Territorial Life Cycle Assessment (LCA): what exactly is it about? A proposal towards using a common terminology and a research agenda

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Author-produced version of the article published in Journal of Cleaner Production, 2018, N°176, p. 474-485.
The original publication is available at
http://linkinghub.elsevier.com/retrieve/pii/S0959652617331402
Doi: 10.1016/j.jclepro.2017.12.169

Amount of words: 9635

Territorial Life Cycle Assessment (LCA): what exactly is it about?

A proposal towards using a common terminology and a research agenda

Authors: Eléonore Loiseau[1], Lynda Aissani[2], Samuel Le Féon[2], Faustine Laurent[3], Juliette Cerceau[4], Serenella Sala[5], Philippe Roux[1]

[1]ITAP, Irstea, Montpellier SupAgro, Elsa Research group, Univ Montpellier, Montpellier, France
[2]UR OPAALE, Irstea, 17 avenue de Cucillé, CS 64427, Rennes, France
[3]AKAJOULE, 18 boulevard Paul Perrin, Saint-Nazaire, France
[4]Associate fellow, UMR PACTE, Institute of Political Studies, Grenoble, France
[5]European Commission, Joint Research Centre, Directorate D: Sustainable Resources, Bioeconomy Unit, Via Enrico Fermi 2749, Ispra, Italy

Abstract

Evaluating holistically environmental impacts of land planning policies implies to take into account several aspects, intimately related both to territorial features and to production-consumption patterns, which have a specific local character and a potential impact at different scales. To address these challenges, life cycle thinking and assessment methods are crucial. Indeed, beyond the traditional application of Life Cycle Assessment as a product-oriented methodology, a new LCA-based approach called "territorial LCA" has gradually emerged to assess geographically or administratively defined systems. This paper aims to analyze how this new LCA-based approach differs from conventional LCA, highlighting main differences and added values. Territorial LCAs can be divided into two main approaches, i.e., i) type A, which focuses on the assessment of a specific activity or supply chain anchored in a given territory, and ii) type B, which attempts to assess all production and consumption activities located in a territory, including all environmental pressures embodied in trade flows with other territories. These two approaches are described and compared according to the four LCA phases to highlight differences and similarities with conventional LCA. This comparison is based on a detailed case study analysis for each territorial LCA type and it shows that most of the differences are in the goal and scope definition, especially for the territorial LCA of type B where the functional unit definition is no more the starting point of the assessment. Concerning territorial LCA of type A, there are no main divergences with conventional LCA as territorial contextualization already exists in some LCA applications, even if not systematically applied. Improvements in the application may entail a comprehensive contextualization of the four LCA phases, developing the synergies with the use of Geographic Information System (GIS) tools. Other specific challenges affecting both type A and B are related to i) territorial unique intrinsic multifunctionality determined by all human activities located within its boundaries, ii) specific territorial characteristics (i.e., spatial variability and organization), and iii) multiscale issues and the consideration of interactions between territories.

Keywords: Spatial planning, Environmental assessment, Multifunctionality, Spatialized LCA, Geographic Information System, Decision-making support

Highlights:

Territorial LCA is a new area of methodological developments.

Two types of territorial LCAs (T-LCAs) are described and discussed.

T-LCAs of type A focus on the contextualization of a single anchored activity.

T-LCAs of type B assess the eco-efficiency of a territory as a whole.

The systematic use of T-LCAs can support land planning policies at different scales.

1. Introduction

Life Cycle Assessment (LCA) is a well-established methodology for assessing the environmental impacts of a product, a process or a service throughout its life cycle (Finnveden et al., 2009). Although LCA was initially designed as a product-oriented approach, recent proposals have sought to broaden its object of analysis including mesoscale and macroscale objects (Guinée et al., 2011). In this sense, Hellweg and Milà i Canals (2014) described the various applications of LCA to larger systems including companies, consumer lifestyles or nations as a whole. The main aim of these emerging approaches is to identify environmental hotspots, which may then support decision-making to improve the environmental performances of future policies.
This is in line with the first guidelines that have been proposed by the World Resource Institute (WRI) and the World Bank Committee on Sustainable Development (WBCSD) in 2004 to account for energy and greenhouse gas at community-scale. These guidelines emphasized the necessity to compute comprehensive inventories and to include indirect emissions due to upstream activities wherever they take place (inside or outside the studied territory). However, broader perspectives including multicriteria approaches are currently lacking for assessing the environmental impacts of land planning policies defined at subnational scales such as those required by the Environmental Impact Assessment (EIA) or the Strategic Environmental Assessment (SEA) European directives (European Commission, 2009). Consequently, several authors proposed to use LCA in SEA and territorial planning to adopt a life cycle and multicriteria approach (Beloin-Saint-Pierre et al., 2016; Bidstrup, 2015; Björklund, 2011; Loiseau et al., 2013, 2012). Mazzi et al. (2017) also suggested to use LCA in the European Union EMAS (Eco-Management Audit Scheme) standard (European Commission, 2013) at the territorial level. Given these elements, broadening the object of analysis in LCA points the way towards a new LCA-based approach, that can be called “territorial LCA” (Loiseau et al., 2013).

1.1 Towards territorial LCA applications

As a first issue, the concept of territory needs to be better defined and addressed. Since the 1980s, social geographers have used this concept to understand the relationship between societies and their environment. Territory is designed by the eco-bio-sociologic relationships between society and environment (Raffestin, 1989). Through the decades, territory appears as a rather polysemous concept. From an anthropocentric point of view, geographers agree at a minimal level that territory covers three dimensions (Laganier et al., 2002), i.e., i) the *material dimension* of a geographic area defined by the physical properties that can be considered as opportunities or constraints for the development of human systems, ii) the *organizational dimension* defined by social and institutional actors structured within activities, organizations or jurisdictions that embody the strategies of territorial development, and iii) the *identity dimension* defined by the way social and institutional stakeholders think and implement a project for their territory.
These three dimensions can be linked in a systemic definition of the territory, defined as a complex system combining a geographic area, a system of stakeholders and a system of representations (Moine, 2006). Territory can thus be understood as a geographical system defining opportunities and constraints for organization and development of the human system. In geography, this territorial complexity is grasped by land cover and land use. Land cover addresses the layers of natural vegetation, crops and human structures that cover the land surface. Land use refers to human observable activities of land exploitation as well as structural elements in the landscape (Verburg et al., 2009). The interactions between different land uses constitute a land use system, including socioeconomic information and governance issues, that approaches the notion of territory. For Verburg et al. (2009), the goods and services provided by the land use systems define land functions. A territory can thus be described as a multifunctional system through the territorial functions that provide goods and services depending on the nature of the land and the way it is exploited (from material functions including provision of food or housing to intangible types such as landscape quality or cultural heritage).
In the LCA literature, there is a progressive gradation in the consideration of the territory object. On one hand, a lot of LCA applications tend to assess specific sectors of activity that are located in a given territory, such as agricultural systems (Acosta-Alba et al., 2012; Cellura et al., 2012; Salomone and Ioppolo, 2012), waste management systems (Bergsdal et al., 2005; Morselli et al., 2008, 2007; Rigamonti et al., 2013; Wittmaier et al., 2009) or water management systems (Lassaux et al., 2007; Lemos et al., 2013; Lundie et al., 2004; Muñoz et al., 2010). These studies aim at supporting decision-making by providing useful information, identifying hotspots, prioritizing actions and optimizing the studied systems. In these examples, great emphasis is placed on the territorial contextualization of the systems under study, especially in terms of data collection (O’Keeffe et al., 2016). However, the use of territorial contextualization is often implicit in these case studies, and methodological proposals on how to consider territorial specificities in a consistent way in LCA are lacking.
On the other hand, some LCA applications consider the territorial object as a whole by grasping all its production and consumption activities to assess the eco-efficiency of a territory as a whole (Loiseau et al., 2014; Nitschelm et al., 2015). Eco-efficiency is defined by Seppälä et al. (2005) as the ratio of services provided the territory and the corresponding environmental impacts. This approach is relatively new and elements are needed

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Doi: 10.1016/j.jclepro.2017.12.169

to understand its main issues and the further improvements to be done to broaden its use. In the end, two types of territorial LCA applications can be defined. The first one is called type A, which contextualizes the LCA of an activity (i.e., production or consumption activities) that is anchored in a specific territory and dependent on the geographical context. The second one is called type B, which assesses the environmental impacts of all production and consumption activities located in a given territory. Both of them aim at supporting decision-making at subnational level (from city level to regional level) to elaborate environmentally friendly policies through the provision of a territorial baseline and the comparison of spatial planning scenarios. This first proposal of definitions is important as explicit mentions to territorial approaches in LCA are often lacking in the literature. This lack of formalism can prevent the development of this new LCA application. Besides, additional insights are needed to understand where territorial specificities should be integrated in LCA steps, and guidance should be provided to harmonize practices. Finally, this type of assessment is promising for policy making, and it is important to understand the issues at stake and clearly define the future research to be led to favor the use of these approaches.

1.2 Objectives of the paper

The aim of this paper is to describe and analyze the territorial LCA applications to assess how they differ from conventional LCAs, and explicitly emphasize the LCA steps where territorial contextualization is required. This work is also important to discuss where future developments are needed to improve the interest and robustness of such approaches. We propose to base our analysis on two case studies according to the way of considering the territorial object, i.e., i) territorial contextualization in LCA (territorial LCA of type A) or ii) LCA of all production and consumption activities within a given territory (territorial LCA of type B). These case studies are first described and then compared to conventional LCA according to the four standardized LCA phases, i.e. goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation (ISO 2006a; b). According to this comparative analysis, methodological proposals are made to include territorial specificities in all LCA steps and several methodological challenges have been identified to improve territorial LCA applications. They are related to a better integration of the three territorial dimensions. More specifically, these challenges deal with multifunctionality, territorial characteristics (e.g., spatial variability), or multiscale modeling. Different concepts and tools are described in the last part of this paper as potential approaches to broaden territorial LCAs. They include interdisciplinary approaches, economic modeling, and tools such as the Geographic Information System (GIS).

2. Territorial LCA applications: illustration and comparison through two case studies

In this section, two case studies are described and compared to illustrate what kind of applications can fall under the “territorial LCA” category, i.e. territorial contextualization (type A) or assessment of a territory as a whole (type B) and analyze how they differ from conventional LCA. The comparison is based on the four methodological phases of the standardized LCA framework (ISO 2006a; b) to stress the similarities and differences with conventional LCAs, and the main results are summarized in Table 1. More information on territorial LCA principles is provided in appendices (see appendix A).

2.1 General description of the two case studies

2.1.1 Territorial LCA of type A: implementation of collective biogas plants in French West territories

A framework and a case study of territorial LCAs of type A for the assessment of collective biogas plants were proposed by Laurent (2015). Based on the assessment of territorial constraints and needs, the framework aims to define, in a systemic (Le Moigne 1977) and objective way, the nature of the system and its functional unit that matches the territorial main interest for implementing a biogas plant. This methodology was deployed on two contrasted territories in Western France, i.e. i) an agricultural area and ii) an urban area.

First, the biogas production pathway is described through a *territorial analysis* (Figure 1 a.) involving the use of Database Management System (DBMS) and GIS. During this stage, the main system items and their interactions are listed, quantified and georeferenced. They include stakeholders (e.g., farmers, households), stocks (e.g., energy, nutrients), networks (e.g., road, gas grid) and environmental variables (e.g., water quality, soil vulnerability).

Second, the biogas system is designed based on the outcomes of the territorial analysis (Figure 1 b.). They are expressed as three types of indicators, i.e., i) the *function indicators* that specify the territory’s main interest for implementing a biogas plant —in other words, the main function that the system fulfils, ii) the *scenario indicators* that specify the relevant technical options for designing the biogas plant according to its main function and its surrounding environment, and iii) finally, the *geographical indicators* that specify suitable sites for setting up the biogas plant by combining restriction areas or areas of interest.

This approach can be embedded in the LCA methodology because it determines the functional unit of a biogas system from the analysis of its implementation territory and provides specific and territorial data for LCI (Figure

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1 c.). The goal and scope are thus defined in an objective way, i.e., the territory constraints and needs regarding the biogas plant implementation are addressed through the systemic approach, rather than presumed by the decision-makers as in conventional LCA. It provides a consistent picture of the territorial background to arouse the stakeholders' commitment in the project. Obviously, they are then expected to make the goal and scope more precise afterwards. In addition, specific implementation scenarios of a collective biogas plant within a given territory are defined. Then, a classical LCA can be performed (i.e., using site-generic LCIA) to compare the environmental performance of different contextualized scenarios.

Figure 1

2.1.2 Territorial LCA of type B: baseline of all production and consumption activities in a French Mediterranean case study

The territorial LCA framework of type B has been implemented in a French Mediterranean case study to provide a territory environmental baseline for 2010 (Loiseau et al., 2014). This case study has been chosen because of its diversity of human activities and the existence of an administrative unit in charge of elaborating territorial development strategies. All production (i.e., agriculture, fishing, industry, building, transport and storage, trade and services) and consumption activities (i.e., food, goods and services, transport, housing, waste and wastewater management) located in the studied area were considered. At the end, the results can be used to screen all territorial activities to identify hotspots and highlight where actions should be taken to reduce the overall territorial footprint. This assessment is thus dedicated to all stakeholders concerned with spatial planning in subnational territories such as decision-makers, citizens, firms, or public organizations. The territorial LCA framework could also be used to compare land planning scenarios defined by stakeholders based on eco-efficiency ratios.

2.2 Functional unit

In both case studies, the systems under study are multifunctional. Biogas facilities are multifunctional systems because they provide several services to the territory in which they are implemented. These services include i) the treatment of organic waste and effluents generated by agriculture, agribusiness or households within a given area, ii) the conversion of waste into renewable energy through biogas production, iii) the degradation of organic matter into a nutrient-rich residue (the digestate) generally used as a fertilizer, and iv) the export of the surplus nutrient from livestock out of the territory. Consequently, the main interest of a biogas plant can differ from one territory to another, and the system design should match this main function. To handle the multifunctionality issue, Laurent (2015) proposed a procedure to define the main function of the studied system in close relation to the territory where it is located. Different function indicators were quantified (i.e., waste management energy production, fertilizer production, and nutrient export) to highlight the studied territory needs and constraints. For instance, the function indicator *Waste Management (WM)* is assessed according to different criteria such as the fact that a treatment plant is already implemented in the studied territory, the transportation distances to the actual treatment plant and the territorial annual waste production. WM's score is expressed on a scale from -5 (there is no major need to implement a waste treatment plant within the territory) to 5 (the waste treatment plant implementation within the territory is a main issue) (Figure 2).

Figure 2

Every function indicator is expressed as a single score on a common scale to allow comparison. The one with the highest score reveals the main function that a biogas plant should provide for the studied territory. The functional unit is then defined, like in conventional LCA, but based on this main function.

The function indicators results showed that the needs of a collective biogas plant implementation vary depending on the territorial characteristics. Within the two selected territories, urban area is more concerned by waste recovery and local renewable energy, whereas agricultural area pays more attention to nutrient excess from livestock farming and the mineral fertilizer dependence. This study overtakes the classical environmental assessment of a biogas plant by suggesting that the LCA should fit into the system's surrounding environment in the first phase, beginning with the functional unit definition. In a conventional LCA, the functional unit of the studied system, i.e. biogas facilities, will be the same, whereas in type A territorial LCA, the functional unit of the same system will differ according to territorial characteristics.

In the territorial LCA framework of type B, the multifunctionality is handled differently. As no main function can be attributed to a given territory, the framework proposes to define a set of functions and associated indicators of service provided for the land planning scenario on the studied territory. In the given case study, the definition of the functions is based on the work of Pérez-soba et al. (2008). Three main land use functions are identified, i.e., economic, societal and environmental, and four quantified indicators of services provided are proposed to evaluate each of them (see Table 1).

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2.3 System description and boundaries

In the type A territorial LCA case study, the biogas plant must then be designed to fulfill the identified function in compliance with the territorial needs and constraints. The *scenario* and *geographical* indicators are related to the inputs, the processes and the outputs involved in the biogas plant for this purpose. For example, the scenario indicator *Heat Recovery* indicates whether the biogas can be efficiently used as heat, depending on the number and the type of entities consuming heat (e.g., swimming pool, industries) and their consumptions including seasonal variations. The geographical indicator *Heat Outlets* then indicates where to implement the plant to minimize heat losses by setting a maximum distance from each potential heat outlet. Both scenario and geographical indicators will be calculated and weighted so that the main function is maximized. At the end, the biogas plant is designed in an objective way, through the optimization of a set of parameters ruled by its main function. This results in that the boundaries for the coupled system/territory are iteratively sketched by the flows and processes of the studied activity.

In type B territorial LCA, the territory is understood as a black box whose shape is politically designed by spatial planning strategies. Then, the principle of total responsibility defined by Eder and Narodoslawsky (1999) was chosen for territorial responsibility. This means that the system boundaries include all production and consumption activities that take place in the studied territory and all upstream activities related to these activities, regardless of where they take place (inside or outside the studied territory). This principle involves that if the results of territorial LCA of type B in different territories are summed up there is a double counting issue. However, this choice is justified by the need to consider all activities that can contribute directly to environmental impacts on the territory.

In both approaches, the lifecycle perspective allows considering upstream processes that can take place all around the world to identify pollution transfers between territories. However, only downstream processes that are confined to the studied territories are considered as it assumes that other downstream processes are beyond the responsibility of the studied territory. On one hand, all activities that are confined to the studied territory define the territorial foreground system. On the other hand, upstream activities induced by the territorial foreground system and that occur outside the studied territory define the territorial background system (Loiseau et al., 2013). These definitions of foreground and background systems slightly differ from the ones in conventional LCAs as they do not directly refer to activities under the influence of territorial stakeholders.

2.4 Allocation rules

As described above, the important difference in functional unit and system definition between the two territorial LCA approaches will result in methodological differences in terms of allocation. In territorial LCA of type A, multifunctionality must be addressed to compare scenarios that provide the same services at the end. This multifunctionality is handled with system expansion or allocation rules as in business-as-usual LCA case studies while considering territorial characteristics.

In territorial LCA of type B, all production and consumptions activities are assessed with the quantification of a set of indicators of services provided by the territory as a whole (e.g., provision of jobs, housing of inhabitants, or wealth generation). There is no need for system expansion or allocation rules.

2.5 LCI and LCIA

In territorial LCA of type A case study, the territorial analysis provides territory-specific data to compute the LCI. First, real transportation distances are calculated using GIS, since all items are georeferenced. Second, the size and location of the arable land plot required to recover the amount of nutrients coming out of the biogas plant are defined using geographical analysis of national agricultural statistics on land occupation. Finally, as all items are georeferenced, it is possible to propagate the geographic coordinates in order to obtain a spatialized LCI. This would be useful then to apply site-specific LCIA methods.

In territorial LCA of type B, hybrid approaches are used to compute LCI for all production and consumption activities located in the territory. First, information on the types and the amounts of goods and services consumed or produced in the territory are collected in the form of monetary flows or physical flows. Second, these flows are then connected to an existing LCI database according to a bottom-up approach (i.e., process LCA) for physical flows or a top-down approach for monetary flows (i.e., environmental extended input–output LCA). The data on the types and amounts of goods and services directly produced or consumed in 2010 were collected from different sources (i.e., reports, surveys, statistics) at different scales (i.e., national, regional, local). This information was then connected to existing LCA databases (e.g., Ecoinvent or the US IO database (Suh, 2004)) to quantify environmental impacts. These different sources were also used to assess various services provided by the territory (see Table 1).

In both case studies, only site-generic LCIA methods were used to quantify all impacts. However, site-specific information and modeling should be used to assess the main contributing activities and identify the main environmental issues that are generated on the studied territory. This information could be based on GIS tools.

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2.6 Interpretation

Territorial LCA of type A provides comprehensive and specific environmental information that the decision-maker can use when implementing a project within its territory. If biogas plant LCAs have been disconnected from their geographical context, their results were difficult to use in a decision-making process as they could lead to inconsistent decisions because of a particular situation. For example, their environmental interest could appear limited on an energy-sufficient territory if the functional unit was based on the energy production. By developing a systemic approach to define the goal and scope of the study, the methodology ensures to obtain environmental results that will be appropriate for supporting decision-making in a specific territorial context. Maps can also be used to make the interpretation easier for the stakeholders.
Territorial LCA of type B provides a first estimate of the territory eco-efficiency in terms of the environmental impact associated with territory-driven activities. Although a compromise was reached between the data quality and the feasibility of the study, territorial LCA of type B was successful in determining the main environmental issues and impacting activities, and identifying the high pollution transfers towards other territories. For the latter, a particular emphasis is put on quantifying the share of direct and indirect impacts. Direct (in-site) impacts are directly induced by environmental flows that occur within the territorial boundaries. Indirect (off-site) impacts are due to environmental flows related to upstream processes and occurring beyond the territory border. At the end, territorial LCA of type B can be considered as an iterative approach, and once the first results are computed, more emphasis should be placed on the assessment of the identified hotspots.

3. Main issues and research needs

Both approaches aim at considering territory as a complex, multifunctional and evolutive system embedded in a geographical area, an organization of stakeholders and a development strategy. In the two approaches, a particular emphasis is placed on the material dimension of a territory as it can influence the four phases of territorial LCAs. However, the two illustrative case studies show that improvements must still be made to better integrate spatial variability in LCI and LCIA. Practical implementations can be simplified with the development of dedicated tools based, for instance, on GIS.
Currently, organizational and identity dimensions are less developed because they are only partially considered in the goal and scope definition phase and the LCI phase. However, they could provide interesting inputs for these two LCA phases, and more specifically for the handling of multifunctionality that is a core difference between territorial LCA approaches and conventional LCAs.
Besides, the socio-economic interactions between territorial activities and other territories are currently missing. Improvements in considering these multiscale issues could be made by adopting consequential modeling. All these issues are discussed below.

3.1 Toward a better consideration of material territorial dimension, including spatial variability in LCI and LCIA

Insofar as the foreground activities studied in the territorial approach are site specific, spatial differentiation and variability in LCI and LCIA are core issues.
Considering LCI, important efforts on data collection must be made to obtain representative inventories of territorial activities. Often, this phase is very time-consuming. However, new developments in the LCI database can be used to perform data collection more efficiently using more representative data. For instance, the new version of the Ecoinvent database provides now inventories at different scales—i.e., global, national and even regional[1]. These developments are required for supporting regionalization in LCIA.
This LCIA phase allows the translation of a set of inputs and outputs (raw materials and emissions, respectively) into potential environmental impacts through the use of characterization factors. During this phase, in conventional LCAs, all spatial (and temporal) information is lost. This can lead to poor correlation between the predicted potential environmental impacts and the expected occurrence of actual environmental impacts (Owens, 1997) (see appendix B for a brief summary of works on spatial variability in LCIA).
Currently, there is a consensus among the LCA community on the importance of considering spatial variability in LCIA (EC-JRC, 2010), especially in policy decision making (Blanc et al., 2012). However, an important question remains—i.e., how much should spatial differentiation be used in LCIA considering that LCA is a global and applicable environmental assessment methodology? Moreover, most conventional LCA practitioners lack accurate information about the location of most of the background activities associated with the studied product. The literature showed that despite the awareness of the need, few LCA studies include spatial differentiation. This is due primarily to a difficult and unsatisfactory implementation (Reap et al., 2008). Consequently, because of this lack of regionalized LCIA integration in existing software and databases, research

[1] http://www.ecoinvent.org/database/ecoinvent-version-3/ecoinvent-version-3.html

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on spatial differentiation in LCIA has thus focused on providing different operational models and characterization methods in accordance with the site-dependent approach (Potting and Hauschild, 2006). Thus, spatial differentiation in LCIA should at least be performed to better integrate spatial parameters that contribute the most to overall local and regional impact categories regarding spatial data availability (Potting, 2000).
The developed models are intrinsically consistent, but they are disconnected from the LCI and do not rely on spatialized (georeferenced) inventory data (Bare, 2010). The use of such characterization methods or models in LCIA without a spatial differentiation in LCI is thus questionable (Mutel and Hellweg, 2009).
At this stage of LCA development, more consistent integration of spatial characteristics through the whole LCA methodology is needed among the research priorities of LCA and should be continued, especially for territorial LCA approaches. Indeed, working at the territory level emphasizes the need to include local conditions in the decision-making process. This is facilitated by the knowledge of the location of all the activities that take place in the territory. A spatial differentiation should at least be considered for the territorial foreground activities. Practical implementations in both LCI and LCIA phases can be made easier with the use of GIS tools as described in the next section. The spatial differentiation is needed for territorial LCA at least for inventory. This spatial differentiation is a pre-requisite for spatial differentiation in LCIA. However, the LCIA spatial differentiation needs depend on the studied system type and the decision maker requirements but it obviously appears that it would be useful to complete the territorial LCA relevance for local decisions.

3.2 Toward a better integration of territorial organizational and identity dimensions to better define goal and scope and to improve LCI

Organizational and identity dimensions are important elements for territorial LCA approaches as they could provide interesting inputs for at least the two first LCA phases, i.e., goal and scope definition (e.g., the function unit definition) and the LCI of territorial activities. As discussed above, one first phase in territorial LCA approaches is to define the different functions of the studied territory. In the type B territorial LCA case study, this phase is based on existing literature. However, this preliminary approach could be strengthened. First, as discussed by Junqua et al. (2012), the definition of a set of territorial functions could also involve stakeholders. Besides, their contribution is also important to define their territorial project and the related spatial planning scenarios. Undertake participatory approaches in the first LCA phase could therefore improve the overall approach. Second, other scientific works could be used. Recent works in geography focus on the multifunctionality of rural areas and communities. For instance, Wilson (2010) assumed that multifunctionality is achieved when the environmental, social and economic capitals of communities are equally well developed. Indicators of well-developed capitals are even provided (e.g. pluriactivity for economic capital, availability of skills training and education for social capital or high level of biodiversity for environmental capital), and connections with indicator of services provided by a territory could be looked for.
Concerning the LCI phase, socio-economic inputs derived from the territorial organizational and identity dimensions are required in territorial LCA approach (both type A and B) to collect representative data and identify the impact drivers. Socio-economic drivers shape the key elements affecting the LCI of a given territory (e.g. influences on typology and quantity of certain emissions). This information may come from different sources, such as local and regional statistics, or sectorial information including in input output tables.
Moreover, future developments may entail considering socioeconomic aspects not only as inputs for environmental assessment or for territorial function quantification but as areas of potential impacts as in Social LCA (Benoit Norris, 2012; Macombe et al., 2013) or in Life Cycle Sustainability assessment (LCSA) (Guinée et al., 2011; Heijungs, 2010; Hoogmartens et al., 2014) approaches (see appendix C for more discussion on connections with LCSA and also organizational LCA).

3.3 Multiscale issues and the needs for consequential LCA

According to ILCD classification (EC-JRC, 2010), two main goals can be pursued in territorial LCAs: i) accounting, which focuses only on describing the system under study (e.g., territorial diagnosis), and ii) meso/macro-level decision support, which assesses the environmental impacts of spatial planning scenarios and their potential consequences.
Although there is a consensus that attributional LCA (ALCA) is appropriate for the accounting context, the case of meso/macro-level decision support is more complicated. To model the consequences of a decision, consequential LCA (CLCA) can appear more relevant. Developed in the 1990s, the CLCA approach aims at modeling cause–effect chains incurred by a decision in the economy (Ekvall and Weidema, 2004).
The choice between ALCA and CLCA approaches depends on the importance of the changes induced by a decision and the importance of the surrounding economic or political environment.
Based on these two criteria, Frischknecht and Stucki (2010) defined the “relative economic size of the object of investigation”. Applied to territories and spatial planning scenarios, the relative economic or political size of a

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Doi: 10.1016/j.jclepro.2017.12.169

decision is expressed by the amounts of goods and services produced or consumed that will be directly affected by a decision (in physical or monetary units) related to the total economic sectors or political entities.
For instance, a spatial planning scenario on a territory can be a decision to implement a biomass plant within its geographical boundaries. Depending on the size of the plant, this implementation can have important consequences on the regional or national supply chain of biomass. Similarly, if the plant is designed to produce huge amounts of energy, this can lead to important effects on the energy market.
According to Frischknecht and Stucki (2010), if the relative economic size of the decision (e.g., the amount of territorial biomass consumed divided by the total regional or national biomass consumed or the territorial energy produced divided by the total regional or national energy produced) is higher than 0.1%, then the potential consequences of the decision both within and outside the studied territory must be considered. Similarly, the ILCD handbook defined a threshold of 5% (EC-JRC, 2010).
Consequently, the decisions taken on a territory can have large potential environmental consequences on activities embedded within and outside the studied territory. This emphasizes the fact that microscale policies can potentially interact with macroscale policies. In this context, territorial LCAs should enlarge the scope of their study to consider these consequences and define the most appropriate method to identify and quantify them.
Different methods can be used to model these consequences and identify the affected activities to be considered in the system boundaries including an analysis of future-oriented scenarios (Camillis et al., 2013). However, these methods are not all adapted to all geographical scales. Figure 3 shows that the choice of the appropriate modeling tools depends on the geographical scale of the affected surrounding economic or political environment.

Figure 3

Among modeling tools, methods based on economic models and market mechanisms (Earles and Halog, 2011) such as general equilibrium models (i.e., modeling of the entire economy) are widely used. These methods are particularly suited for modeling consequences at continental or global scales. They are less appropriate for national or subnational scales because the behavior of economic agents within a nation are modeled in an excessively basic way (Vázquez-Rowe et al., 2013).
Consequences on national or subnational systems can be better modeled through partial equilibrium models (i.e., modeling of several markets disconnected from one another). Lesage et al. (2007) even used these types of models at a local scale in a spatial planning context to assess the consequences of brownfield rehabilitation in urban areas. In addition, economic models are not the only way to assess the consequences of a decision on the economy. Querini and Benetto (2015) recently developed an agent-based model to assess the effects of mobility policies at a subnational scale. This type of modeling could also be developed at a local scale. Finally, heuristic approaches have also been proposed by Weidema (2003) and Schmidt (2008) and could be appropriate for all geographic levels.
Moreover, some modeling tools could also be used to quantify certain economic or social aspects. For instance, general or partial equilibrium modeling can assess the value added within the territory or job creation. This information can then be used as the indicators of services provided by territory.

3.4 Integrating existing tools and methods

The analysis of territorial LCA principles and practices shows that this approach still must be deepened and broadened. The sections above show that different concepts and methods can be used in this sense and that territorial LCA could be combined to other tools to improve its interest and robustness. Table 2 gives an overview of these different tools according to the four LCA phases.

Table 2

A significant part focuses on tools that require stakeholders' involvement such as interviews, surveys, or consultations. This participation is particularly needed when procedures are missing such as when assessing land use functions or communicating results. Moreover, table 2 shows that specific tools can be useful for the whole approach such as GIS or simplified LCA software.
GIS could be applied to any LCA phase to increase the realism of the results brought by the inclusion of spatial information. In this section, we selected some examples of the most representative and complete applications to illustrate the use of GIS for territorial LCAs, highlighting the role of each LCA phase.
First, in goal and scope definition, as described in the case study section for territorial LCA of type A, Laurent (2015) developed a systemic approach that couples LCA and GIS to define the functional unit and the optimal scenarios and location of a biogas plant within a territory. Engelbrecht et al. (2014) used both GIS and remote sensing to determine farm locations and types within a specific territory before practicing LCA.
Second, thanks to GIS, Tessum et al. (2012) obtained a spatialized LCI of air pollutants from gasoline and ethanol production in the US. In contrast to usual inventories, this one is available as maps and could allow mapped results to be obtained after characterization.

Author-produced version of the article published in Journal of Cleaner Production, 2018, N°176, p. 474-485.
The original publication is available at
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Doi: 10.1016/j.jclepro.2017.12.169

Third, a recent EU project (LC-impact) focused on the calculation of spatially resolved characterization factors for LCIA, relying on GIS for calculation and visualization. A general discussion on the application of GIS is available in Mutel et al. (2012). Beyond more conventional impact categories, such as eutrophication or acidification, Sala et al. (2011) used GIS for assessing the appropriateness of spatial differentiation in toxicity-related impact categories. In their study, spatial aspects affect the emission, fate and effect of chemicals.
Fourth, as a perspective in interpretation, results can be given as maps: Padey (2013) proposed to map the optimal areas to implement photovoltaic systems. These areas depend on different local characteristics assessed through GIS and identified as important thanks to Global Sensitivity Analysis (GSA) on GHG emissions.
Even if its use tends to improve the LCA results, GIS involves increasing the volume of collected data, which is already an issue in LCA. Furthermore, it is currently impossible to draw conclusions about the added value of spatial differentiation in terms of result reliability because there seems to be a lack of comparative studies between spatialized LCA and results without it.
For now, it would be premature to speak about hard linking LCA and GIS software because their joint use has been only empirical thus far. Nonetheless, these tools are database oriented and use common programming languages. An operational coupling thus seems feasible.
However, some problems could appear. First, which solution should be chosen between implementing an LCA unit in the GIS framework or GIS calculations in the LCA software? Second, which tools should be used to implement such a model (freeware versus commercial software, which programming language, etc.)? This set of discussed elements is highlighted by Mutel et al. (2012). For example, Rodríguez et al. (2014) took the openLCA freeware as a basis to develop a coupling with GIS to include regionalization in agricultural LCA.
To conclude, GIS appears to be essential to develop territorial LCA. However, some bottlenecks still remain for the implementation, e.g., software hard linking, data collection, or map result interpretation.
All these tools, including GIS, could be integrated into a simplified LCA software or modeling tool that could be used directly by stakeholders and decision-makers to compare spatial planning scenarios. As proposed by Loubet et al. (2015; 2016), the LCI of a set of production and consumption activity components can be integrated in a modeling tool that can be used to design and compare spatial planning scenarios. In addition, these components could be tracked geographically to use spatial information and analysis for the different LCA phases.

4. Conclusions

Broader applications of LCA have recently emerged in the LCA community, opening the way to new LCA approaches (Guinée et al., 2011; Hellweg and Milà i Canals, 2014). Among them, territorial LCAs seem to offer a promising perspective. While remaining a global approach, territorial LCAs attempt to provide more appropriate indicators to stakeholders in charge of managing and developing their territories. At the subnational levels, authorities are increasingly encouraged by regulatory or voluntary measures to ensure that all their spatial plans are subject to an *ex-ante* environmental assessment. Thus, there is an increasing need for comprehensive tools such as territorial LCAs.
While still at an early stage of development, we consider it is important to propose now consistent definitions for the object of analysis, i.e., the territory, and the two main types of territorial LCAs, i.e., type A and type B. This is a first step towards practice harmonization.
On the one hand, we define territorial LCAs of type A which aim at assessing the environmental impacts of a specific activity or supply chain embedded in a given territory. On the other hand, we describe another type of approaches, territorial LCAs of type B, which consider all production and consumption activities located in a territory to quantify its eco-efficiency. Even if territorial contextualization in LCA case studies already exists in LCA applications, explicit mentions are often lacking in the literature as well as methodological guidance to include it in a consistent way. The case study illustrations emphasize that contextualization could be included in all LCA steps in both types of approach. Territorial specificities are hence important to consider from the goal and scope definition step. In both case studies, a particular emphasis is placed on the functional unit definition. In territorial LCA of type A, the three territorial dimensions need to be considered to determine the appropriate main function of the studied system. In territorial LCA of type B, no more functional unit is required. Instead, a set of land use functions need to be defined and quantified as for environmental impacts to provide at the end two kinds of outputs required to compute eco-efficiency ratios. Differences between the two types of territorial LCA approaches are less important in the other steps and territorial contextualization is required for both of them in the LCI, LCIA and interpretation steps. This includes the needs to consider spatial variability for computing representative inventories and taking into account local environment when assessing site-dependent impacts. Besides, important challenges remain to better consider territorial dimensions in all LCA steps.
One important challenge is to better consider the territorial material dimension. This challenge can be addressed by including more systematically territorial physical properties in LCI and LCIA. The use of GIS tools could support this development. The propagation of spatial information throughout the four LCA phases appears essential to carry out consistent territorial LCAs. Even if technical issues must be solved for an effective coupling between LCA and GIS software, the latter presents a real possibility to work with spatial information.

Author-produced version of the article published in Journal of Cleaner Production, 2018, N°176, p. 474-485.
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Doi: 10.1016/j.jclepro.2017.12.169

In addition, important issues regarding territorial organizational and identity dimensions should be addressed to increase the comprehensiveness of territorial LCAs. These dimensions should be considered when defining and assessing territorial functions, a key specificity of both territorial LCA approaches as mentioned above. The stakeholder involvement in this stage is of paramount importance. One last challenge is the multiscale issue. A territory is an open system that is embedded in other territories. Consequently, spatial planning strategies implemented within its borders can have significant effects on other territories. To perform a consistent assessment, these effects should be considered by adopting, for instance, a consequential modeling approach. The need for territorial economic models represents an important future research issue and should support the development of a robust methodology for territorial LCAs.
Finally, territorial LCA approaches should address different challenges to consider all territorial dimensions in a consistent way. A set of existing tools is currently available to deepen and broaden these approaches. In addition to these methodological developments, practical implementations in a wide range of case studies are also required to test and strengthen these approaches.

List of tables and figures

Appendices:

Appendices include the following detailed information: territorial LCA principles for both type (appendix A), brief summary of LCA works on spatial variability (appendix B) and connections of territorial LCA with other approaches, i.e., Life Cycle Sustainability Assessment (LCSA) and Organizational LCA (O-LCA) (appendix C).

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