumed that 18 953 t of cereal straw is used for animal production. This represents 3% of the total amount of straw produced in North Aube; thus, 3% of straw's impact was allocated to livestock. The remaining impact was allocated to grain, following standard LCA methodology when straw is not sold.

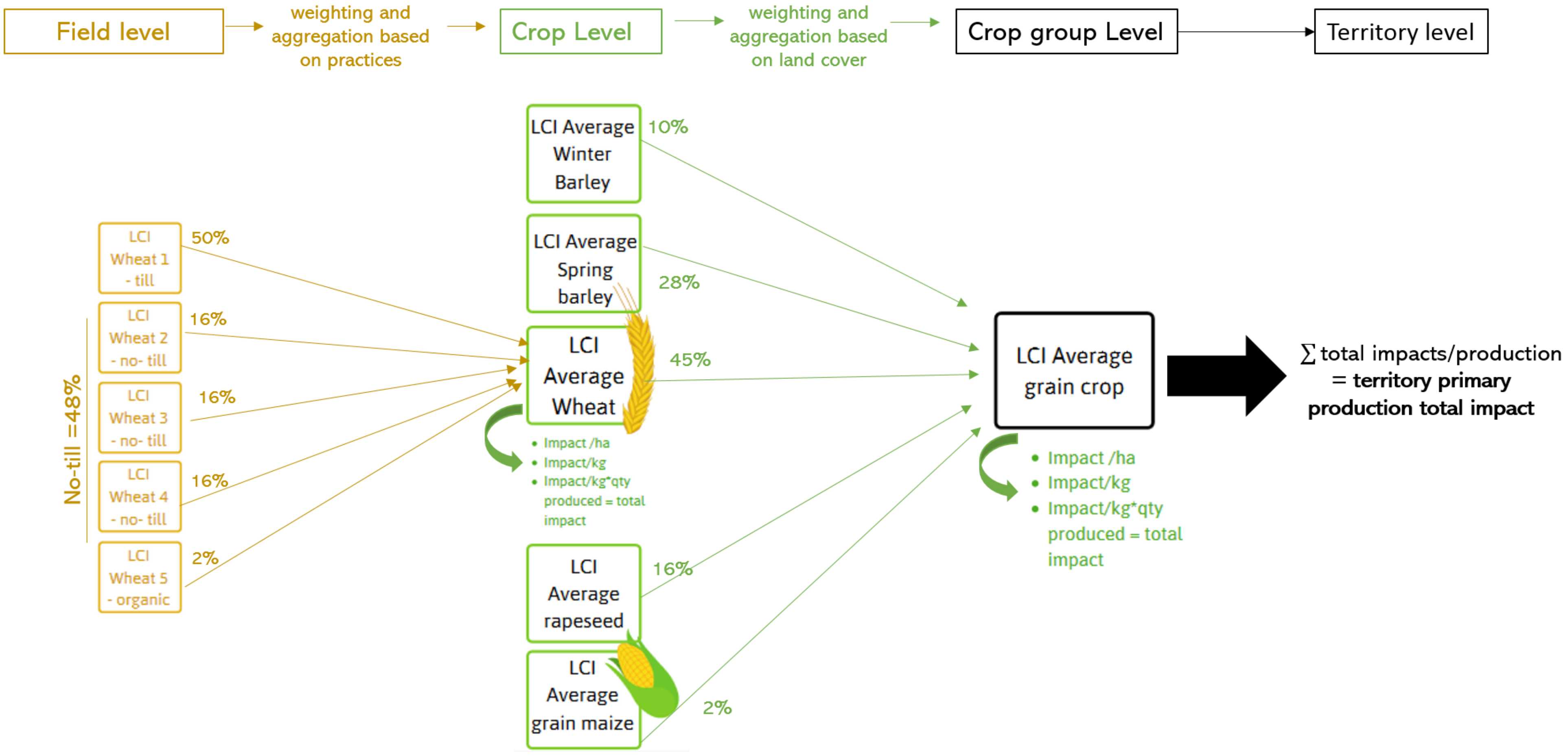

Figure 6 How to proceed from the impact of individual fields to the territory's impact? Method diagram, with the example of winter wheat. LCI : life cycle assessment

To proceed from field level to crop level, when several LCIs are available they were weighted based on representativity of the practices according to expert's opinion. For instance 5 wheat LCIs were created , and according to experts at the Chamber of Agriculture ca. 48% of the farmers practice no till on grain fields. So assuming that half of the farmers means half of the area , no-till LCIs were integrated in the averaged LCI in order to represent 48% in total.

Several LCI were gathered for grain crops, sugar beet and ruminant systems. Data for weighting were available for grain crops (proportion of farmers practicing reduced tillage, number of organic farms) and sheep husbandry systems (outdoor/indoor). For sugar beet, no distinguishing practice was identified, so they were all averaged without weighting.

To proceed from crop level to category level weighting was performed as a function of land cover, using data from the French agricultural census.

At each level, multiplication of impact/kg by the total kg produced gave the total impact in the territory. To obtain the total territory's impact, total impact of each group level was summed

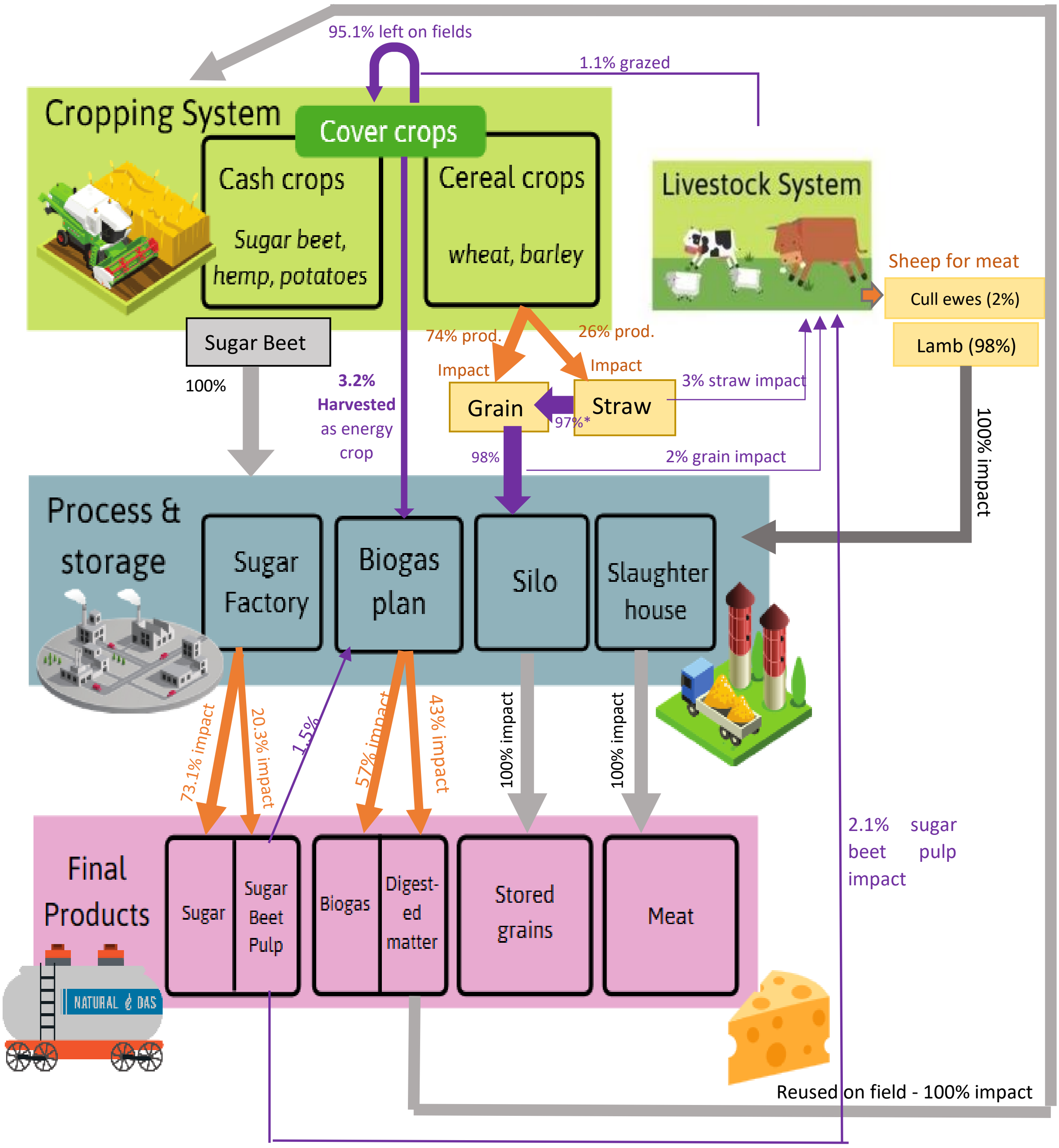

Figure 7 - Representation of the allocations performed in for some of the territory's production types.

Prod.: production - Orange arrows represent economic allocations, which were performed when a single system produces two or more co-products. Purple arrows represent mass allocations, which were performed to avoid double counting when a product is used in another agricultural system.

2.6.3 Uncertainty Analysis

Assessment of uncertainty in LCA is strongly recommended (Williams et al. 2009, Chen and Corson. 2014). SimaPro includes a tool to perform uncertainty analysis. Starting from qualitative assessment in a pedigree matrix with five data quality indicators, each having a score from 1-5 (Weidema and Wesnaes 1996) (Appendix 6), uncertainty factors are calculated for each inventory item in MEANS InOut during LCI construction. It is assumed that uncertainty follows a lognormal probability distribution (Ciroth et al. 2013) Thus, uncertainty factors are aggregated into a standard deviation. In this study, surveys data as well as process and transport data were scored, allowing uncertainties to be calculated for each inventory item.

Using Monte-Carlo simulation (in SimaPro) to run 5000 iterations of input variables taken randomly from their distribution, the range of variation of the results was assessed for each impact category, with a confidence interval of 95%.

2.7 Scenario development

After obtaining actors' feedback during fieldwork, two scenarios were selected and deepened. These scenarios are explorative, meaning they aim to answer the question *What can happen*? (Börjeson et al. 2006). Among them, one focuses on strong future development of biogas production and the other one on the potential reintroduction of sheep production in the territory. The temporal horizon is 10 years.

In an initial approach, the extent of developing of these types of production was fixed. Then, biogas and sheep feedstock were estimated and quantified. Impacts of this newly used biomass were allocated to their new destinations using mass allocation. It was assumed that all the biomass used in scenarios is local; therefore, weaned lamb feeding practices were modified so that all their feed could be produced in the territory. In addition, when there was not enough production of a commodity (e.g. silage maize, meadow) in the territory to feed biogas plants or sheep, land use change was assumed, so some rapeseed cultivation was replaced by the new crops. Rapeseed was chosen because local actors stated that its cultivation will decrease in the next few years due to pest management issues, regular crop failure and poor economic use.

The fact that new organic matter (manure and digested matter) is available locally was included. The amount of organic matter available was quantified for both scenarios and was used to fertilize local fields.

Intermediate crop impacts are usually allocated to the following main crop. In the scenarios, however, intermediate crops could be used either for biogas production or grazed. Separate LCIs were constructed from interview data to calculate impacts of intermediate crops separately. When intermediate crops were used, their impacts were allocated to sheep or biogas and subtracted from the main crop impact to avoid double counting. Benefits of intermediate crops such as nitrate capture were still included, however, when calculating impact of the main crop.

Scenario impacts were calculated using the same method that was used to assess current impacts. In addition, two other indicators were calculated. The first was a nutrition performance index describing how many people can be fed by the territory's production of energy, total protein and animal protein. The tool used to calculate performance was Perfalim, developed by Cereopa (Lapierre and Lapierre 2013). The second was an estimate of the self-sufficiency of the territory's agricultural sector in energy. Another thesis study in the scope of the BOAT project demonstrated that the current energy need of North Aube agricultural sector is 0.75 PJ (M. Khenissi, intern in charge of energy flows assessment in the BOAT project, personal communication 2019). To estimate self-sufficiency, the ratio of energy produced by biogas plants (kWh converted to MJ) to this energy need was calculated.

3 Results

This section presents impacts of primary (unprocessed) products in North Aube, those of final products (i.e. the territory's impact), and scenarios and their results.

3.1 Impact of Primary production

For animal productions, impacts per ha are expressed according to hectare on and off farm, which means that agricultural land necessary to grow crops used as animal feed is added to buildings and forage surface.

3.1.1 Contribution to total impact

Grain crops cover more than 60% of agricultural land in North Aube (Fig.4). For all impact categories except water resource depletion, their cultivation contributes 60-70% of the total impact generated by production in the territory. Cash-crop cultivation (ca 18% of agricultural land) represents 12 -16% of land use, global warming, acidification and eutrophication potentials (Fig. 8.c, 8.d, 8.e, 8.f). Its contribution to abiotic depletion is somewhat higher (23%) (Fig.8.b). Lastly, cash-crop cultivation was by far the largest water user (96% of total territory impact, Fig. 8.a). Fodder crops usually did not contribute much to North Aube's production impact. They cover about 6% of the land surface.

Production of beef, milk and sheep usually contributed 1% or less to total impact (except that beef production represented 2% of global warming potential– Fig.8.d). Pig and broilers production contributed respectively from 3 to 9% of land competition, global warming, acidification and eutrophication potentials.

Figure 8 - Impact of primary (at farm gate) agricultural production in North Aube, per ha, per kg and considering contribution of the category to the total territory's impact (represented by circle size).

Systems contributing to less than 1% of total impact are not represented – Impacts are presented per kg (x-axis) and per ha (y-axis) for each impact category. Each circle represents a product group, its size varies according to the contribution of the production to the total impact of the territory

8.a Water Resource depletion (m3)

8.b Abiotic depletion (MJ)

8.c Land competition (m2.year)

8.d. Global Warming Potential (kg CO2 eq)

8.e. Acidification Potential (kg SO2 eq)

8.f. Eutrophication Potential (kg PO4--- eq)

3.1.2 Impacts per functional unit

Patterns differed by functional unit (kg and ha). Appendix 2 and 3 provide with all detailed impacts for each production.

For abiotic depletion (Fig 8.b), milk production had the most impact per ha, followed by cash-crop cultivation and pig production. Grain-crop and broiler production consumed 17 000 and 18 000 MJ.ha^{-1}, respectively. Fodder crop, beef and sheep production had the lowest abiotic depletion impact per ha. This order is changed for impact per kg. Beef and broiler production had by far the most impact with 25 and 20 MJ.kg live weight^{-1}. Cash-crop cultivation, which was one of the main fossil fuel consumers per ha had the lowest abiotic depletion impact per kg (0.4 MJ.kg^{-1}). Milk's impact also ranked differently; it had the lowest impact per kg among animal products.

For global warming potential, grain-crop and cash-crop cultivation emitted 3700 and 3000 kg CO2eq.ha^{-1} (fig 8.c), while fodder production emitted 900 kgCO2eq.ha^{-1}. Except for broilers, livestock global warming potential was usually higher than those of crops. Again, cash crops had the lowest impact per kg (0.062 kgCO2eq.kg^{-1} product) vs 0.6kgCO2eq for grain crops although they show similar global warming potential per ha.

Animal production systems had the highest acidification and eutrophication potentials per ha and per kg. Per ha, pig production had the highest acidification and eutrophication potentials, followed by milk. Again, when impact per kg were considered, the trend reversed, with beef production having the highest impacts, followed by sheep production. Concerning cropping systems, grain crops had the highest acidification and eutrophication potential, both per ha and per kg whereas fodders had the lowest impacts per ha and cash crops had the lowest per kg.

3.1.3 Identification of impacts origins

The following section considers the four cropping systems (soft winter wheat, sugar beet, rapeseed and spring barley) and two livestock systems (pig and broiler production) that contributed the most to total impacts of North Aube to identify which stages of production within these systems contributed the most to selected impacts (Fig. 9 and 10.). For cropping systems, direct on farm emissions/resource use contributed most to land competition (>90%), global warming potential (>40%), acidification potential (>50%) and eutrophication potential (>80%), followed by fertilizer production. For the three grain crops, fertilizer production contributed most to water resource depletion and abiotic depletion (>60% for both), followed by machinery and seed production. For sugar beet, irrigation contributed almost all water use, while machinery production contributed most to abiotic depletion.

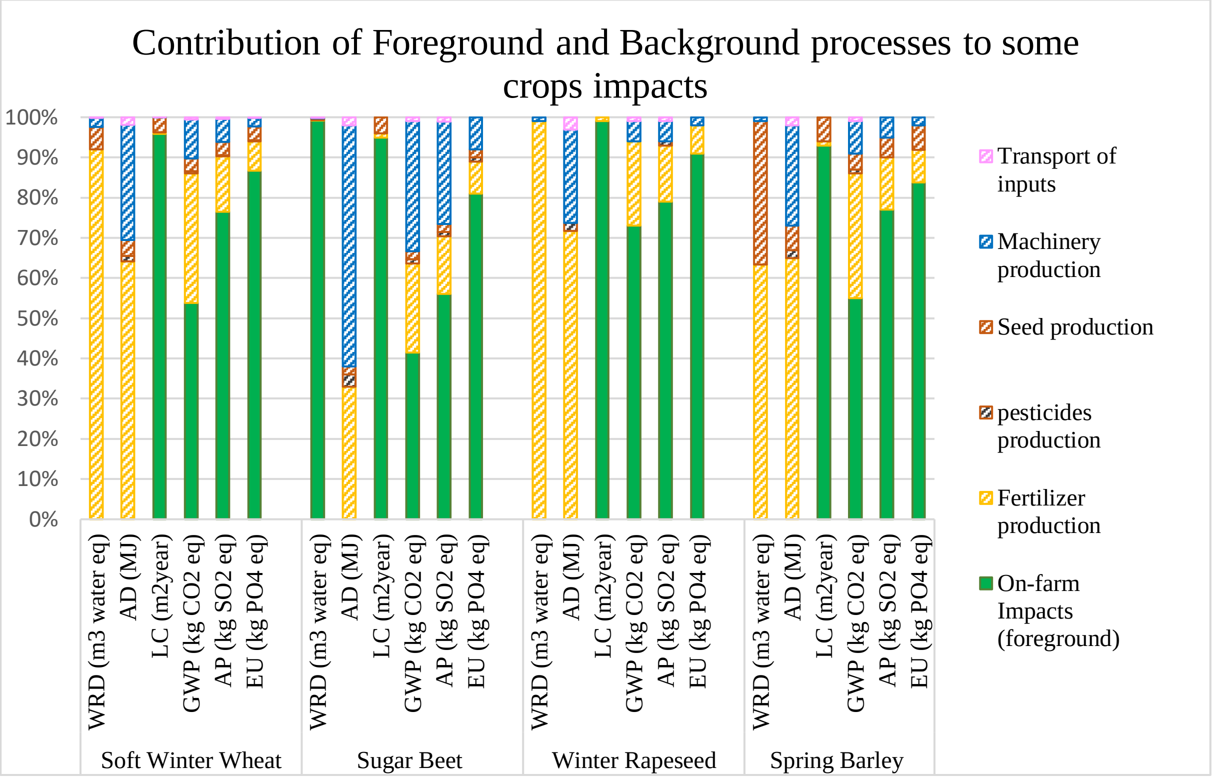

Figure 9 - Contribution of foreground and background processes to some selected crop systems impacts. WRD: water resource depletion – AD: abiotic (fossil fuels) depletion – LC: land competition – GWP: Global warming potential – AP: acidification potential – EU: eutrophication potential. Striped boxes represent background impacts, plain boxes represent foreground (direct) emissions.

For livestock systems, animal feed production contributed at least 35% of all emissions (CO2eq, SO2eq, PO4---eq) and 60% of water resource depletion, land use and abiotic depletion. For pig production, direct emissions from animals contributed 30-60% depending on the impact category. Direct impact was less visible for broiler production (<10%), but the impact of producing the breeders had to be added as a background impact because only the fattening stage takes place on the territory. This indirect impact of reproductive stages contributed 5-17% of all impacts.

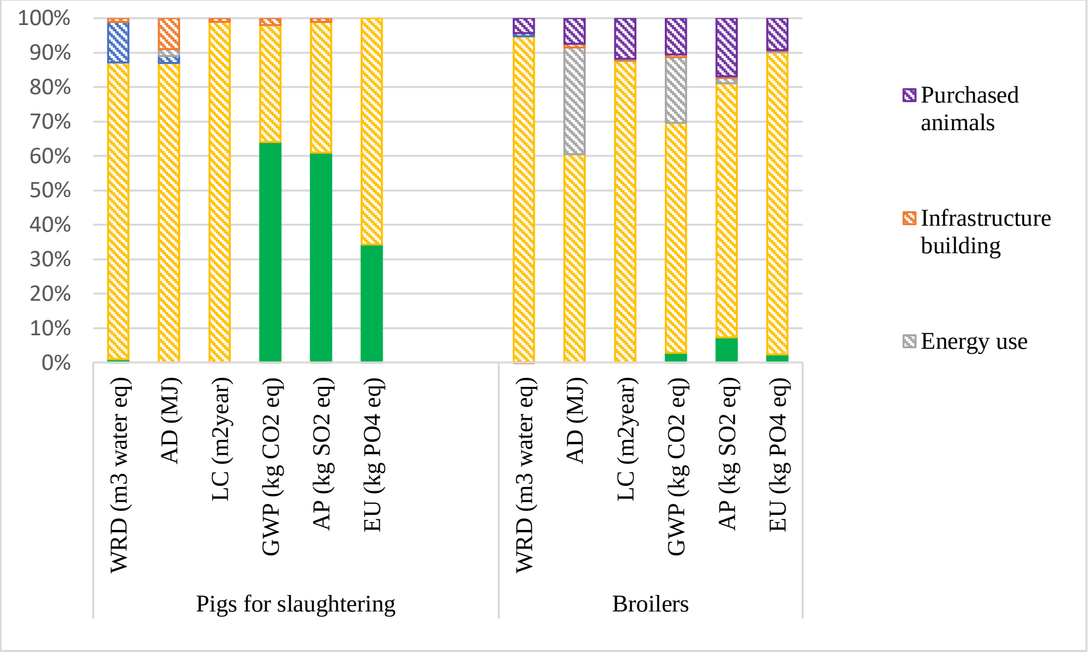

Figure 10- Contribution of foreground and background processes to some selected animal systems impacts. WRD: water resource depletion – AD: abiotic (fossil fuels) depletion – LC: land competition – GWP: Global warming potential – AP: acidification potential – EU: eutrophication potential. Striped boxes represent background impacts, plain boxes represent foreground (direct) emissions.

3.2 Territorial impact assessment

Once processing impacts and local consumption of primary agricultural resources were included, total impacts of the North Aube agricultural territory were estimated, from input production to the first processing gate (Table 2). For each impact category, the relative contribution of each product to the territory's total impact was calculated (Fig. 11). Details are available in Appendix 7.

Categories	Units	Total Impact	ha^{-1} agricultural land in the territory	ha^{-1} total agricultural land used (on and off farm) *	kg^{-1} of processed product
WRD	m3 water eq	49 846 543	313	288	0.023
AD	MJ	5 240 630 313	33100	19100	2.47
GWP	kg CO2 eq	1 491 757 933	5270	3700	0.39
AP	kg SO2 eq	7 662 404	48	40	0.003
EU	kg PO4--- eq	4 633 563	29	26	0.002

Table 2- North Aube Impact after inclusion of processing and local reinjection –

off farm ha = ha needed to produce poultry feed + ha needed to product processed feed for other livestock (rapeseed meal, sunflower meal, soybean meal, corn gluten feed and sugar canes molasses). These ha are understood as being outside the territory. WRD: water resource depletion – AD: abiotic (fossil fuels) depletion – LC: land competition – GWP: Global warming potential – AP: acidification potential – EU: eutrophication potential

Stored grain (wheat, barley and grain maize) contributed most to abiotic depletion, land competition, global warming potential, acidification potential and eutrophication potential (31-57% of the total impact). Storage itself accounted for less than 2% of total impact. Rapeseed co-products (oil and meal) contributed 7-13% of total impact for all categories (except water depletion). Rapeseed grain crushing contributed less than 2% for all category.

Sugar beet production (sugar, sugar beet pulp and molasses) contributed 4-9% of the territory’s impacts, except for water resource depletion. It contributed to almost all (83%) water use in the territory. Sugar extraction was 13% of abiotic depletion, 5% of global warming potential and 2% of acidification potential.

Alfalfa cultivation accounted for less than 2% of most impact categories. It contributed slightly to eutrophication potential (2%) and land use (4%). Its dehydration, however, contributed considerably to abiotic resources depletion (14%) and global warming potential (9%).

Among all types of animal products, pork and chicken meat were the only ones that contributed more than 2% of the territory’s impact. Together pigs and broilers production contribute to 10% of eutrophication potential, 12% of acidification potential and 8% of global warming potential. Pig slaughtering contributed 9% of abiotic depletion and global warming potential. Finally, biogas production contributed 2% of water resource depletion, land use and eutrophication in North Aube.

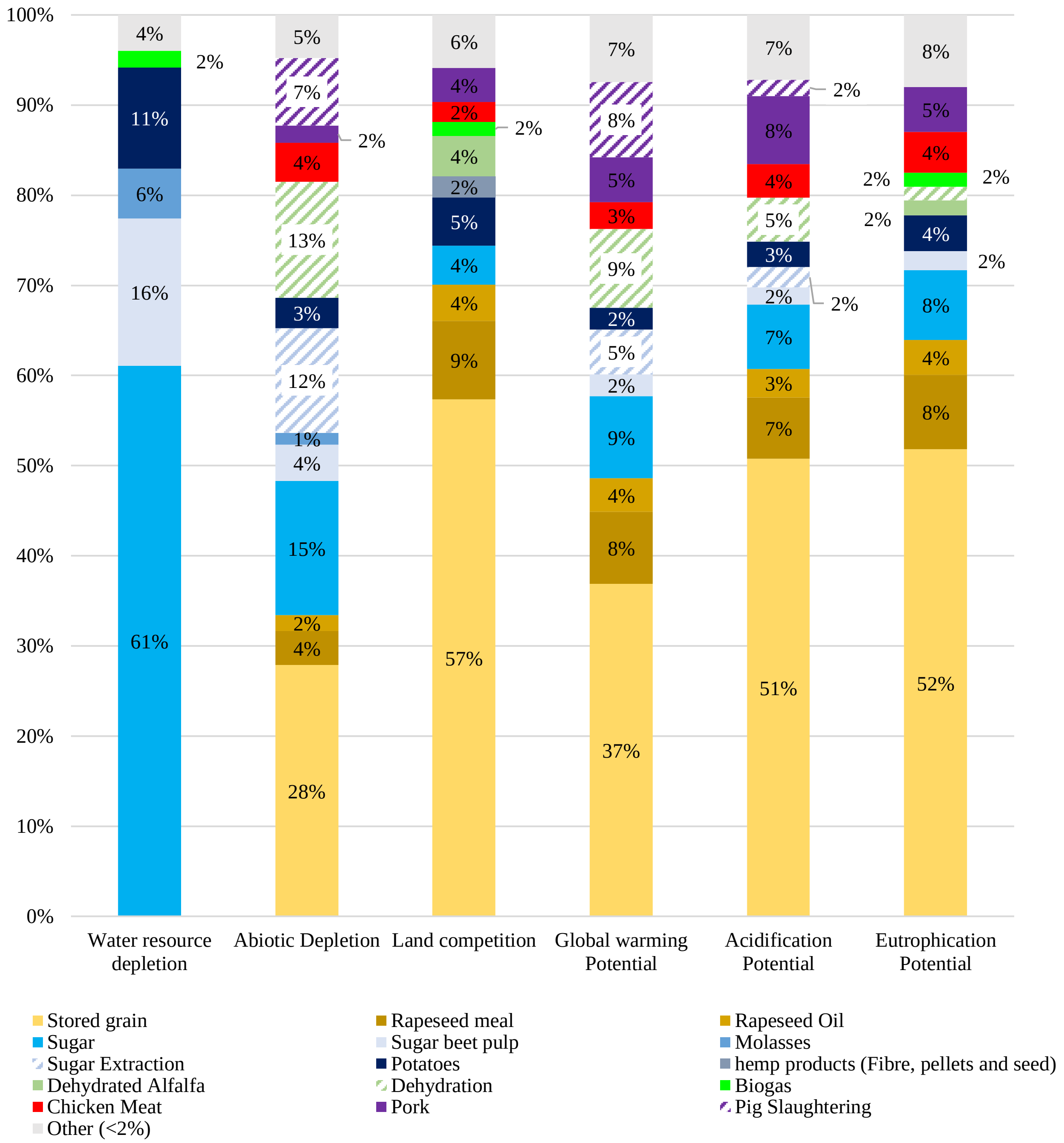

Figure 11 - Contribution of each agricultural sector to total territorial impact.
Contribution is expressed comparatively to the total impacts (%). Solid bars represent production activitites. Hashed bar represent processing activities. Systems that contribute to less than 2% are excluded

3.3 Sensitivity analysis

Monte Carlo analysis showed that estimated impacts are likely to vary by ±10% for abiotic depletion and acidification potential and ±15% for land use and water resource depletion (fig 12). Global warming potential and eutrophication potential may vary by ±13 and ±11%, respectively.

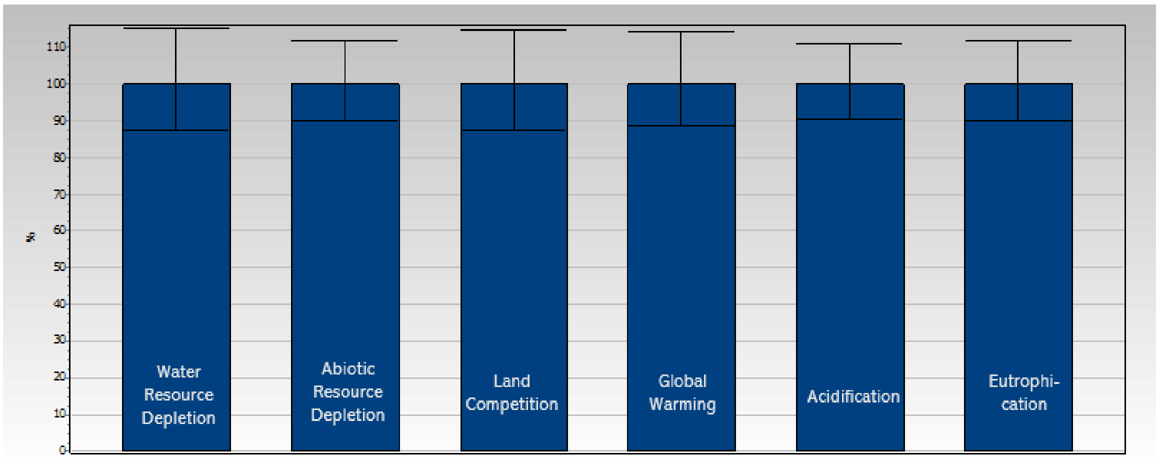

Figure 12 - Monte Carlo Simulation on territorial Impact Assessment (5000 occurrences, confident interval 95%)

3.4 Scenarios

3.4.1 Scenarios Description

A biogas-sector growth scenario was chosen because development of biogas production has already started in the territory. In each interview, actors mentioned that many more plants will be constructed in the future. During fieldwork discussion, the reintroduction of sheep production appeared less conceivable to actors than an increase in biogas production. This may be because most farmers are so specialized in arable farming that the transition to mixed farming seem inconceivable to them. However, it seemed relevant to explore a livestock-oriented scenario given the territory's context, in which semi-extensive livestock grazing is becoming less common. North Aube has a history of sheep farming, and there have been re-launch initiatives in the past, which is why sheep grazing was chosen although development of indoor monogastric production (laying hens, broilers or pigs) seems more likely to occur in the future. In addition, both scenarios are interesting to consider since they may provide some solutions to address issues caused by the lack of locally produced organic matter in North Aube

3.4.1.1 Scenario 1 – Biogas sector growth

North Aube currently has seven biogas plants in operation and two under construction (A. Croenne, methanisation project manager at the Aube chamber of agriculture, personal communication 2019). In this scenario, the extent of development of biogas plants was set by assuming that the development path would be similar to that in Bretagne, another French region where biogas production is already well developed. From 2002-2012, 40 biogas plants were constructed there (AILE 2019). Since 2002 seems to correspond to the current situation in North Aube, it was decided that 40 was a credible number of biogas plants to include in this scenario.

Since the biomass source is mostly plants, then biogas would be produced from plant substrates and food-industry coproducts. The biogas plant feedstock (Fig. 13) was designed mainly by using feedstock data from interviews with farmers already producing biogas in the territory, with two exceptions. First, the percentage of food crops devoted to biogas production was fixed to 15% of the total amount of substrate (7% silage maize, 7% alfalfa), which is the maximum allowed by French law (Ministère de la transition écologique et solidaire 2017). Second, cereal straw and grass silage was added in percentages of 11% and 2% of the total feedstock, respectively, although the farmers interviewed add no straw or grass. Intermediate crops for biogas production were assumed to be sorghum producing 6 t dry matter/ha, following the local biogas plant model. Silage maize cropping area was increased by 664ha to provide sufficient biomass.

The total biomass used by the construction of 40 biogas plants was 453 920 t.year^{-1}. These units produced 55 296 000 m^{3}.year^{-1} of biogas and 453 920 t.year^{-1} of digested matter (digestate). Digestate was assumed to have an NPK ratio of 4-2-4 (t^{-1}), which was the elemental ratio indicated by a surveyed farmer. Economic allocation was performed between biogas and digestate, following Jury et al.'s (2010) hypothesis that digestate could have a positive economic value in the future. In this scenario, digestate was assumed to be spread on biogas-dedicated crops; thus, silage maize fields received 15 t digestate.ha^{-1}, while intermediate crops for biogas production (sorghum) received 12.5 t.ha^{-1}. The remaining digestate was spread on sugar beet (33% of sugar beet area received 50 t digestate.ha^{-1}, which covered the crop's N needs according to COMIFER (2013)).

3.4.1.2 Scenario 2- Resettlement of grazing sheep systems

The North Aube territory currently has three flocks of grazing sheep in the region, for a total of ca. 1100 suckler ewes (F. Desné, livestock production advisor at Aube chamber of agriculture, personal communication 2019). For this scenario, the number of grazing sheep increased ten-fold (i.e. 11 000 ewes). These new flocks operated in the same way as those observed in the study zone: ewes graze intermediate crops and, to a smaller extent, meadow. They are brought back in buildings a couple of weeks before lambing until lambs are weaned. Lambs are fattened indoors. As explained, lamb feeding practices were changed to obtain a scenario in which all feedstock is locally produced, except vitamins. In this scenario, weaned lambs were fed a mix of barley grain, spring pea, grain maize and straw, following the French Livestock Institute (CIIRPO 2008, Institut de l'elevage 2010) formulation. During suckling, ewes were fed with grass and maize silage, alfalfa hay, sugar beet pulp and cereal straw. In total, 11,000 suckler ewes would use 49 793 t of territorial BAO.year^{-1} (Fig. 13), mostly grazed (59% of grazed intermediate crops, 33% of meadows). Straw used as litter was included in the amount of straw used (800 t in total). Meadows and silage maize surface were increased by 1219 and 313ha respectively.

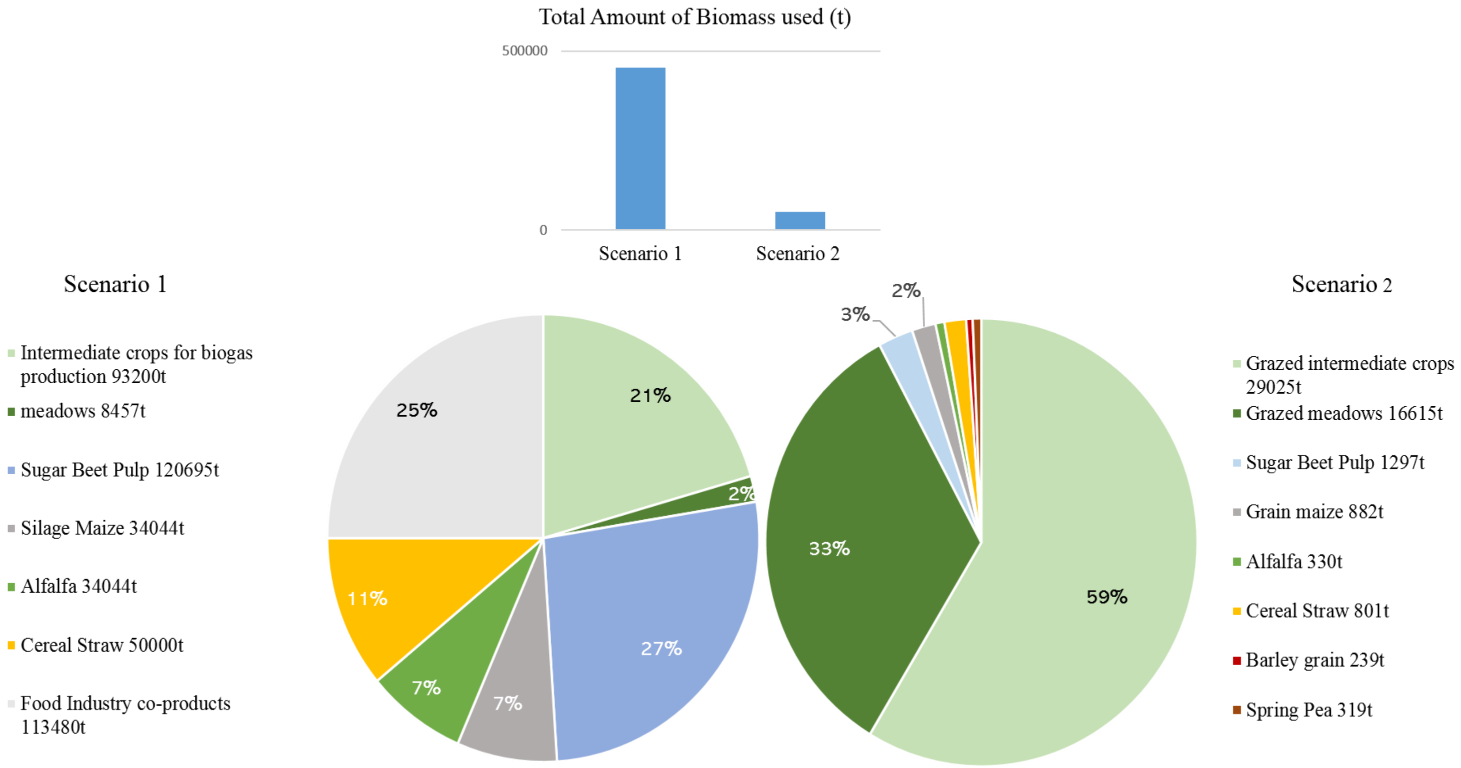

Figure 13 - Presentation of Biogas feedstock on scenario 1 (left) and sheep feedstock + litter on scenario 2 (right). Diagram at the top shows the total amount of biomass coming from the territory mobilized for each scenario per year (453 920 T for scenario 1, 49 793 T for scenario 2). Pie charts show the proportion of the different products for each feedstock

3.4.2 Scenarios Impact Assessment

Table 3 describes consequences of scenario changes in the territory.

Table 3- Comparison of Scenarios impact assessment with the current situation in North Aube. The first six lines show changes related to LCA impacts categories, the following lines show changes in terms of feeding potential and energy autonomy. Green boxes : positive trend, red boxes : negative trend, grey boxes : neutral trend.

	Current State	Scenario 1 - Biogas Production Increase	Scenario 2- Sheep farming Increase
Water resource depletion	100	+3%	=
Abiotic resource depletion	100	-8%	-1%
Land competition	100	+6%	-1%
Global warming potential	100	-3%	-1%
Acidification potential	100	=	-1%
Eutrophication potential	100	+3%	-2%
Feeding potential - Energy (Mcal)	100	=	-1%
Feeding potential – Proteins (kg)	100	=	=
Feeding potential - Animal Proteins (kg)	100	=	+1%
Energy Autonomy of Agricultural Sector in the territory (%)	21	+263%	=

In scenario 1, there was a decrease in abiotic depletion (-8%) and global warming potential (-3%) but an increase in water resource depletion (+3%), land competition (+6%) and eutrophication potential (+3%). The agricultural sector increased its autonomy in energy by 263%, which means that it produced more than twice what it consumed (in MJ). Feeding potential did not change. In scenario 2, almost all impacts decreased by 1% (except eutrophication potential: -2%). Water use and energy autonomy did not change. For feeding potential, the territory produced more animal protein but fewer calories because some grain production was used to feed the newly introduced sheep.

The uncertainty analysis showed that the impacts could vary by 10-15% (Fig 12.). Since the sheep reintroduction scenario generated a 1-2% difference in environmental impacts, conclusions about any changes to the territory cannot be drawn. In the biogas-production scenario, however, changes in impacts lay closer to uncertainty limits; so, although concluding is also prevented in this case, results still provide insights into how the biogas sector may develop. For this reason, and because the reasons for changes in impacts were similar in both cases, description of the results focuses mainly on scenario 1.

Table 4 - Presentation of productions for which there is an impact shift induced in scenario 1 compared to current situation -Changes are expressed in % relatively to the current situation. WRD: water resource depletion AD: abiotic depletion LC: land competition GWP: Global warming potential AP: acidification potential EU: eutrophication potential

Product	Changes compared to current situation		Reason
Biogas	WRD	+218%	Construction of 40 new plants: Biogas plant direct emissions; Feedstock production impacts alloc. to biogas
	AD	+752%	
	LC	+511%	
	GWP	+267%	
	AP	+394%	
	EU	+405%	
Stored grain	All impacts	-2%	Mass Allocation. (2% of straw used as feedstock > 2% impact alloc. to biogas)
Rapeseed products	All impacts	-7%	Surface reduction (1% less area) to produce silage maize Crushing avoided
Sugar beet products	WRD	-1%	-Mass allocation: 27.5% pulps alloc. to biogas; 19% intermediate crops alloc.to biogas -Digested matter used on sugar beet fields: changes in fertilization practices; 80% digestate impacts alloc. to sugar beet
	AD	-2%	
	LC	+97%	
	GWP	+17%	
	AP	=	
	EU	+27%	
Potatoes	WRD	=	Mass allocation: 6% intermediate crops alloc. to biogas
	AD	-3%	
	LC	-47%	
	GWP	-5%	
	AP	-2%	
	EU	-38%	
Grass silage	All impacts	-97%	Mass allocation: 97% production alloc. to biogas
Dehydrated alfalfa	All impacts	-52%	Mass allocation: 50.6% production alloc. to biogas Dehydration avoided

Table 4 presents the changes induced in each sector by the construction of 40 biogas plants in scenario 1 and the reasons for them. The same table for scenario 2 is available in Appendix 8. To a small extent, changes were due to construction of all infrastructure and the resources needed for biogas production. Otherwise, they were due mainly to new allocation of BAO, whose consequences were changes in practices and avoided processing. Usually, a decrease in a product's impact was due to allocation of part of its production to the biogas sector (Table 4). In this case, there was no change in the product's impact, which was simply allocated to another product: biogas. Changes in impact were due to some extent to avoided processing of some products (rapeseed and alfalfa). For instance, alfalfa represented 7% of biogas feedstock

(Fig 13). Since this percentage was not dehydrated, some dehydration impacts were avoided. Second, changes came from modified agricultural practices. Fields fertilized with digestate required fewer mineral fertilizers, which decreased abiotic depletion and global warming potential, but involved PO4--- eq emissions. Thus, the eutrophication potential increase was due mostly to spraying of digestate on sugar beet, silage maize and intermediate crops. Silage maize contributed most to water resource depletion (Fig. 14). The local reference for "energy maize" cultivation is irrigated, and its area was significantly increased to harvest enough biomass, which is why water used increased in scenario 1.

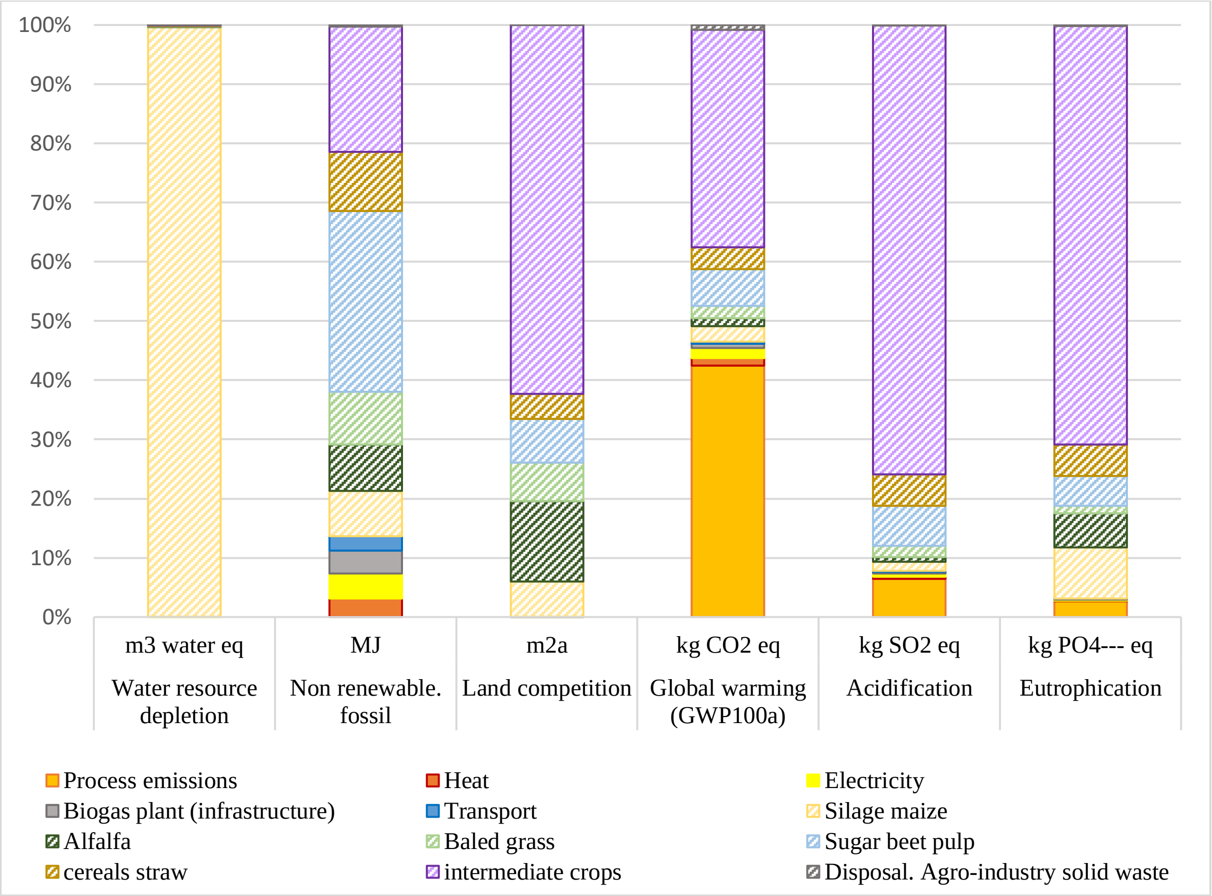

Figure 14 - Processes contribution to Biogas impact in Scenario 1. Hashed bars represent feedstock

For simplification, it was decided that the intermediate crops harvested would be only those cultivated before sugar beets or potatoes. To some extent, impact reduction for sugar beets and potatoes was due to allocating impacts of intermediate crops to biogas. However, much impact of biogas production comes from production of intermediate crops for energy (Fig 14.). In this case, the impact subtracted from sugar beet and potatoes did not equal the impact added to biogas. Because practices differed, different LCIs were constructed. For instance, intermediate crops for biogas are usually fertilized to harvest more biomass. Fig 15 compares impact of regular intermediate crops vs intermediate crops cultivated for energy.

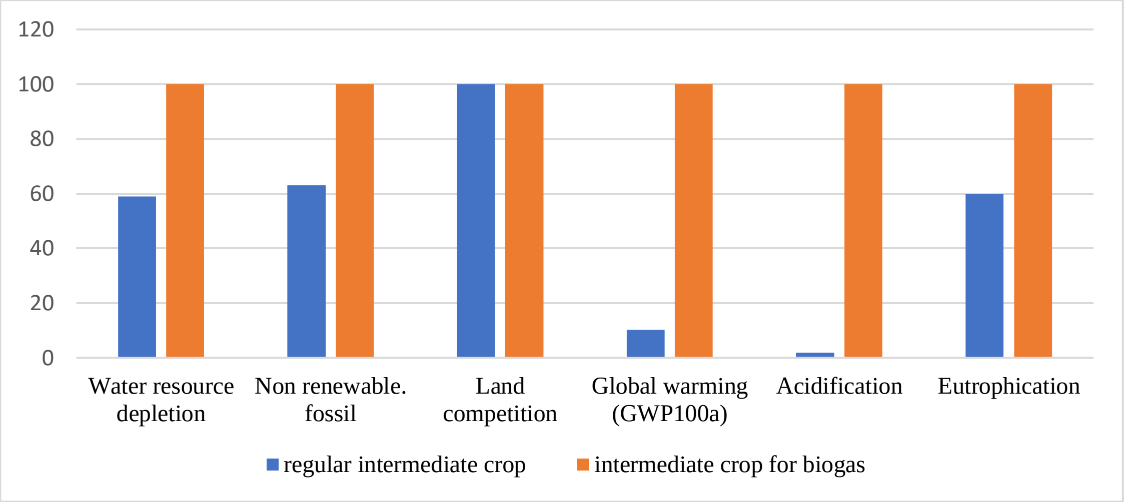

Figure 15 - Comparison of impacts per ha of regular intermediate crops vs intermediate crop harvested for biogas production - Most impacting production for each category is fixed to 100% and the other's impact are expressed relatively

4 Discussion

4.1 Towards a sustainable territory: challenges and opportunities

This part of discussion draws on study results to identify some challenges and impact mitigations opportunities, coming back to the first research question of the study.

4.1.1 Arable cropping in North Aube: a strong dependency to mineral fertilizers

As expected, LCA results showed that grain, oilseed, and cash-crop cultivation contributed the most to all impacts estimated in the territory, since these crops cover almost 85% of the agricultural area. The main contributors to cultivation impacts were fertilizer production and on-farm emissions.

On-farm emissions are related to fertilizer use. For instance, for acidification potential, Brentrup et al. (2004) highlighted the likelihood of high emissions of NH3 due to volatilization during and after application of urea and ammonium-based fertilizers. In addition, wheat cultivation in North Aube, which is by far the main production, seemed to emit more PO4--- .ha-^{1} than references in the literature (see 4.2.1). The main cause of eutrophication in arable systems is nitrate leaching (Beusen et al. 1995), which depends strongly on agricultural management. Eutrophication is not a new issue in North Aube, which is classified as a Nitrate Vulnerable Zone, which means that agricultural pollutants are affecting or may affect surface and ground water quality of the zone (SANDRE 2019).

Thus, fertilization practices and manufacture of mineral fertilizers are key elements to consider to decrease environmental impacts. Research have shown the potential of Low External Input (LEI) farming systems to reduce environmental burdens (Liebman and Davis 1999). Keys components of such systems are crop diversification and organic soil amendment. In North Aube, there are strong barriers hindering the development of LEI systems. First, rotations used to be much more diverse in the territory, but low economic benefits associated to some crops (e.g : pea, sainfoin) induced a decrease in their occurrence. Thus, most cropping systems in the territory depend greatly on mineral fertilizers, especially for N and only a small amount of organic matter is available in the territory. Besides, lack of interaction between animal and crop systems are obstacles to a change in fertilization practices. Organic fertilizers are imported mainly from the Netherlands, even when local fertilizer is available (preliminary interviews 2018).

Nonetheless, farmers have a growing desire to reduce such dependence on commercial inputs (fertilizers, but also pesticides) and renewed interest in local organic fertilizers. Initiatives are currently emerging; for instance, there is a strong development of conservation farming practices in the territory. Besides, some specialized crop farmers are considering adding animal production (mostly laying hens) as a diversification activity, which would also produce local organic matter.

Beyond farm scale, the potential of benefits of crop-livestock integration at the territory level has been investigated and is promising (Martin et al. 2016), although empirical evidences highlighted that crop/livestock interactions between specialized farmers does not always bring environmental benefits (Regan et al. 2015). Instead, evidences showed that this cooperation led to arable and livestock farmers intensifying their systems rather than diversifying them. This could mean reducing their reliance on external inputs (mineral fertilizers; pesticides and concentrate feed) if intensification only happens through a more efficient use of local resources. This type of intensification may reduce products impact per kg, but it may also increase their impact per ha.

4.1.2 Processing activities can significantly contribute to an agricultural territory's impacts

Processing activities usually have much less impact than production activities. Pig slaughtering, sugar extraction and alfalfa dehydration, however, contributed to a large extent to abiotic depletion and global warming potential. Since proxies were used to characterize processing activities, it is difficult to discuss their environmental impacts in detail. Nonetheless, some of the study's findings about processing can be highlighted.

4.1.2.1 Re-locating the animal product sector

Transport was responsible for 4-10% of impacts of pig slaughtering (Fig. 16), since most pigs are slaughtered in Orleans, which is ca. 240 km away from North Aube. In general, animal-product sectors are not found in the territory, unlike crop production. For instance, milk is transformed in Raival's cheese factory, which is ca. 150 km away from North Aube, even though half of the milk produced is under a controlled designation of origin. Developing local processing units for animal products seems like a relevant option to both decrease environmental impacts (although to a small extent since transport does not account for much comparing to production's impact) and develop local value chain. Some actors are taking the lead by working with the local slaughterhouse or practicing direct selling. (194 farms (11% farms) selling part of their production to the local network in 2012 (Agreste 2012)).

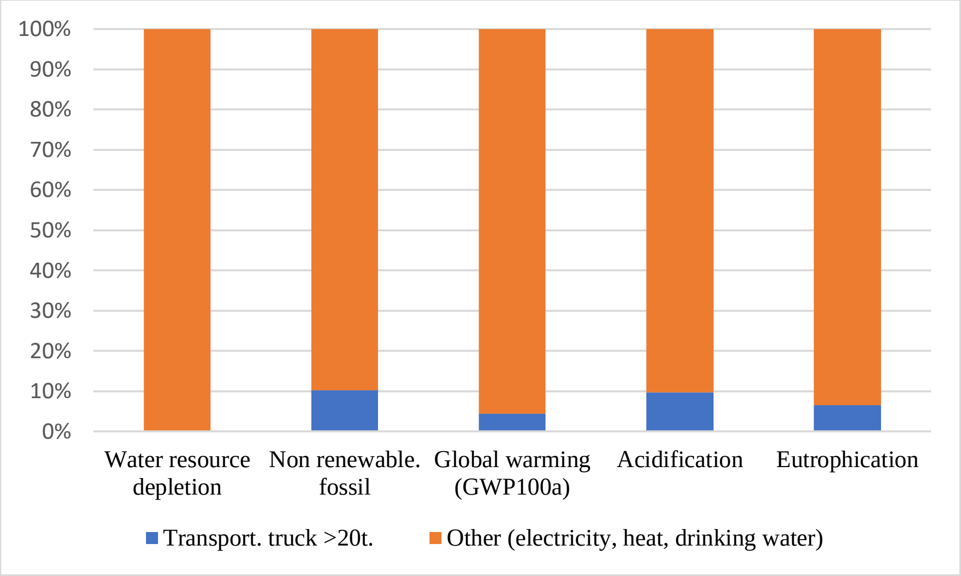

Figure 16 - Contribution of transport to the total impact of pigs slaughtering (production excluded)

4.1.2.2 Developing collaborative strategies

The territory's agricultural sectors operate in a highly specialized and closed way. There is no interaction between them, since optimization is perceived as an intra-sector mechanism. For territorial dynamics, evidence shows that there are effective solutions to reduce environmental impacts at each stage of production. Many of them focus on collaborative strategies and on closing the loop of material flows (Simboli et al. 2015).

There are opportunities for cooperation between sectors. For example, alfalfa dehydration raises the issue of North Aube's environmental impact. Dehydration plants operate mostly by burning coal, which is why they contribute so much to abiotic depletion and global warming potential. Nonetheless, alfalfa cultivation is the production activity with the lowest impact per ha and per kg in the territory. Since alfalfa is the only N-fixing species that is cultivated at a large scale in the territory, it is therefore important to maintain. CAPDEA, the company that owns the dehydration plants and supports the entire sector in North Aube, is conscious of this issue and has added new energy sources such as biomass and natural gas to generate heat. There could be opportunities for looping biomass flow by coupling the dehydration and biogas sectors, the latter of which is likely to grow in the area. When functioning in cogeneration, biogas plants generate heat and electricity. The heat, which is usually lost if there is no animal building to warm, could be used to dehydrate alfalfa.

4.2 Results validity

Reap and al. (2008a, 2008b) identified several causes of weaknesses in LCAs that threaten the validity and reliability of the study. They were summarized by Nitschelm (2016a) (Table.5) and will be discussed in latter part (4.2.1; 4.2.2; 4.4).

Table 5 - Causes of Weaknesses in LCA studies

LCA Stage	Causes of Weakness	In this study
Goal and Scope Definition	Choice of the functional unit	Different functional units (ha, kg) represent the different functions of the territory. Financial function could be added. (impact per euro)
	Selection of system boundaries	From input production to first processing gate. Ideally boundaries should go to recycling/end of life.
	Consideration of alternative scenario	Draft of two scenarios.
Inventory Analysis	Selected allocation methods	Mass and Economic allocation.
	Negligence of minor contributions	All processes in LCIs, from inputs to processing, were included. At territory scale, some minor production types were not included (e.g. lentils)
Impact Assessment	Selection of impact categories	Impact categories cover local, regional and global effects. Biodiversity, soil fertility and toxicity categories could have been added.
	Negligence of spatial variation, temporality and ecosystem dynamics	Neglected
Interpretation	Weighting and normalization	not performed
Each Stage	Data availability and quality	Results often similar with those in literature. Uncertainties causes identified in 4.1.2

4.2.1 Comparison of impacts with those in the literature

The literature provided mostly results for impact per kg. When no reference article was identified, impacts of the included production systems were compared to mean impacts calculated in SimaPro for average French LCI from the AGRIBALYSE database (Koch and Salou 2016)

For grain-crop production, results per kg usually matched literature references well (Charles et al. 2006, Taki et al. 2018, Niero et al. 2015, Bartzas et al. 2015, Peletier et al. 2008, Kim and Dale 2008, Iriarte et al. 2010), especially for global warming potential and abiotic depletion. This study's results for eutrophication potential seem relatively high for barley cultivation. Water resource depletion is not often used as an environmental impact indicator, only spring barley cultivation could be compared, and results match those of Niero et al. (2015) for rain-fed barley cultivation.

Per kg of extractable sugar, this study's results for sugar beet cultivation seem consistent with those of Brentrup et al. (2001). Again, no reference was available for water resource depletion, which raises a serious validity issue, since according to the results of this study, sugar beet was responsible for more than 80% of water use in North Aube farms. Likewise, North Aube sugar beet production used considerably more water (1820 m3 water eq.ha^{-1}) than average French sugar beet cultivation in the AGRIBALYSE database (88 m3 water eq.ha^{-1}).

Although livestock production is sparse in the study zone, its impacts are a non-negligible part of total impact, especially monogastric production. De Vries and de Boer (2010) reviewed many livestock product LCAs, and presented results usually match those reviewed. Pig production in North Aube consumed less fossil fuel.kg^{-1} than that in the literature (Basset-Mens et al. 2009, Blonk et al. 1997): 8 MJ.kg^{-1} meat in this study, 16-18 MJ.kg^{-1} in the literature. This is because the system chosen to represent the study zone combined animal production and biogas production from pig slurry. The heat generated when the biogas is burned is used to heat the pig-production building. This practice is common for pig production in the territory according to the reference farmer (at least 2 out of the 5 pig farms of the study zone), so this difference does not seem to affect validity of the results much for pig production.

Impacts per ha could be compared only for soft wheat and rapeseed cultivation. Rapeseed impacts per ha correspond well to those in the literature (Malça et al. 2014). Charles et al. (2006) compared wheat cultivation impacts under different N treatments. For a similar treatment (220 N unit.ha^{-1} for Charles et al. and 246 N unit.ha^{-1} on average in this study), results were similar for global warming potential, acidification potential and fossil fuels use. However, the mean Aube wheat had a eutrophication potential 5.6 times as high as the wheat in the literature. This could be because phosphorus fertilization for all the crop rotation is done on wheat. Integrating the whole rotation in the study would help confirm or refute this hypothesis.

Finally, for biogas impacts, when crops are cultivated for biogas production, their production becomes the main contributor to biogas impacts (Hijazi et al. 2016). Here, findings are consistent with this observation (feedstock contributed 60-99% of total impact). Thus, the validity of biogas impacts is related to that of crop impacts.

4.2.2 Causes of uncertainty

Among the main uncertainties related to data quality that decrease confidence in the results of this study, the representativity of the farm sample can be questioned. To extrapolate the results of the survey of a sub-set of farms, a farm typology based on production or practice indicators would have been required (Payraudeau and van der Werf. 2005). In this study context, lack of data on practices prevented a typology based on practices. A typology based on crop rotations would be an appropriate improvement to this study's results.

For cropping systems, some interview data were compared to a summary report provided later by the department's Chamber of Agriculture (Vegellia 2018). This report ensures that collected data for N input and the number of insecticides, fungicide and herbicide applications are representative of the study zone. To guarantee consistent assessment of impact per kg, all impacts per kg were associated with a summary report on crop yield. Representativity issues are particularly striking for water resource depletion. The strong contribution of sugar beet cultivation to this category may be due to sampling bias. Indeed, water use in this case came mostly from irrigation (Fig. 9). One of the four farmers interviewed to build the average LCI of sugar beet performed irrigation. Without more data on the percentage of irrigated area in the territory, it is difficult to assess the validity of this result.

The second level of uncertainty is related to construction of LCIs in the MEANS InOut platform. First, interview data, especially for livestock systems, were not always detailed enough to provide the data needed to construct an LCI. For instance, the quantity of feed fed per day was sometimes estimated. Moreover, specific machinery or fertilizers mentioned during interviews were not always available in the MEANS database. In this case, they were replaced by similar products.

Finally, the inclusion of processing is one of the main sources of uncertainty. Assumptions were made to identify a main processing type and mean transport distances. Some assumptions were stronger than others. For instance, since the Aube department is a major producer of sugar and dehydrated alfalfa, it seemed appropriate to assume that all sugar beet went to the local sugar factory and that all alfalfa was dehydrated in local plants. In contrast, crushing is indeed French rapeseed’s main destination, but this may not be true in the study zone. Slaughterhouse locations were provided by actors. For pigs and poultry, because the sectors are institutionalized, it seemed acceptable to assume that all animals were slaughtered in the same place, but the assumption of transport distance for sheep and cattle was far less reliable. In addition, proxies were used to estimate impacts of all processing, since time was missing to collect data on processing factories.

4.3 Assessing the environmental outcomes of future BAO management strategies

In this section, results and implications of scenarios’ development and impact assessments are discussed to answer the second research question.

4.3.1 Grazing sheep reintroduction, a topic to be further investigated

The small difference in impact between the current situation and the sheep introduction scenario is presumably due to the small magnitude of change considered: an additional 10,000 ewes do not represent much in comparison to the entire territory’s activities. In North Aube, sheep reintroduction plans have been implemented for many years, but with small success. Developing a scenario with a stronger increase in sheep production would have impacted its credibility. As said in 4.1.1, crop-livestock integration is considered beneficial in farming systems to enhance ecosystem services and nutrient cycling, but its environmental benefits at larger scale can sometimes be less certain. However, the positive trend of the impacts suggests that the topic may be worth exploring further. In addition, livestock reintroduction could help mitigating alfalfa dehydration impact without threatening the occurrence of the crop in rotations because it would increase local consumption, thus avoiding the need to dehydrate it for export.

In an area such as North Aube, specialization is so strong that it seems unlikely that arable landowners would reintroduce grazing livestock. In particular, land use issues are often raised when considering livestock farming because fodder cultivation uses land that could be used to grow human food (Institut de l'elevage and INTERBEV 2014). The scenario developed in this study, in which sheep graze mostly intermediate crops, offers a potential solution for land use and could be implemented at the landscape scale only through cooperation between arable-crop farmers and livestock owners.

4.3.2 Feedstock is the main contributor of biogas production's impact: its choice should be carefully considered

According to scenario assessment results, construction of 40 biogas plants in the territory could help reduce abiotic depletion and global warming potential. LCAs of biogas production usually consider avoided use of fossil fuels (e.g. coal, diesel), which explains lower impacts for these two categories in the literature (Styles et al 2016). In this study, this aspect was not included. Since the energy autonomy indicator indicates that the agricultural sector could produce twice as much as it consumes, however, impacts would probably be similar to those in the literature if avoided fossil-fuel use were included. In this study, abiotic depletion and global warming potential decreased due to the choice of biogas feedstock and the subsequent avoided alfalfa dehydration and rapeseed crushing.

Literature on short term effects of digestate has showed the improvement on soil quality, however, risks of nutrient leaching and losses of ammonia increase when mineral nitrogen fertilizers are replaced by digestates (Nkoa 2015). In particular, storage of digestate was not considered in the study but is understood as being an important contributor to eutrophication due to potential emissions of CH4, NH3 and N20. (Tufvesson et al. 2013, Styles et al. 2016); including it would probably increase eutrophication potential.

This scenario's results highlight the importance of assessing intermediate crops separately from the main crop. Intermediate crops are usually considered to have neutral impacts because they are not sold. When harvested to produce biogas, however, they have higher impacts than regular intermediate crops. Since they have different purposes and impact than regular intermediate crops, their impact should be considered and allocated to their final destination. Land competition increased in the scenario mainly because of intermediate crops. To consider intermediate crops separately, their LCI was created using the method usually used for meadows. Land use in ecoinvent v2 is generic for meadow and assumes that land is covered the entire year, so this approach is not valid for intermediate crops. Since intermediate crops cover land for ca. 3-4 months, their land use should be less than half of what was estimated in this study. This is also applicable to the LCI of the grazed intermediate crop that was created for the other scenario. To better understand consequences of using intermediate crops, specific characterization models need to be developed.

Ultimately, investing in the biogas sector is appealing for farmers in North Aube since it ensures secured incomes and allows them to use biomass that is usually left as residues, such as straw and intermediate crops. With different feedstock, results would probably have been different. In this scenario, almost all plant alternatives were included to provide an overview of biomass types that could be available for biogas production, but all possibilities would have to be envisioned to identify the best options for environmental performance of North Aube, especially to decrease water use and eutrophication potential. Territorial LCA seem promising to support stakeholder's feedstock selection if the growth of the biogas sector pursues its trend.

Moreover, serious concerns are raised competition for biomass use when discussing development of the biogas sector (Tufvesson et al. 2013). In North Aube, competition could arise primarily between livestock systems and the biogas sector, since both may consume the same local resources. Although they were not assessed in this study, suitable options to sustain both activities could be tested, such as a system in which grasslands and crop byproducts are used as animal feed in priority, the surplus being used to feed biogas plants.

4.4 Strengths, limits and perspectives for territorial LCA

In this section, findings with regards to territorial LCA methodology are highlighted.

4.4.1 Territorial LCA as an environnemental impact Indicator

4.4.1.1 A detailed picture of the territory

Agriculture and, by expansion, agricultural territories sustain different functions. The LCA performed in this study represented two of these functions in the choice of functional units and highlighted that impact may greatly vary according to the selected functional unit. For instance, in North Aube, cash-crop cultivation consumes the smallest amount of fossil fuels per kg of product but among the largest amount per ha of agricultural land. Thus, this sector performs well environmentally from a productivity perspective but not from a land management perspective. These findings are consistent with literature: it is increasingly argued that all functions should be considered since results may depend greatly on the function chosen (Salou et al. 2017). Moreover, results show that contribution to the territory's total impact should be also considered and put in perspective with the functional units, to identify impact mitigation opportunities. In this study, animal production usually had higher impacts than cropping systems, both per ha and per kg. Since animal production is so sparse in the territory, however, its contribution to the total impact never exceeded 8%. Thus, animal production practices may not be the first activity to focus on to improve the territory's environmental performance. Finally, assessing impact per kg of product is relevant when considering a unique production, but the unit is not the most convenient to compare the different productions. At territorial level it would be more relevant to use functional unit such as kg of protein or energy eq unit to assess the productive function. Financial function could also be considered by expressing impact per euro generated. This could be particularly useful in a prospective approach, coupled with market trends analysis. For instance, sugar beet price has been decreasing. If yields are maintained, the environmental impact per kg is likely to be unchanged in coming years, but from a financial perspective the sector could become less environmentally performant.

Selecting impact categories is a way to characterize the territory. Selecting additional categories in this study such as soil fertility and biodiversity would have allowed assessing the territory's function of provision of ecosystem services. Moreover, selecting a toxicity indicator could have allowed assessing the impact of pesticides. However, existing characterization methods for these categories were not selected due to their limitations (Garrigues et al. 2012). Complementing territorial LCAs with other relevant approaches would be a great improvement to this study.

A main obstacle to the accuracy of territorial LCAs is the loss of spatial and temporal characteristics (van der Werf et al. 2011). Indeed, environmental impacts depend in part on characteristics of the receiving environment (Finnveden et al. 2009) and thus on the location of the emission source for local and regional impacts such as acidification and eutrophication (Nitschelm et al. 2016b.). For instance, knowing the location of major polluting substances sources would be useful for policymakers. The spatialized territorial LCA methodology, developed by Nistchelm et al. (2016b), seems like a promising improvement to this study.

4.4.1.2 The challenge of boundaries selection

As Loiseau et al. (2013) state, the issue of boundaries selection for territorial LCA is to decide how to allocate responsibility for environmental impacts (production, consumption or both). In this study, total responsibility was considered, with consumption by agricultural activities represented by the resource use indicators (water resource depletion and abiotic resource depletion) and by the consideration of background processes.

Another issue that emerged in this study is whether geographical borders of the territory should correspond to the LCA's boundaries, since several processing activities do not occur inside the territory. The question raised here is whether a territory is responsible or not for the entire processing chain of the products produced within its borders. Loiseau et al. (2013) recommend stopping LCAs at the territory's borders because the territory has no influence on what happens beyond them. In this study, first processing stage was included whether or not it occurs inside the territory, for a different reason. First, by stopping at the territory borders, only certain processing activities would have been included, potentially making comparison of impacts disadvantageous. Also, although a territory's actor cannot control what happens "downstream" in the production chain, they can control their products' destinations. The question of their responsibility in this case remains open, although following this argument to the end would lead to territories being responsible for the consumption patterns of other territories, which is counter-intuitive to the aim of developing management strategies at the territory scale. To follow the concept of total responsibility, the next step of this study would be to include processing within the territory of imported raw products, although it would generate double counting at the global scale (Eder and Narodoslawsky 1999).

Conclusively, there are many available options for boundaries selection. There can be different territories depending on included data (actors and flows). The importance lays in adapting territory's boundaries to the challenges that are addressed. There can even be spatial discontinuity if the territory is considered as a web of actors. For instance, a study focusing on the entire food chain of a product could include within the territory borders production, processing, consumption and recycling spots even if there are not spatially closed.

4.4.1.3 A fragmentary approach

As stated by Payraudeau and van der Werf (2005), interactions between farms are emerging properties of farming systems. They can have positive or negative outcomes and need to be considered. The LCA approach is fragmentary, in the sense that impacts are assessed for one system's coproducts at a time. Integrating consideration of biomass recycling and interactions among different sectors in territorial LCA is necessary to better reflect the territory's dynamics. The study attempted to consider some of this recycling (when some production is used by another agricultural system) using allocation. However, the allocation assumptions that were considered are simplifications of real-life processes, so much more precise data would be required. In addition, there are many more interactions to consider, such as equipment sharing. Territorial LCA in itself cannot provide much information on the loops and synergies occurring in territories. Nonetheless, associated with strong analyses of biomass flows and relations among actors, LCA could be used to reflect positive or negative outcomes of these interactions on the environment.

Despite its numerous advantages, LCA is not a complete assessment method. Associating it with complementary indicators helps refining the analysis. For instance, adding nutrition potential and energetic autonomy to scenarios assessment helped stepping out and better foreseeing the big picture. In addition, the three pillars of sustainability should be considered. Combining characterization of environmental, socioeconomic and biomass flows is the next step of the BOAT project's approach, in order to perform a holistic territorial assessment.

4.4.2 Territorial LCA as a prospective tool

In this study, scenario development allowed to focus on management of non-food BAO (in particular intermediate crops) by examining two options: grazing or biogas production. This allowed to examine territorial LCA as part of a prospective approach.

Important quantity of non-food BAO is produced in territories, and demand for it is increasing, in particular by the energy sector (Gauvrit and Mora. 2010). From this perspective, BAO appears to be an important factor for ecological transition. At the territory scale, actors need to agree upon how they want to use non-food BOA. Territorial LCA seems a promising method to contemplate environmental impacts associated with these potential future strategies.

In this study, however, interactions among sectors and consequences of changes beyond the territory's borders were not considered sufficiently. For instance, in the biogas development scenario, impacts changed to some extent due to the decrease in alfalfa dehydration. This decrease may have significant consequences outside of the territory, since most dehydrated alfalfa is exported as animal feed. The decrease in its production in North Aube may lead to a decrease in livestock production elsewhere, or to the need to look for another protein source, which could lead to areas being deforested to produce soybeans. Studies have shown that land-use changes resulting from the use of land for energy crops can lead to massive GHG emissions and radically lower success at minimizing them (Searchinger et al. 2008, Tufvesson et al. 2013). On the other hand, decrease in dehydrated alfalfa availability may convince farmers involved in mixed farming to further integrate both systems by diversifying their crop rotations or by increasing pasture practices.

To improve understanding of consequences in the scope of a territorial forecast, it seems essential to perform consequential LCA, which would better represent the global processes modified by changes at the local scale. Consequential LCA typically performs system expansion. For instance, for dairy farming, it means considering that a change in the milk-production system (e.g. increased production) will change environmental impacts beyond it because of the strong connections between beef and milk production (Cederberg et al. 2003). However, consequential LCA uses marginal data (Schmidt 2008), which means only data subjected to changes in scenario are included.

To conclude, although it was not developed as a prospective tool, LCA is very relevant to include in a participatory prospective approach. Indeed, its transparency allow tracing back why results were obtained, so it serves as a strong basis for dialogue with local actors (Lazarevic et al. 2012). Then, it can be used to reflect on consequences of adaptations that are considered. Therefore, recommendations from this study findings are in a first time to perform attributional LCA to identify the keys environmental burdens in the territory. Then consequential LCA should be used to investigate strategies identified by local actors.

5 Conclusion

Performing territorial LCA on North Aube agricultural territory allowed the description of the main crops and livestock activities (production and processing) with regards to six impacts categories: water resource depletion, abiotic resource depletion (fossil fuels), land competition, global warming potential, acidification potential and eutrophication potential. Production's impacts were expressed by the proportion of impact carried by each production relatively to total territory's impact but also per ha and per kg to reflect two of the territory's function: a productive function and a land management function. Financial function could have been added, through the assessment of impact per euro generated. Results show the major contribution of grain and cash crops, in main part due to the use of mineral fertilizer. To a smaller extent, pig and broilers husbandry carry a part of the territory’s impact. Results emphasized that processing should not be neglected. Results should be interpreted with caution as different level of uncertainties are associated to each step of the LCA. In particular, North Aube LCA would have shown much more reliable results if a typology of the farming territory would have been carried out upstream.

This study attempted to include links between farms (when associated to biomass flows), through the allocation of crops impact to livestock or biogas plant when local biomass is reused for these productions. This attempt highlights the fragmentary nature of LCA as well as the need of very specific data to perform such allocations.

Two scenarios were designed and assessed. Uncertainties associated to the territorial LCA prevent from drawing conclusions based on these scenarios. However, they validate territorial LCA as relevant in a prospective approach. To improve the applicability of the method with regards to scenarios, consequential LCA should be performed. In addition, to facilitate decision making at territory scale, LCA should be used complementarily with other indicators, such as socio-economic indicators.

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Appendix list

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Appendix 1 – Detailed presentation of the LCA methodology

- **Goal and scope definition**

LCA must present a goal and identify the applications that will result from findings of the study. (Weitz et al. 1999)

The overall goal of LCA can belong to two distinct categories: i) to describe a system and its environmental impacts or ii) to describe how the environmentally relevant flows can be expected to change as a result of actions taken in the system (Rebitzer et al. 2004). Thus, there are two types of LCA (Finnveden et al. 2009): i) attributional LCA and ii) consequential LCA, respectively.

Scope includes the system boundaries, scale and functional unit(s) (van der Werf et al. 2011). System boundaries should include all operations that contribute to the product life cycle. The functional unit represents the function studied; it provides a reference unit (e.g. kg of product or agricultural area used) to which the inventory data are reported (Roy et al. 2009). The choice of functional unit depends on the goal of the study and the environmental impacts considered. LCA impacts are likely to vary depending on the functional unit chosen (Haas et al. 2000)

- **Life cycle inventory analysis**

LCI analysis is the quantification of the flows of matter, energy and pollutants that cross the boundaries of the system. (Jolliet et al. 2010) For product-specific data, site-specific data that include all the inputs and outputs processes within the system boundaries are required. Inputs include energy, water, raw materials, buildings etc. Outputs are products and coproducts, but also emissions to air, water and soil. (Roy et al. 2009).

Data that are not product-specific should also be included in the inventory. Fortunately, LCA databases are available for data that are not product-specific (such as average LCI of energy production).

During LCI analysis, input and output data are aggregated and standardized to the functional unit. Consequently, spatial and temporal characteristics (place and time of emission) of the input data are lost (van der Werf et al. 2011).

- **Impact Assessment and Interpretation**

The LCIA and interpretation steps estimate the magnitude of environmental impacts associated with the resources and emissions listed in the LCI. In general, LCIA involves three steps: selection of impact categories, classification and characterization (ISO. 2006a), to which normalization and valuation are sometimes added. (Roy et al. 2009)

First, impact categories are selected for environmental issues covered by the study. To produce a quality environmental assessment, van der Werf et al. (2011) recommend that the method considers a range of categories broad enough to cover regional and global impacts. Usually, impact categories include global effects (e.g. climate change or ozone depletion), regional effects (e.g. acidification, eutrophication) and local effects (e.g. land use) (Roy et al. 2009).

Then, through classification, each inventory item is grouped into impact categories (Jolliet et al. 2010). For each category, an indicator that will serve as common unit is defined, and a characterization model estimates the impacts of each LCI flow into one or more environmental impact categories (Roy et al. 2009) (Fig.17.).

Normalization expresses impacts so that they can be compared (using references values to put results in perspective) (Jolliet et al. 2010). Valuation refers to estimation of the relative significance of environmental impacts by weighting them. The goal is to allow for comparison or aggregation, but there is no objective method for weighting (Finnveden et al. 2009).

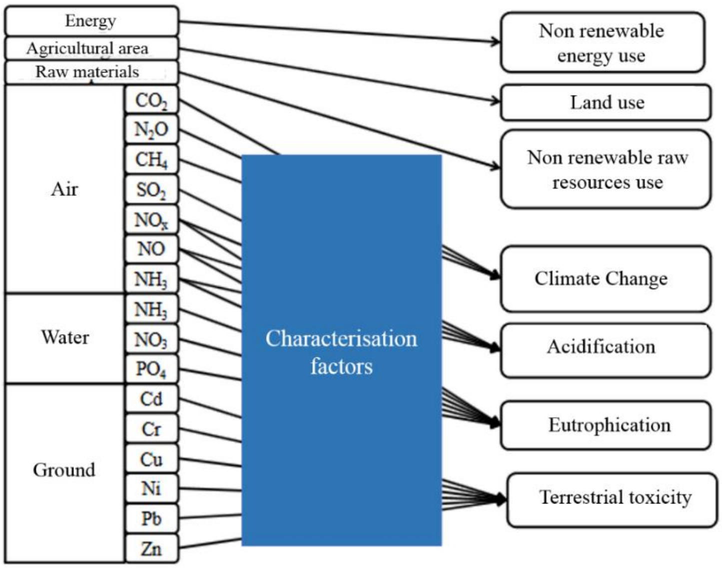

Figure 17 - Diagram of the characterization step performed during life cycle impact assesment - Translated from Nitschelm (2016a). , adapted from Chen (2014)

Finally, the interpretation stage of the LCA is to draw conclusions that will lead to recommendations to the audience of the study, in accordance with the objective and scope of the LCA (Roy et al. 2009, van der Werf et al. 2011).

Appendix 2- Table 6 – Summary table of Impact kg^{-1}, weighting details and data sources at crop level

Product	Surface (ha)	Yield (ha$^{-1,}$)	Impact kg^{-1}						Weighting details	Data sources
			WRD (m3)	AD (MJ)	LC (m2/y)	GWP (kgCO2eq)	AP (kg SO2eq)	EP (kg PO4---eq)		
Soft Winter Wheat	52448	84.8q.	0.0005	2.27	1.22	0.44	0.0054	0.0034	5 data set. Till = 50% / No-till = 48% / Organic = 2%	data for LCIs: farmers surveys, except LCI silage maize and meadow: proxies from Agribalyse database. The farmer interviewed for silage maize was cultivating it as energy crop, so this data set was used for LCI "energy maize" in scenario 1 but not for the current situation. Hemp: proxy. Impact per ha from Van der Werf.et al. 2004 -Weighting data: personal communication A. Pereirra, 2019 (Conservation farming expert at Aube Agricultural chamber) -Yield: Synthesis 2017 – Chamber of agriculture report (except hemp & meadow: surveys data) Surface: RPG 2017
Spring Barley	32602	71.1q	0.0008	2.03	1.00	0.42	0.0051	0.0028	5 data set. Till = 52% No-till = 48%	
Rapeseed	18846	38.8q	0.0012	4.32	2.51	1.37	0.0103	0.0075	4 data set. Till = 52% No-till = 48%	
Winter Barley	11969	76.1q	0.0004	1.69	0.84	0.33	0.0042	0.0026	2 data set. Till = 52% No-till = 48%	
Grain maize	1946	91.2q	0.0006	1.67	0.37	0.27	0.0044	0.0032	1 data set	
Sugar Beet	23280	945q.	0.0192	0.24	0.05	0.03	0.0003	0.0002	3 data set – averaged 1/3 each	
Potatoes	5404	575q.	0.02	0.64	0.27	0.07	0.0011	0.0006	1 data set	
Hemp	3422	90q	/	1.27	1.13	0.26	0.0007	0.0023	2 data set	
Alfalfa	6412	105qdm	0.00008	0.47	1.00	0.04	0.0002	0.0012	1 data set	
Permanent Meadow	2828	60qdm	0.0004	2.09	1.45	0.29	0.0023	0.0010	1 data set	
Spring Pea	1483	36.5q	0.0003	1.41	2.76	0.24	0.0147	0.0098	1 data set	
Silage Maize	311	116qdm	0.003	1.22	0.92	0.19	0.0047	0.0027	1 data set	

Appendix 3 – Summary tables of Impact kg^{-1},ha^{-1}, total impact, weighting details and data sources at category level

Product	Surface ha *(on and off farm for animals)*	Nb heads	Yield (ha^{-1} or head^{-1}) year^{-1}	Impact kg^{-1} WRD (m3)	AD (MJ)	LC (m2/y)	GWP (kgCO2eq)	AP (kg SO2eq)	EP (kg PO4---eq)	Weighting details	Data sources
Grain and Oilseed crops	117813		73.7q	0.001	2.5	1.3	0.57	0.0006	0.0004	45% winter wheat, 28% spring barley, 16% rapeseed, 10% winter barley, 2% grain maize (proportional to land cover)	LCIs : farmers surveys Numbers of heads: personal communications 2019 (J.L Deck and F. Desné (Agricultural chamber, livestock systems experts), T. Gobin, (Cyrhio technical expert), C. Didier (DUC technical expert)
Cash crops	32107		795q	0.017	0.4	0.2	0.06	0.0004	0.001	73% sugar beet, 17% potatoes, 11% hemp (proportional to land cover)	
Fodder crops	11036		82.5q	0.0003	1.0	1.34	0.136	0.0028	0.0023	56% alfalfa, 26% permanent meadow, 13% spring pea, 3% silage maize (proportional to land cover)	
Milk (/kg milk)	1240.8	1196 milking cows	8932L	0.007	3.2	1.0	0.9	0.008	0.003	1 data set	
Beef (/kg live weight)	3487	463 cull dairy cows, 234 cull suckling cows, 613 dairy calves, 257 suckling calves, 139 young bulls	Dairy calves: 40kg, Suckling calves: 350kg, Young bull: 790kg, cull cows 823kg	0.030	25.3	25.8	18.7	0.15	0.06	2 data set -42% Cull dairy cows and dairy calves, 52% Cow calves and cull suckling cows, 6% young bull (proportional to nb of heads)	
Sheep (/kg live weight)	1019	59 outdoor cull ewes, 299 indoor cull ewes, 5738 indoor lambs, 1547 outdoor lambs	Cull ewes: 64kg Lamb: 40kg	0.037	11.8	15.5	7.93	0.08	0.04	2 data set- 60% indoor system, 40% outdoor systems (proportional to nb of heads)	
Broilers (/kg live weight)	13509	5775000 broilers, 16170 cull hens	Broilers: 2.3kg Cull hens: 1.7kg	0.04	19.8	2.56	2.04	0.02	0.02	1 data set -99% Broilers, 1% Cull laying hens (proportional to nb of heads)	
Pork (/kg live weight)	4794	102408 pigs, 1676 cull sows	Pork 130kg, cull sow 180kg	0.047	7.96	3.96	3.08	0.04	0.02	1 data set	
Eggs	465.9	16170 laying hens	18kg	0.077	24.2	5.71	3.51	0.05	0.029	1 data set	

Table 7 - Summary table of Impact kg-1, weighting and data sources for the different categories included in the study

		Impact ha^{-1}						Total Impact					
Product	Surface ha *(on and off farm for animals)*	WRD (m3)	AD (MJ)	LC (m2/y)	GWP (kgCO2eq)	AP (kg SO2eq)	EP (kg PO4---eq)	WRD (m3)	AD (MJ)	LC (m2/y)	GWP (kgCO2eq)	AP (kg SO2eq)	EP (kg PO4---eq)
Grain and Oilseed crops	117813	4.9	17405	9146	3767	41.9	26.4	5.66E+05	2.03E+09	1.07E+09	4.40E+08	4.89E+06	3.08E+06
Cash crops	32107	1503.4	24033	7003	3032	26.6	23.2	4.80E+07	7.65E+08	2.22E+08	9.64E+07	8.45E+05	7.38E+05
Fodder crops	11036	2.4	7253	9988	881	13.6	14.3	2.53E+04	7.95E+07	1.10E+08	9.66E+06	1.51E+05	1.59E+05
Milk	1240.8	58.0	27143	8326	7730	71.0	29.6	7.20E+04	3.37E+07	1.03E+07	9.59E+06	8.81E+04	3.68E+04
Beef	3487	12.1	8305	9072	4783	41.9	15.0	1.57E+04	1.38E+07	1.52E+07	1.05E+07	8.39E+04	3.21E+04
Sheep	1019	11.3	7065	7014	3960	49.8	20.0	1.32E+04	6.02E+06	6.70E+06	3.62E+06	4.20E+04	1.81E+04
Broilers	13509	40.9	18885	2428	1938	21.1	15.4	5.58E+05	2.58E+08	3.31E+07	2.64E+07	2.88E+05	2.11E+05
Pork	4794	139.6	23747	11828	9207	124.2	48.7	6.70E+05	1.14E+08	5.67E+07	4.41E+07	5.95E+05	2.33E+05
Eggs	465.9	48.2	15148	3567	2195	33.4	18.0	2.25E+04	7.06E+06	1.66E+06	1.02E+06	1.55E+04	8.40E+03

Table 8- Summary table of Impact ha-1 and total impact of unprocessed products – Total impact is calculated by summing impact at crop/animal system level, not at category level. For instance, in the case of sheep total impact of indoor and outdoor system were calculated separately (by multiplying impact per kg * number of kg produced) and then summed.

Appendix 4: Allocations rules applied to this study

type	Products	Allocation (2019)	Changes in scenario		Data source
			Scenario 1	Scenario 2	
Economic	Grain/Straw	Grain 75% Straw 25%			Prices: Plein Champ 2019
	Milk/Dairy cattle meat	Milk:89%, Meat: 11%			Cows & calves prices: statistics Plein Champ 2019 Milk price: Interview data
	Egg/Cull hens	Egg 98%, Cull hens 2%			Prices: interview data
	Biogas/Digested matter	Biogas 57% Digested matter 43%			Jury et al. 2010
	Rapeseed Oil/Meal	Meal: 68.3% Oil: 31.7%			Allocation data from EcoAlim database (Wilfart et al. 2016)
	Sugar/Sugar beet pulp/ Molasses	Sugar 73.1% Pulp 20.3% Molasses 6.6%			Allocation data from EcoAlim database (Wilfart et al. 2016)
	Cheese/liquid Whey	Cheese 97% Whey 3%			Prices: Whey Plein Champ 2019 Cheese : Interview data
Mass	Grain stored/Grain for livestock	Livestock: 2% Stored: 98%		Livestock: 4% Stored: 96%	Biogas and sheep feedstock from interview data Hypothesis: all feedstock comes from the territory
	Straw for livestock/ straw on field (only wheat and spring barley's straw)	Livestock: 3% On field: 97% (impact alloc. to grain)	Livestock:3% Biogas: 8% Left on field: 89%	Livestock:3% Left on field: 89%	
	intermediate crops: regular/grazed/harvested for biogas	Livestock 1.1% Biogas: 3.2% On field (impact alloc. to main crop): 95.7%	Livestock 1.1% Biogas: 24% On field: 74.9%	Livestock 1.8% Biogas: 3.2% On field: 95%	
	Sugar beet pulp / Pulp for Biogas / Pulp	Pulp: 96.4% Biogas: 1.5% Livestock: 2.1%	Pulp: 70.4% Biogas: 27.5% Livestock: 2.1%	Pulp: 96.2% Biogas: 1.5% Livestock: 2.3%	
	Ensiled Meadow / Grazed Meadow	Ensiled :52.5% Livestock: 47.5%	Ensiled :2.5% Livestock: 47.5% Biogas: 50%	Livestock: 100%	
	Dehydrated Alfalfa/Alfalfa for livestock	Dehydrated: 98.6% Livestock: 1.4%	Dehydrated: 48% Livestock: 1.4% Biogas: 50.6%	Dehydrated: 98.2% Livestock: 1.8%	
	Silage Maize for biogas or livestock	Insufficient local production – no allocation performed	Biogas 87% Livestock 13% *	Biogas 56%% Livestock 44%	
	Spring Pea / Spring Pea for livestock	Spring Pea 100%		Spring Pea 6% Livestock 94%	

Table 9 - Details of allocations performed in this study *In scenario, surface occupied by silage maize and meadows are changed to produce enough local biomass. Currently there are 311ha of silage maize and 2828ha of permanent meadow. In scenario 1 664ha of silage maize are added (replacing rapeseed). In scenario 2 1219ha of meadow and 313ha of silage maize are added. Alloc. : allocated

Appendix 5: Questionnaires

a- Background Questionnaire

1- The farm

- *Can you describe your farm?*

Surface (ha)	
Livestock	
Main activity	
Diversification activities	

- *Who is working on the farm?*

Cropping system :

- *Can you detail your crop rotations? How many ha are occupied by each crop?*
- *Can you define your practices?*

Livestock system :

- *Can you define your practices?*

2- Management

- *Who are your main retailers? (Machinery, fertilizers, phytosanitary products, seeds, animal feed…)*

PRODUCT	RETAILER	PURCHASE COST

- *How do you sell your production? Who are your main customers?*

PRODUCT	MARKETING MODE	CUSTOMER	SALE PRICE

Other activities :

- *Are you engaged in any activity in parallel with production? (processing, non-agricultural labor…)*

Links with other actors

- *What links do you share with other actors form the territory? (exchange of products, common machinery, farmers group …)*

Representativity

- *Would you define your practices as representative of North Aube farming?*

3-Prospective

- *What have changed on your farm in the last ten years?*
- *What are the upcoming changes on your farm? (in 5 years)*
- *How do you think agriculture is going to evolve in North Aube?*

Can you give me your opinion on the following scenarios? Which one is the most probable? Which one would you like to see happening?

1 - Current trend

In 2030, the evolution of agricultural production systems followed the current trend. There are no major changes in farming practices. Maize cultivation areas have decreased significantly, replaced by barley plantations. The number of winegrowing operations has increased significantly. On the contrary, livestock farming is even less abundant in the region. It has almost disappeared, as have some of the associated grasslands. The various marketing channels have not changed. There has been a significant increase in the number of individual silos.

2-A strong return of sheep farming

In 2030, following the regional recovery plans, sheep farming was strongly resettled in the region. This results in an increase in grazed areas (temporary grassland, longer in rotations), as well as an increase in the availability of local organic fertilizers at low prices. All permanent grasslands are now grazed; The feeding needs of flocks absorb a large part of the production of sugar beet pulp, alfalfa, plant cover and straw from large arable lands.

3- Boom in non-food uses

In 2030, government plans for a carbon-free economy gave biomass a major importance in energy and fuel systems. In north Aube, this means the methanisation of all wet bio-waste as well as grain co-products. Intermediate crops are also harvested as energy crops. The share of cultivation dedicated to alfalfa has increased. Part of maize production is also used for methanisation. The liberalization of quotas has led to higher production of sugar beet which pulp is methanized. A portion of wheat and beet crops is also used for the production of bioethanol. In addition, the territory is a supplier of potato starch for green chemistry. As a result, there is an increase in the number of dedicated areas. The tools for dehydrating pulp and alfalfa are disappearing.

4-Change in farming practices

In 2030, in response to the demand for organic products, many farmers in North Aube changed their production methods. More than a quarter of producers are now certified organic. This has led to significant changes in rotations, with alfalfa and protein peas becoming two major plantations. Crop residues are systematically buried and to meet their needs for organic fertilizers, the actors exchange part of their forage production for the effluents of regional livestock breeders.

5- Diversification

In 2030, rotations were diversified in arable land. In particular, hemp production has grown strongly. Alfalfa and protein peas also play a more important role in rotations. All straws and plant cover are returned to the ground. Livestock farming has not developed very much in the region.

b- Questionnaire for LCA – example for annual crop

Soil and topography

What soil type is there on your fields ? Do you know the slope degree ? How long are your plots ? How far is the closest watercourse ? Is drainage needed on your plots ?

- Slope lenght (m) :
- Degree (+/- 3%) :
- Orientation machinery way / slope :
- Distance from closest watercourse :
- Drainage :
- Soil type :

General informations

- *For this particular production, what is the yield? Is there any coproducts? Do you know the quantity of residues after harvest? (for grain: Do you harvest the straw?)*
- *What is the preceding crop? Its yield? Harvest date? Do you burry its residues? If yes, with which machinery?*

	Type	yield	%valorized	Harvest date	%surface	*Quantity Residus (kgMS /ha)*
Product						
Coproduct						
Preceding crop						

Soil preparation

Do you prepare the soil? What kind of operation do you do? With which machinery? How many passages?

Type	Operation description *(machinery characteristics)*	Date	Number of passages	Done by an external operator ?	% surface

Seeding

How much seed do you put/ha? With which tool? On what date ?

Seed qty/ha	Operation Description	Date	Nb of passages	Done by an external operator ?

Harvest

On what date do you harvest? With which tools/machinery ? How many passages ?

Operation Description	Date	Nb of passage	Done by an external operator ?

After Harvest

Is there after-harvest operations? (transport…)

Type	Description	Date	Nb passages	%surface	Done by an external operator ?

Other mechanical work

Are you practicing other mechanical work? (mechanical weeding, straw crushing…)

Type	Description	Date	Nb passages	%surface	Done by an external operator ?

Intermediate crops

- *Was there a crop cover between the preceding crop and this one? On what proportion of the field? Which machinery did you use for seeding? When did you stop the intermediate crop? Was it destroyed mechanically or with chemistry?*

Type	Seeding operation	Date of seeding	% surface	Date of termination	Destruction practices	Done by an external operator ?

Fertilization

At which step do you fertilize? What type of fertilizer do you use? How much? Which machinery do you use for spraying

Type (chemical..)	Product name	Ratio NPK	Qty/ha	Operations	%surface	Date	Nb passages	Done by an external operator ?

Phytosanytary products

How many phytosanitary product do you spray ? At which step? What type of product is this ? How much do you spray? With which machinery?

Type (herbicide, pesticide..)	Product name	Active substance and concentration	Qty /ha	Operations	%surface	Date	Nb passages	Done by an external operator ?

Is there a treatment on seeds?

Other inputs (energy, fence..)

Is there any other input on the field ?

Type	Usage	Qty (/ha)	%surface	Operations

Irrigation & energy

- *Do you irrigate your field? With which equipment? How much irrigation water do you use? Where does the water come from? Do you use energy? Which type?*

Type	equipment	Qty (m3)	% surface	Energy type	Qty energy

Appendix 6– Pedigree matrix

Indicator Scores	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumption or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimated (eg by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate period	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal Correlation	Less than three years of difference to year of study	Less than six years difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than IS years of difference
Geographical Correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Table 10 - Presentation of the Pedigree matrix, used to associate a quality grade to each data during LCA – from Weidema and Wesnæs (1996)

Appendix 7- total environmental impact of the territory after inclusion of processing and consideration of locally reused biomass.

Category	**Stored Grain**				**Rapeseed products**		**Sugar Beet products**			**Other cash crops products**	
Product	Soft Wheat grain Stored	Spring Barley grain Stored	Winter Barley Grain stored	Grain maize stored	Rapeseed meal	Rapeseed Oil	Sugar	Sugar beet pulp	Molasses	Potatoes	Hemp fibre, pellets and seed
Qty produced (t)	**435625**	**227134**	**91084**	**8140**	**40804**	**31005**	**296999**	**424063**	**83600**	**311822**	**7393**
WRD	230 915	178 987	46 007	4 669	66 069	30 664	30 443 381	8 150 295	2 748 650	5 600 030	738
AD	991 581 019	469 181 605	190 342 406	13 856 382	271 547 471	126 033 014	884 663 825	236 819 326	79 873 888	199 210 893	40 152 853
LC	530 885 436	228 685 308	93 890 983	2 990 647	130 207 190	60 432 913	64 602 245	17 181 007	5 832 761	79 781 337	34 909 451
GWP	193 212 265	95 721 776	36 652 046	2 190 783	73 801 641	34 253 470	80 661 037	21 592 569	7 282 665	21 277 849	8 060 780
AP	2 323 544	1 165 600	463 864	35 606	541 612	251 378	559 266	149 728	50 495	219 288	33 986
EP	1 467 737	646 175	293 162	25 927	390 352	181 174	364 660	97 416	32 924	186 848	70 311

Category	**Fodder products**			**Biogas**	**Animal Products**						
Product	Grass Silage	Dehydrated Alfalfa	Spring Pea	Biogas	Cheese	Liquid whey	Sheep Meat	Beef	Chicken Meat	Egg	Pork
Qty produced (t)	**8753**	**66396**	**5413**	**4147200m3**	**1368**	**9315**	**154**	**375**	**9126**	**291**	**75884**
WRD	3 446	27 659	1 922	923 684	69 808	2 159	13 245	15 859	559 543	22 476	706 336
AD	18 314 260	794 058 298	7 638 593	13 887 402	35 347 392	1 093 218	6 643 970	15 391 568	281 782 512	7 058 689	556 151 728
LC	12 682 300	67 712 200	14 946 948	23 272 938	10 021 934	309 957	6 701 316	15 206 678	33 135 769	1 662 172	56 706 443
GWP	2 546 955	80 157 093	1 306 055	9 500 322	9 504 548	293 955	3 715 194	10 763 789	30 399 426	1 022 624	117 886 975
AP	20 791	400 299	79 402	103 810	85 688	2 650	42 305	84 628	295 531	15 559	737 375
EP	8 709	148 533	53 190	75 777	35 711	1 104	18 120	32 205	213 071	8 397	282 058

Table 11 - total impact of the territory- per category - after inclusion of processing and allocation of reused biomass - WRD: water resource depletion AD: abiotic depletion LC: land competition GWP: Global warming potential AP: acidification potential EP: eutrophication potential

Appendix 8 – Changes in impacts for production systems affected by the sheep comeback scenario

Product	Changes compared to current situation		Explanation
Sheep	WRD	-48%	Settlement of 11000 suckling ewes: WRD decreases due to animal feeding practices changes. Main contributor of WRD currently is molasses, which was take out from lambs feed.
	AD	+167%	
	LC	+564%	
	GWP	+258%	
	AP	+160%	
	EP	+172%	
Stored grains	All impacts	-0.2%	Mass Allocation. (0.2% of straw used as feedstock > 0.2% impact alloc. to sheep)
Rapeseed products	All impacts	-11%	Surface reduction to produce silage maize and meadow Crushing avoidance
Sugar Beet products	WRD	-0.1%	-Mass allocation: 0.3% pulps alloc. to sheep; 1.4% intermediate crops alloc.to sheep -Ovine manure used on sugar beet fields: changes in fertilization practices
	AD	+0.1%	
	LC	-10%	
	GWP	+3%	
	AP	+10%	
	EP	+1%	
Potatoes	WRD	=	Mass allocation: 0.4% intermediate crops alloc. to sheep
	AD	-0.7%	
	LC	-9.5%	
	GWP	-3.6%	
	AP	-3.9%	
	EP	-10%	
Grass silage	All impacts	-100%	Mass allocation: 100% production alloc. to livestock
Dehydrated Alfalfa	All impacts	-2%	Mass allocation: 1.8% production alloc. to livestock Dehydration avoidance

Table 12 - Presentation of productions for which there is an impact shift induced in scenario 2 compared to current situation -Changes are expressed in % relatively to the current situation. WRD: water resource depletion AD: abiotic depletion LC: land competition GWP : global warming potential AP: acidification potential EP: eutrophication potential

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