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Analyzing the vulnerabilities and capabilities of wealth creation activities in the Maurienne valley in the French Alps

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Abstract

Alpine valleys constitute fragile environments and are very sensitive to environmental change. Current trends constitute major upheavals challenging these communities' adaptation abilities. Coupling quantitative modeling and qualitative social sciences analyses is necessary to provide insights on sources of vulnerability but such endeavors remain rare in the scientific literature. We present a metabolism-capabilities-vulnerabilities framework, which describes local communities and their environment as a network of wealth creation activities. We apply this framework to one of the main farming activities in the Alpine valley of Maurienne, the production of Beaufort cheese. We describe how stakeholders are involved in the supply chain and then quantify the economic and environmental aspects of the flows. We introduce the concept of 'territorial capabilities' to analyze the ability of stakeholders to cope with change through a reorientation of their activities. We highlight that while current environmental pressures do not seem to exceed local environmental limits, climate change is likely to be a source of future vulnerability. On the socio-economic side, the analysis points out the dependence on subsidies and the aging of the workforce as other potential threats to this activity. Conversely, the local cooperatives system appears to be the main asset in vulnerability reduction.

Keywords

Vulnerability; capabilities; metabolism; material and economic flow analysis; environmental assessment; adaptation; French Alps

1. Introduction

Global change challenges the sustainability of human activities in socio-ecological systems and several vulnerability frameworks have been devised to characterize them on this front. For example, Adger (2006) defines vulnerability as the susceptibility to harm from exposure to stresses associated with environmental and social change, and from the absence of adaptation capacity. Füssel (2007), on the other hand, characterizes vulnerabilities along four dimensions: the system of interest, the main attribute of concern (what is valued and threatened), the hazard or stress under scrutiny and the temporal reference (e.g., short or long term).

When applied to *territoires*¹ or local communities, these generic definitions and characterizations lead to two broad lines of analysis. The first one focuses on specific types of stresses or hazards. For instance, the vulnerability of mountain communities and mountain farming to climate change and natural hazards is often pointed out (Deléglise *et al*, 2019; Shukla *et al*, 2018; Birkmann *et al*, 2013; Fuchs, 2009). The second one, conversely, starts from the functioning of a *territoire* in order to identify potential sources of vulnerability. This second approach seems much less common, in spite of its usefulness for stakeholders. Wilson *et al* (2018), building on Emery and Flora (2006) and Kelly *et al.* (2015), argue that higher levels of development of the social, economic, cultural, political and environmental spheres of activity make communities less vulnerable. More generally, Sharifi (2016) conducted a review of community resilience tools, mostly targeted on urban areas. According to this author, though, current community resilience tools have failed to account for cross-scale or temporal dynamics and environmental dimensions.

Two research gaps in the vulnerability literature motivate this article. First, few studies have analyzed territorial vulnerabilities from a metabolic perspective, i.e., based on the study of material and/or energy flows (MFA). Bahers *et al* (2019) explicitly introduce the notion of metabolic vulnerability in the context of islands. While environmental vulnerability “*questions a society’s ability and preparedness to cope with brutal changes in its environment, metabolic vulnerability focuses on the effect of these perturbations on resource circulation, from extraction and production to end of life as wastes, between consumer areas and resource-supplying or waste-disposal areas*”². This point of view seems promising to provide a complementary perspective on vulnerability. Second, while the necessity to address sustainability issues in a transdisciplinary way is largely recognized, endeavors that explicitly take into account the role and interactions of local actors in flow circulation remain rare in metabolism studies (such as, e.g., Binder 2007a, or Dijst *et al* 2018). Conversely, *territoire* studies – focusing for instance on the relationship between value chains and territories (e.g., Muchnik *et al.*, 2008; Paus and Reviron, 2010; Fares *et al.*, 2012) – seldom address to a sufficient extent the environmental and biophysical dimensions of the systems analyzed (Madelrieux *et al.*, 2017).

In this article, we argue that coupled quantitative metabolic and qualitative territorial analyses lead to a better understanding of the coupled social, economic and ecological vulnerabilities of a *territoire*. Our goal is also to inform stakeholders on their *territoire* vulnerabilities, and point out relevant factors to enhance capabilities (Sen 1999), in order to effectively cope with related weaknesses. Our endeavor builds on previous work in territorial ecology (Buclet, 2021). This emerging field in France attempts to bridge the gap between social-ecological system (SES) studies

¹ A synthetic definition of a *territoire* is a delimited geographic area considered as a collectively constructed network of relations and as a shared living environment (Cunha 1988). The French concept of *territoire* reflects this meaning much more closely than the English “territory” does, and in this article, we usually keep the French wording to stress the distinction.

² Translation by the authors.

and *territoire* studies, the latter finding their origin in social geography. Territorial ecology is also related to the Vienna school of social ecology (Haberl *et al.*, 2016), with however more emphasis on stakeholders' roles and territorial dynamics.

The Maurienne valley in the French Alps was chosen as a case study. Alpine valleys constitute fragile environments, are very sensitive to environmental change (Fuchs 2009) and have undergone vast socioeconomic changes in the past decades (Zucca 2006), challenging these communities' adaptation capacities³. Our case study bears on a single activity, namely the Beaufort cheese production, with some focus on its relation to territorial dynamics and on trade with the rest of the world. This choice is motivated by the fact that agriculture in general and cheese production in particular is a structuring wealth creation activity in a number of Alpine valleys. This activity contributes to the territorial identity of the Maurienne valley and plays a decisive role in the maintenance of the valley landscape and the level of local employment (Buclet *et al* 2015). In other words, Beaufort production stands at the cross-road of the material, organizational, and identity dimensions of the *territoire*, in interdependence with other local activities. Therefore, focusing on this single value chain is not detrimental to a territorial perspective.

2. Conceptual approach

The cornerstone of the metabolism-capabilities-vulnerabilities (MCV) framework adopted here is to characterize a wealth creation activity (WCA) by its metabolism, encompassing both quantitative (material and energy flows, environmental pressures, monetary flows, infrastructures, land use, environmental assets) and qualitative dimensions (stakeholders' relationships and motivations/goals, cultural and institutional contexts). Some interactions with the rest of the world and with the other WCAs of the *territoire* are also considered. In this way, we are able to assess territorial capabilities (defined as the stakeholders' capacity to identify common goals and to meet them collectively, see section 3.2) and vulnerabilities (section 3.3). Finally, we qualitatively analyze the interactions between territorial capabilities and vulnerabilities: in what way do territorial capabilities enhance the *territoire* adaptive capacity and therefore reduce its vulnerabilities? Conversely, how can vulnerabilities undermine territorial capabilities?

Figure 1 illustrates the MCV framework and its conceptual connections. In this work, we do not analyze in detail all the elements listed in this figure; section 3 specifies the aspects specifically addressed in this paper.

In the following subsections, WCA, territorial resources and territorial capabilities are defined and discussed in turn.

³ In addition, an earlier collective study in the field of territorial ecology did focus on a typical touristic village of the Maurienne valley (Buclet *et al* 2015) and this same valley is currently the focus of a cross-disciplinary project (<https://trajectories.univ-grenoble-alpes.fr/en/>).

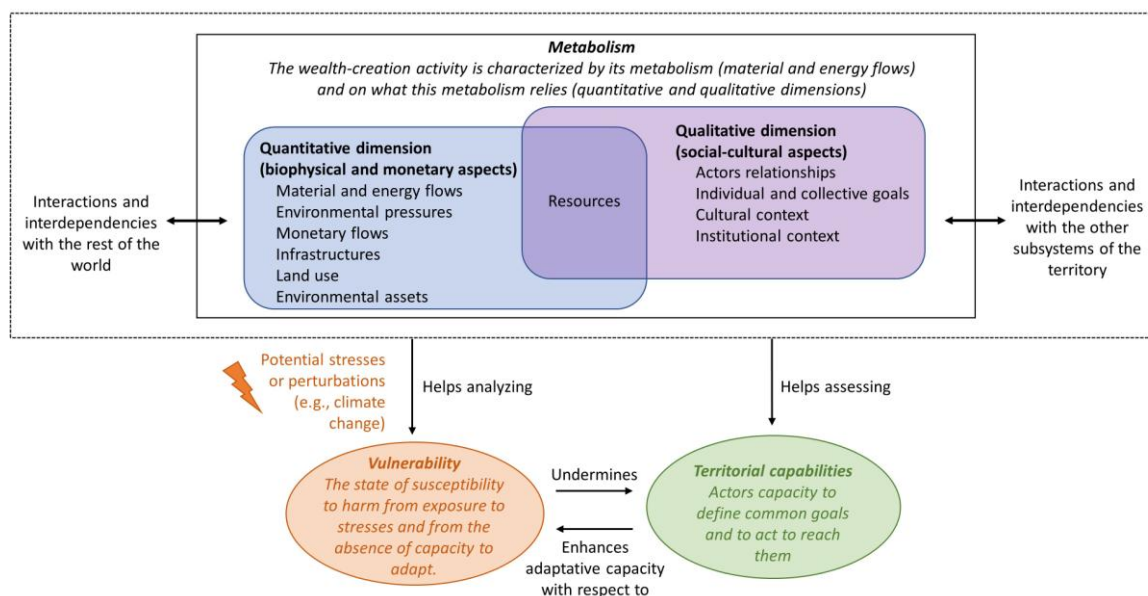


Figure 1: Concepts used in the metabolism-capabilities-vulnerabilities (MCV) framework, and their relations. A wealth-creation activity (WCA) is described from the point of view of its qualitative and quantitative bases, including its relations with other territorial WCAs and with the rest of the world. These material and social characteristics of WCAs are then used to analyze territorial capabilities and vulnerabilities, which are in dynamic interaction with one another.

2.1. Wealth creation activities and territorial resources

We rely on a framework describing a given *territoire* through its constituting wealth-creation activity subsystems (Buclet *et al.*, 2015). This approach relates dominant metabolic functions (material flows and stocks) to structuring activities, from material and socio-economic points of view. This approach also aims at integrating immaterial resources to material ones. These immaterial resources include, e.g., know-how, cultural assets, reputation..., and, coupled to material and financial resources, produce a clearer picture of the stakes and dynamics involved in material flows, as well as the role of the (local or distant) stakeholders involved in the process. Further details can be found in section A2 of the Electronic Supplementary Material (ESM).

The MCV framework enables us to take into account the multi-dimensional aspects of the concept of resources. This is especially true of territorial resources (Gumuchian and Pecqueur 2007), a specificity at the crossroad of geography and economics. From an economic point of view, territorial resources induce unrecoverable transaction costs (Colletis and Pecqueur 1993), i.e., these resources cannot be used in other contexts. This follows because, for example, they relate to the feeling of belonging to a place (Colletis and Pecqueur 2005), to a landscape (Peyrache-Gadeau and Perron 2010), to heritage (Landel and Sénil 2009), or to any other material or immaterial element valued for its local specificity. Territorial resources can be material or immaterial. Understanding material flows relies in an important way on the recognition of the role played by these fundamentally immaterial resources. In particular one needs to pay attention to the way they combine with material and financial resources, usually more generic. This combination is at the root of wealth-creation in any local subsystem. It leads us to grasp the characteristics of a sub-system in a territorial way, rather than in a sectorial way, as many of these territorial resources are necessary to several wealth-creation activities (Buclet, 2021). In this perspective, the dynamics of the *territoire* as a whole, with its specificities, explains

many aspects of each activity and conversely the analysis of these activities highlights the networks characterizing the territorial dynamic.

2.2. Territorial capabilities

The study of territorial capabilities is based on the concept of capability (Sen, 1999). As Kleine (2009) puts it: “in Sen’s approach, ‘functionings’ are the various things a person may value doing or being, such as being adequately nourished, being healthy and being able to take part in the life of a community. [...] a person’s ‘capability’ refers to the alternative combinations of functionings that are feasible for her/him to achieve. The focus of development, thus, becomes increasing a person’s capability set, or her/his substantive freedom, to lead the life she/he values”.

In the present work, we make use of a similar concept is at the level of a *territoire*, rather than at the level of individuals, and refer to *territorial* functionings instead. This variant is referred to as territorial capabilities (Buclet and Donsimoni, 2018), in order to focus on the potential of autonomy in deciding and acting at the territorial level. Beyond the capacity to anticipate and absorb disturbances or shocks of various sorts (Dauphiné and Provitolo, 2007), the learning and innovation capacities of the *territoire* and its ability to improve on its own inner workings play a crucial role to reduce vulnerabilities (Buclet and Donsimoni, 2018). The level of territorial autonomy of wealth-creation activities is an important piece of information to assess these capacities.

Hence, the notion of territorial capabilities refers to a form of collective capability (Evans 2002; Ibrahim 2006) existing in a specific *territoire*, depending on the local stakeholders’ ability to make use of their resources and to engage in a collective dynamics, in particular through the *territoire* (formal or informal) institutions and networks. Such territorial capabilities condition the local possibility of mastering future trajectories and of anticipating disturbances or major changes, while taking into account the specific objectives of local stakeholders. Finally, territorial capabilities also depend on the ecological sustainability of wealth-creation activities, in their local and external dimensions.

Relatedly, strategies aimed at enhancing the specificity of local productions tend to improve the capabilities of local stakeholders, due to increased profit margins (Pecqueur 2001); this helps increasing local autonomy and maintaining local activities, in particular in mountain areas (Janin *et al.* 2015). In the case of productive supply chains, changes in individual capabilities may affect the capability structure of the whole production supply chain, and vice versa. These points contribute to the ability of the *territoire* to control its own evolution, and allow stakeholders to anticipate events while taking into account local objectives.

2.3. Comparison with other frameworks

Several features of the MCV framework can be emphasized in relationship to other works. The ones selected here share several key aspects with the MCV structure and aims (for more details, see Table A1, ESM, itself inspired by the work of Binder *et al.*, 2013):

- it is compatible with other well-known frameworks in the fields of vulnerability, resilience or sustainability, namely Turner *et al.* (2003), Füssel (2007) and McGinnis and Ostrom (2014). Indeed, these frameworks provide grids of analysis but are not prescriptive in terms of methods to investigate each component.
- Contrary to social-metabolism studies (Haberl *et al.*, 2016) which can be deployed at all scales, it specifically targets local scales because it investigates the roles, motivations, and constraints of individuals and groups involved in the territorial metabolism.

- It is knowledge-oriented rather than action-oriented, even though the goal is *in fine* to facilitate action by making actors reflect on these analyses,
- It does not produce any ecological assessment (on ecosystems exposure or sensitivity to climate change etc.), but can however mobilize pre-existing ecological knowledge to highlight consequences of stresses or perturbations on flow circulation.
- As in Binder (2007b) and Binder et al (2004), it couples MFA with agent analysis describing the cultural, institutional and power-related factors enhancing or restricting options accessible to stakeholders. MCV however develops the notions of territorial capabilities and vulnerabilities.
- Many similarities also exist with Wilson et al. (2018), although these authors do not rely on a detailed analysis of the material functioning of the *territoire*.

3. Material and methods

3.1. Metabolism

Exploratory interviews and existing reports led us to reorganize the items of Fig. 1 for the purpose of our specific case study. Indeed, some items did not seem important to the understanding of the Beaufort WCA, and some could be grouped together, for instance, the institutional context is mentioned along with actors' relationships, and land use and environmental assets are mentioned in the MFA subsection. Little is said about infrastructures. The focus would be different for a different case study. The sources of qualitative and quantitative data used in our case study are detailed in table B1 (ESM).

3.1.1. Actors relationships

Ten interviews and eight non-participant observations of various stakeholders' meetings allowed us to draw a map of the interactions between the main groups (Stein and Barron, 2017). They also helped us to understand the organizational and institutional context of the Beaufort supply chain, as well as its stakeholders' motivations.

3.1.2. Material Flow Analysis

The interviews made it possible to identify existing reports providing data for the MFA (itself performed along the lines of Courtonne *et al.*, 2015): fodder production, imports and consumption, water for irrigation, use of mineral fertilizers and pesticides, production and sales of milk, cheese and other products. Details are presented in ESM, section C1, along with the references used to estimate livestock excreta, grazed biomass and water for animal watering.

3.1.3. Environmental pressures

The estimation of environmental pressures is performed by coupling material flows to Life Cycle Analysis (LCA) databases (ISO, 2006). The method used is straightforward (Courtonne *et al.*, 2016): we multiply a pressure intensity per unit mass (e.g., GHG emissions per liter of milk, from LCA) with a total volume or mass (e.g., total volume of milk produced per year).

We rely on the Agribalyse LCA database (Koch and Salou, 2016). This LCA database is devoted to French agricultural products and distinguishes a number of production techniques (e.g., organic or conventional farming) in various types of landscapes (e.g., plains or mid-mountain ranges). The database did not consider the alpine type of agriculture and cattle farming, but did analyze a very similar one for the production of "mountain milk" in mid-mountain Massif Central (the mountain range occupying the center of France). We have used these data as a starting point, updating them

whenever possible with relevant data directly collected in our study area (milk yield and fodder consumption). Three impact categories were then computed: Global warming potential (*ReCiPe Midpoint (H) V1.13, climate change, GWP100*), eutrophication potential (*CML 2001, eutrophication potential*) and acidification potential (*ReCiPe Midpoint (H) V1.13, terrestrial acidification, TAP100*).

Regarding water, we relied on existing reports and interviews to try to assess the extent of the pressure due to Beaufort production on local water resources.

Direct pressures are the ones generated by a process itself whereas indirect pressures are associated with process inputs. By definition, direct pressures occur on the *territoire* (except, in our case, for direct pressures from heifers overwintered outside the *territoire*). Indirect pressures can occur inside or outside the *territoire*. We make the hypothesis that indirect emissions associated with the following flows occur outside the *territoire*: imported fodder and feed, electricity, equipment, buildings. Conversely, we consider that the following flows generate intra-territorial pressures: local fodder and straw, heat, water. This distinction is useful to analyze not only local vulnerabilities but also vulnerability transfers.

3.1.4. Monetary flows

Monetary flows through the supply chain (Dahlström and Ekins, 2006) are estimated in two steps. Flows associated with milk production are estimated based on farms' loss and profit statements detailing the sources of income and areas of expenditures. In addition, we estimated income related to farmers' multi-activity. Flows associated with cooperatives are based on their annual reports. In a few cases, economic flows are estimated by multiplying mass with unit prices. Whenever possible we used the same classification as in the mass diagram. Details are provided in section C3 of ESM.

3.1.5. Potential stresses or perturbations

For this study, we decided to focus on internal (i.e. not exogenous) stresses or perturbations and on external stresses or perturbations that would specifically affect the WCA. For instance, we analyzed the potential impact of climate change through a literature review, because it is expected to have specific impacts on mountain agriculture, but we did not analyze the consequences of generalized economic shortages, as these would lead to impacts in all sectors of the economy.

3.2 Territorial capabilities

As defined above, this concept corresponds to the capacity of local actors to decide collectively the future of their *territoire* and to agree on the means to accomplish it, ensuring the sustainability of territorial activities. In this perspective, the authors analyze:

- The capacity of the actors of WCAs to control the decisions impacting their activity,
- The economic performance of WCAs and the capacity to seize territorial opportunities to generate more income,
- The environmental viability of WCAs and environmental pressures occurring on resources available to actors,
- The capacity of local actors to become aware of issues threatening WCAs and to engage in strategies to address them (such strategies can consist in reducing exposure, sensitivity and/or enhancing coping and adaptive capacities),
- The positive/neutral/negative effects of the studied WCA on the other WCAs of the *territoire* (and vice-versa) and their impact in terms of capabilities strengthening or weakening.

This analysis is performed on the Beaufort cheese WCA, both for its importance for the present case study and for illustration purposes.

3.3 Vulnerabilities

The identification of structural flows and structural elements of the Beaufort WCA follows from the territorial metabolism and its qualitative and quantitative dimensions (Fig. 1). These are considered either because one deals with high volume, and/or non-substitutable flows (e.g., certain production inputs), and/or impact-intensive flows, and because actors play a key role in these circulations.

The weaknesses of these structural flows/elements can be questioned: what exogenous events or conditions could harm them and to what extent? Interviews conducted with actors and a literature review provide elements of answer to this question, but this vulnerability analysis is by no means exhaustive. In particular, the authors attach more importance to understanding structural elements than to listing every possible source of perturbation that could harm them. Finally, as shown on Fig. 1, one has to analyze the interactions between capabilities and vulnerabilities. For instance, it is reasonable to expect that the actors' awareness of their vulnerabilities increases their capabilities and adaptive capacities, which in turn can reduce the overall vulnerability level.

4. Results from the Beaufort case study and discussion

4.1. The metabolism of the production chain in the Maurienne valley

4.1.1. Actors relationships

In order to understand better the interplay between metabolism quantitative analyses and stakeholders' capabilities, it is useful to first present a general picture of the various stakeholders types and relations in the context of the Beaufort cheese WCA. These are shown on Fig. 2.

Beaufort production was certified as a Protected Designation of Origin (PDO) in 1968. This label guarantees both the origin of the product and the quality of the production process, and is at the basis of the valorization of the Beaufort cheese as a territorial resource (Janin et al. 2015). The technical requirements for the PDO label concern cows' breeds (only two local alpine breeds are authorized), cows' nutrition (mainly based on fodder and grass, of which 75% at least must be locally produced), milk production (limited at 5000 kg/cow/year), and a strict adherence to traditional practices of milk processing and transformation (INAO, 2010).

Our interviews and observations allowed us to draw a clear picture of the Beaufort actors' network. Beaufort production in the Maurienne valley is structured around three cooperatives, each one collecting milk and making Beaufort cheese in its geographical sector. Furthermore, they supervise together milk by-products (whey and cream) and partake in the economic development of these by-products in a common production unit. Milk producers directly manage the Maurienne valley Beaufort cooperatives through an elected bureau and administrative council; they take part in the decision-making process of the cooperatives and in strategic choices. Representatives from each cooperative constitute the Federation for the protection of the Beaufort cheese; this structure defines production quotas for each cooperative (in order to adjust supply to demand) and is in charge of the commercial promotion of this production. The Union of Beaufort Producers ensures the conformity of the production to the technical requirements of the PDO label and performs inspections to this effect. It also offers optional technical advice to producers and cooperatives. The valley cooperatives have created dedicated structures for cheese direct sales and are in charge of negotiations with wholesalers. The Beaufort cheese is renowned, and the cooperatives have some edge in these negotiations.

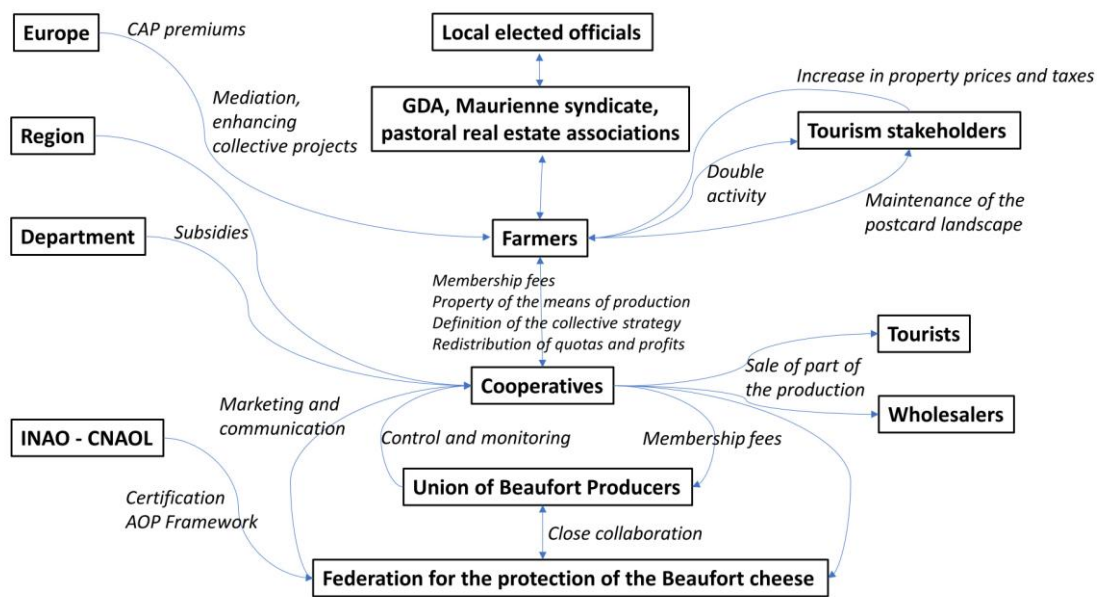


Figure 2. Stakeholders' network diagram, in relation to Beaufort production. NB: a "département" is a French administrative and territorial subdivision, associated with one or more local urban poles of attraction, and of typical extent of a few tens to a hundred kilometers.

Producers benefit from various subsidies, the largest share coming from the common agricultural policy of the European Union (Rivier, 2019). Producers are also members of the two *Groupements de Développement Agricole*⁴ of the Maurienne valley.

Agriculture and tourism strongly interact in the valley (Buclet *et al.*, 2015). Producers commonly have a seasonal job in ski resorts, and this constitutes a substantial source of income, contributing to the viability of the farming activity (Clavel, 2014; Schoch, 2014a; Schoch 2014b). Furthermore, cooperatives' managers emphasized that (i) sales to tourists represent a dominant fraction of all sale shares, through direct sales or wholesalers, and (ii) cattle farming in alpine pastures maintains the characteristic scenic mountainous landscapes of the alpine region, a major asset for tourism.

Finally, according to our interviews and non-participant observations, local stakeholders share a strong attachment to their way of life and aim at preserving farming in the valley.

4.1.2. Material Flow Analysis

MFA reveals that the supply chain is dependent on external resources (imported fodder, imported concentrated feeds, heifers overwintered outside the *territoire*), but that this dependence is limited. For instance, in addition to local grazing, nearly 80% of the fodder is grown locally (see Fig. C1a in ESM). Fodder land and summer and high altitude pasture land (*estive*) are therefore an environmental asset of the Beaufort cheese WCA.

Water flows are predominant, quantitatively speaking, and roughly equally divided between irrigation and livestock watering. One may therefore wish to evaluate the possible stress on local water resources exerted by this WCA, be it quantitatively through direct water use, or qualitatively

⁴ *Groupements de Développement Agricole* (GDA) are farmers' associations dedicated to mediation between agricultural activities and local jurisdictions; they center on local farming issues and foster collective projects in the Maurienne valley.

through eutrophication due to fertilizer use. On this last point, our estimation confirmed that mineral fertilization was very limited with a contribution of less than 20% of total nitrogen inputs of the activity (see section C1, ESM), which in itself is a fraction of organic standards (see next subsection). The other issues related to water use are addressed right below in the next subsection.

In addition to the diagram in real mass (C1a in ESM), a diagram in fat mass is drawn (C1b in ESM). Comparing the MFA in fat mass and monetary flows (section 4.1.4) shows that fat mass is a good proxy for economic value.

4.1.3. Environmental pressures

Direct GHG emissions associated to Beaufort production amount to ~10 kt CO₂ eq/yr (see table C2b in ESM). They represent one fourth of direct emissions of agriculture in the Maurienne valley (40 kt/yr, ORCAE, 2020). In comparison, industrial activities in the valley generate about 580 kt and transport about 110 kt/yr (ORCAE), underlining the importance of industrial activities in the *territoire* and the small relative responsibility of local agriculture regarding climate issues. To put these results into perspective, at the national level, agriculture represents 19% of total GHG emissions (Ministère de la transition écologique, 2021). Furthermore, Table C2b (ESM) contains a comparison between milk production in the Maurienne valley system and the French average. This indicates that, overall and unlike other cattle-based systems in France, the Beaufort supply chain will most likely be little affected by emission reduction strategies, even if the impact per kg of milk is about 30% larger than the French average (because of a lower productivity). Indeed, total emissions remain small because the system is very extensive per ha (66% lower than the French average), while creating economic and environmental value (maintenance of landscape and, indirectly, carbon sequestration, although not quantified here).

Turning to the eutrophication potential affecting local watersheds, the authors computed the nitrogen input on fodder-land through the spreading of manure and found a total of 42 kg N/ha/yr. Mineral fertilization amounts to about 8.5 kg/ha/yr (see section C1, ESM). The total of 50.5 kg/ha/yr is very low compared for instance, to the standards of organic farming (170 kg N/ha/yr). Thus, in general the supply chain does not seem to be a burden for water quality, but this may be the case in some specific areas. For instance, according to the water agency (Syndicat du Pays de Maurienne, 2020), about 25% of water bodies in the Arc river watershed, which corresponds to the study area, have their physico-chemical state degraded by ammonium, phosphorus or phosphates. A more detailed analysis would be necessary to determine if this is related to Beaufort production.

Regarding water quantitative balance, there is no indication that current water withdrawals occurring on the *territoire* threaten waterbodies: to our knowledge, no planning document exists to deal with such a problem (e.g., no study of withdrawable volumes, no zone of water allocation), meaning at least that the watershed was not considered a priority by the water agency for Rhône-Méditerranée-Corse. This does not necessarily mean that tensions on water use do not exist in some specific areas but the subject was not cited as an important issue during our interviews. For the Beaufort milk production in the valley, only a few tens of hectares of meadows and pastures located in “Haute-Maurienne” (upstream) are irrigated (see ESM, section C1), although irrigation networks are in extension (see also section 4.6.2).

Finally, it is interesting to quantify externalized pressures and to identify what they are associated to. Among total emissions, 17%, 26% and 28% occur outside the *territoire* respectively for GHG, eutrophication and acidification potentials. Hence, pressure externalization to other territories exists but is limited. It is mostly due to imports of concentrated feed.

4.1.4. Monetary Flows

Four salient features can be drawn from the economic Sankey diagram shown in Figure 3:

- Direct sales represent 28% of Beaufort mass but 34% of Beaufort income, confirming that the profit margin is higher in the absence of intermediates. One kilogram of Beaufort generates one third more income for the cooperative when sold directly.
- The direct involvement of farmers in cooperative management results in an efficient redistribution of income from cheese sales to the farm level, leading to a higher milk price with respect to the national average (RICA).
- This type of production is highly dependent on subsidies from the European Union agricultural policy – a generic feature of farming in France (RICA). Subsidies are quite important for cattle farming in open pastures⁵ in general and in mountain areas in particular.
- Income originating from winter jobs in ski stations may seem low compared to other flows but is in fact non-negligible if compared to the net income of farmers: the authors estimated that nearly 20% of multi-active farmers' income originates from winter jobs and about half of the farmers are multi-active (see ESM section C4 for estimation hypotheses).

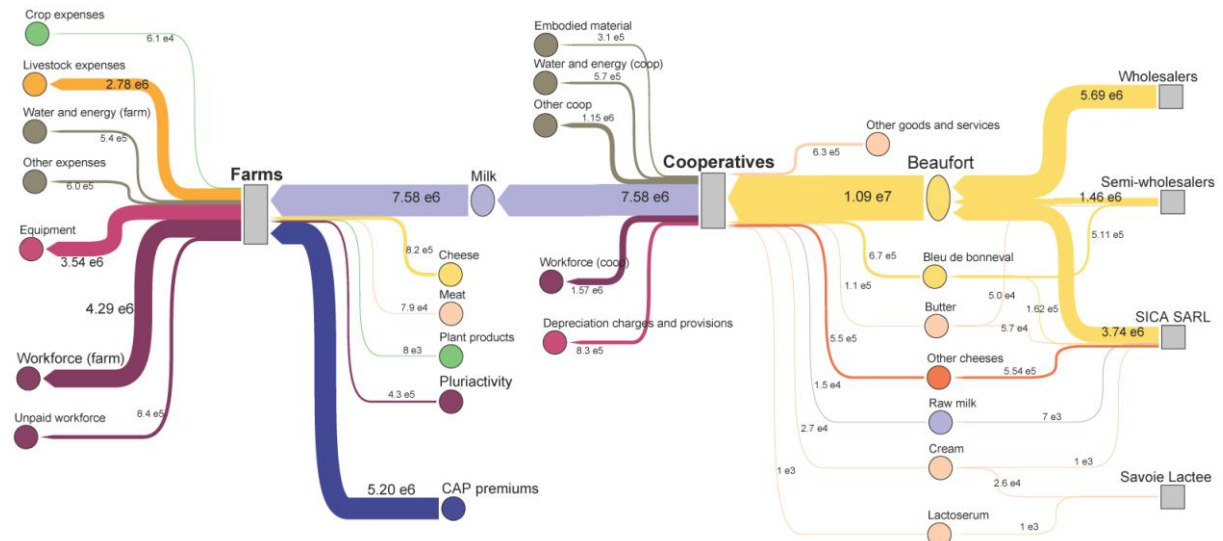


Figure 3: Economic flows for Beaufort cheese production in the Maurienne valley, in euros (€). Note that monetary flows are opposite to the material flows of Fig. C1a (see ESM). We use the scientific notation, e.g., $4.2 \text{ e}3 = 4.2 \times 10^3 = 4200$. Color code: yellow and dark orange = cheese; blue = raw milk; orange = other milk products; dark purple = workforce salaries; dark blue = subsidies.

In order to put these features into perspective, it is useful to keep the two following points in mind:

- In the Maurienne valley, about 90% of all collected milk is used for Beaufort cheese production (Chambre d'Agriculture de Savoie-Mont Blanc, 2011). This is much more than the national average, where about 10% of the milk production only is assigned to the making of PDO certified cheese. On average, the price of PDO cheese (more accurately the revenue per kg of cheese) is about 75% higher than non-PDO cheese (calculation by the authors based on CNAOL and Agreste data).

⁵ 50% for grazing livestock compared for instance with 32% for dairies (Matthews, 2019).

- In the Maurienne valley, one finds about 10 cows for 30 ha of pastures. The average production is ~3850 liters/cow/year. The national average is about 60 cows for about 70 ha of pasture for a production of ~6630 liters/cow/year (Centre national interprofessionnel de l'économie laitière, 2020). The lower production rate is due to the higher elevation and to the breeds of cows used for Beaufort production as well as to the PDO restrictions in their nutrition. However, this difference has little or no impact on farm income (comparison between RICA and Cerfrance data).

4.1.5. A potential stressor: climate change

According to Gobiet *et al* (2014): *“From the late 19th century to the end of the 20th century, Alpine temperatures have risen at a rate about twice as large as the northern-hemisphere average, amounting to a total annual mean temperature increase of about 2 °C”*. In the future, climate change is expected to be especially strong in the Alps (Calanca, 2007), impacting in particular the seasonal cycle of precipitation (less rainfall in the summer and more in winter) and temperature and precipitation extremes. Snow cover is expected to decrease drastically below 1500-2000m (Gobiet *et al*, 2014). These changes will affect summer mountain pastures in both the short and long term with high interannual variability in the forage supply (Deléglise *et al*, 2015 ; 2019).

According to GIDA Haute-Maurienne (2016), the Haute-Maurienne area has already experienced successive droughts since 2003, leading to deficits in soil moisture, which constitutes according to them *“the only serious limiting factor for fodder and grass production”*.

Hence, even if quantification remains difficult because of climate modelling uncertainties at local scales, an increased risk of consecutive bad production years does exist, with potentially severe consequences on the viability of a number of mountain farms. Furthermore, the likelihood of such events increases as climate change unfolds.

4.2. Territorial capabilities

The discussion presented here relies on the above analyses as well as selected material from stakeholders' interviews. The main objective is to illustrate the criteria presented in section 3.2.

The manager of one of the cooperatives emphasized that, thanks to the cooperative system, producers have a large say on their conditions of production and of sale of their products. This is an exception in French agriculture, rather than the rule. It is rooted in the specific Beaufort collective structure, which in turn enhances the sustainability of local agricultural practices (Lallau and Dumbi 2008)⁶. In this respect, Beaufort cheese producers have a better control over their own future than most farmers. Moreover, the balance of power is favorable to cooperatives regarding Beaufort sales as the demand for this reputed product is relatively important. Finally, according to Clavel 2014, Schoch 2014a, Schoch 2014b and Schoch 2015, a large fraction of farmers obtains additional income with winter jobs in ski stations. This constitutes a significant form of territorial opportunities.

Environmental pressures do not constitute a serious issue. Pressure externalization is limited (since only 17% to 28% of studied pressures are externalized, see 4.1.3) and mostly due to the external supply of concentrated feed.

⁶ Conversely, for “captive supply-chain production” (Ballet *et al*. 2008), producers are highly dependent on wholesalers whose leverage in negotiation is substantially stronger. Wholesalers can influence or even manipulate the supply-chain functioning and this represents a risk for producers' capabilities (Randrianasolo and Randrianasolo 2008).

Hydroelectricity production, primary industrial production, tourism and agriculture are the most important wealth-creation activities in the Maurienne valley, the first playing an important role for the others (Buclet *et al.*, 2015). These activities are all highly dependent on their local environment, making alpine valleys a prime example of socio-ecosystems in developed countries. Tourism benefits from agriculture thanks to the conservation of scenic open landscapes and from the image of quality products such as the Beaufort cheese. In turn, the Beaufort WCA benefits from winter tourism regarding winter jobs (see above) and regarding direct Beaufort sales, about three quarters of which occur during the winter or summer tourist season, according to our interviews with the three cooperatives.

4.3 Vulnerabilities

Based on sections 3.3 and 4.1, the following structural/flow elements are considered with respect to the vulnerability analysis performed here:

1. farmers (workforce) are structural elements of the WCA;
2. the current economic model of farmers relies a lot on subsidies (about half the annual revenue, Rivier 2019),
3. the PDO requires a large fraction of local fodder as winter feed; this fodder is produced on fields that are submitted to real estate pressure and depend on current climate conditions.

These structural flows/elements may be undermined in a number of ways:

(i) The farmers' average age is rather high (45 years, Clavel, 2014; Schoch 2014a; Schoch 2014b) and this population keeps aging, a common problem for agriculture throughout France (*Centre national interprofessionnel de l'économie laitière* 2020). According to the Chamber of Agriculture, farmers' retirement without takeover⁷ is expected to lead to a 14% reduction in milk production in the Maurienne valley within the next ten years. This would lead to a reduction of income on the remaining farms due to shared fixed charges, further weakening the viability of the whole production process (see Fig D1 in the ESM). The authors estimate that a 14% reduction in global milk production would lead to a 16% loss of income per farmer on average under the assumption of fixed Beaufort cheese price (but see point ii right next). The most vulnerable farms are expected to suffer even more from this abandonment.

(ii) If EU subsidies were reduced or suppressed, Beaufort cheese would need to sell up to 40% higher to compensate for the induced economic loss (calculation of the authors based on Rivier, 2019). This in turn could induce a lower demand for this type of cheese, a point partially mitigated by the fact that this type of cheese is bought by rather well off segments of the population. In any case, the loss of EU subsidies would affect the whole agri-food supply chain, making cheese price increase only relative.

(iii) Climate change may modify the local rainfall regime and lead to a decrease in fodder yields, as pointed out earlier. Quite clearly, local stakeholders have little influence on climate change and its consequences. The issue rests on identifying adaptation capacities, and some preventive action are required on this front. Deep changes in PDO requirements for Beaufort seem possible but unlikely. Some producers asked for a less constraining limit on local fodder, but INAO threatened to remove the PDO label of Beaufort cheese if this were the case. Producers will therefore be faced with either a reduction of their production – with potential detrimental consequences for the viability of the activity – or a compensation for the lower yields of alpine pastures and hay meadows through an

⁷ The hypothesis of a difficult transmission of the farms is justified by ageing equipment that is costly to upgrade and by hiring difficulties in this type of activity (already experienced today).

increase of farmed areas wherever possible (Perrin, 2012). On top on this, farmers are constrained by the real estate pressure due to tourism on fodder land (Schoch, 2011). The restoration or extension of existing irrigation networks in the Haute-Maurienne area is however already encouraged by relevant authorities, the objective being to ensure a minimum water allotment to high potential plots (non-participant observation during a general meeting of a GDA, 2018).

Vulnerabilities follow also from potential snowball effects and feedbacks loops. Climate change could potentially reduce snow cover in winter, and reduce local fodder production. If winter tourism cannot adapt and declines, this could translate in less income for some farmers who hold winter jobs in ski stations as well as in a decrease in direct Beaufort sales, half of which occur in winter. This will make farms more economically fragile and less capable to adapt to the constraint of lower fodder production. If a fraction of farms ceases its activity, negative consequences for the whole WCA described above ensue.

4.4 Interactions between capabilities and vulnerabilities

Territorial capabilities rely on social, economic and biophysical assets and could be undermined by any of the above sources of vulnerability. A possibly less obvious point is that vulnerabilities, if not addressed, could in the long run affect the representation actors have of the WCA. A reduced trust could trigger a domino effect, reducing in turn territorial capabilities.

According to an observation made during the 2017 general assembly of the *Federation for the protection of Beaufort cheese*, it seems that a few farmers under-valued the benefits of the cooperative system, because of its constraints, such as milk production quotas. Instead, they may consider selling their milk production to large milk companies in the future. This is potentially damaging, as cooperatives constitute the most powerful tool enhancing territorial capabilities (see section 4.2).

Local actors may become aware of vulnerability factors and engage in strategies to address them. Indeed, we have already outlined the important level of collective actions among Beaufort producers, through a panel of networks ensuring decent incomes, improvements in working conditions, and control on product quality and quantity. The main concern revolves around the possibility of maintaining these assets while facing upcoming changes – mostly climate change. The rules of INAO (the French national PDO institution) allow producers to import up to 50% of animal feeds (INAO, 2017), a possibility not fully exploited yet. However, in terms of territorial capabilities, such a dependence on the outside would be a vulnerability in itself.

Another option briefly mentioned above and considered in more detail here is to increase mountain pasture areas. Various factors have led to their reduction in the 20th century: difficulty of mechanized access, decrease of the population of farmers, reduced availability of hired work force.... Recent public policies in Switzerland (2014-2017) have slowed down this tendency through specific subsidies (Société d'Economie Alpestre de la Haute Savoie, 2019). Such collective actions supported by public policies are probably the best way to fight agricultural abandonment or even increase the surfaces devoted to mountain pastures. Furthermore, mountain pasture landscapes have value beyond cheese production and this may provide a useful asset in collective discussions, in conjunction with concerns about large-scale reforestation of pasture areas (a factor reducing landscape beauty and attraction for tourism) and the protection of biodiversity. This relates to NCP approaches (Nature Contribution to People, Diaz *et al* 2018)⁸. Integrated management plans (*plans de gestion intégrée* or PGI), in relation with local pastoral real estate associations, aim at a better

⁸ See in particular Grosinger *et al* in this special issue.

coordination of all involved actors for the promotion of mixed forest/pasture units in mountain areas (Société d'Economie Alpestre de la Haute Savoie, 2019).

The value of local resources may therefore increase territorial capabilities through summer tourism, seen as a potential way to balance the future loss of winter tourism. This may enable a socio-ecological transition, by promoting forms of tourism more adapted to global change. This also constitutes an argument for changing the basis of attribution of EU agricultural policy subsidies, but negotiations in this direction have not yet been successful.

These various leads are typical of collective actions, in line with our definition of territorial capabilities – i.e., a geographically anchored collective capability. The most important asset in this respect resides in production cooperatives and their network of connections with one another and with the various local organizations in charge of the promotion of the cheese production activity. These include the Federation of protection of the Beaufort cheese, the Union of Beaufort Producers, local pastoral real estate associations, and the Maurienne Syndicate (an institution in charge of a coherent territorial project for the whole valley). The territorial specificity of this form of collective capability follows from the rooting of these structures in local resources and practices but also, as pointed out, from the synergies between human activities and local ecological conditions.

5. Conclusion

In this article, the MCV framework (metabolism-capabilities-vulnerabilities) was introduced and applied to the case of the Beaufort cheese production in the Maurienne valley, in the French Alps.

Our territorial metabolism analysis, focused on wealth-creation activities (cheese production for the most part), allowed us to relate purely material and environmental stakes to socio-economic ones. In other words, this enabled us to look at the *territoire* as an actual socio-ecosystem. We recall here the definition of a *territoire* as a network of stakeholders' interactions anchored in a specific area, constituting a shared living space. Attributing capabilities to the *territoire* itself gives it the status of an actor in constant interaction with its environment. In this way, we were able to pinpoint a number of territorial capabilities. Our aim was not to identify these capabilities in a systematic way but to point out their systemic articulations, such as the contribution of farming to tourism through the co-production of landscape, which in turn supports Beaufort cheese sales, as tourists buy about half of the production. In particular, with respect to vulnerabilities potentially produced by climate change, the authors argued that collective capabilities are mutually reinforcing and rooted in collective actions.

From an empirical point of view, several points must be emphasized. While the Beaufort context is common to other mountain areas, the conclusions drawn in this work cannot be replicated without further investigation. Pre-existing information was abundant for the Maurienne valley cheese production activity, and reproducing the present study on other territories would be more time-consuming, or even incomplete if some information remains confidential (e.g., monetary flows). One could imagine instead to conduct the study in a more participative way following Sharifi (2016) who argued that stakeholders' implication is an important part of the learning process. Regarding environmental pressures, it would be interesting to assess the level of carbon sequestration provided by the Beaufort cheese WCA (wealth-creation activity) to compare it with greenhouse gas emissions; similarly, a more precise knowledge on water qualitative and quantitative issues in the *territoire* would be useful. Finally, similar analyses should be conducted on the other structuring activities of the Maurienne valley.

From a conceptual point of view, this work is an attempt to contribute to vulnerability and territorial metabolism/ecology studies. The authors believe that approaching vulnerability through the lens of a WCA's metabolism is promising. First, analyzing territorial economies in subsystems (WCA) is a way to overcome their complexity while retaining their interactions. Second, the framework helps focusing on the relations between the WCA material basis, the network of actors involved, and the social-economic-cultural context.

Further research would help to design more precise criteria in order to identify and classify the structural elements of a WCA, and to study the possible territorial strategies to address vulnerabilities and their relations to territorial capabilities. A deeper analysis of the power relations between actors would be helpful for this purpose. Some of the frameworks discussed in Section A1 (ESM) may be used to this effect.

Although our study was conducted before the covid-19 pandemic, this unexpected and continuing crisis confirms the interest of such analyses. Indeed, this crisis has seriously damaged the winter tourist season, with (focusing on the present work) foreseeable consequences on many interconnected mountain activities.

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Regional Environmental Change

Supplementary Material to:

Analyzing material flows to characterize the vulnerability and capabilities of wealth creation activities in the French Alps Maurienne valley

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A1. Framework description and comparison.

			Comparison with the MCV approach (Metabolism analysis for territorial Capabilities and Vulnerabilities analyses)	
Approach	Literature references	Description	Similarities	Differences
Turner's and Füssel's vulnerability frameworks	Turner <i>et al.</i> (2003), Füssel (2007)	<p>Turner: Vulnerability of social-ecological systems characterized by their exposure, sensitivity, resilience (in the sense of coping and adaptive capacities) to perturbations. All elements are in dynamic interactions with the outside world (human and environmental influences).</p> <p>Füssel: Definition of a vulnerable situation through: (i) system of analysis, (ii) attribute of concern, (iii) stressor or hazard, (iv) temporal reference. Vulnerability factors characterized according to two spheres (internal/external) and two domains (socioeconomic/biophysical). Compatible with Turner's framework: '<i>Internal socioeconomic vulnerability</i>' corresponds to '<i>resilience</i>', '<i>internal biophysical vulnerability</i>' corresponds to '<i>sensitivity</i>', '<i>external socioeconomic vulnerability</i>' corresponds to '<i>human conditions/ influences</i>', and '<i>external biophysical vulnerability</i>' corresponds to '<i>environmental conditions/influences</i>'. (Füssel, 2007)</p>	<p>Territorial metabolism analysis indirectly informs on: (i) exposure and sensitivity to perturbations (are essential social or material components of the value chain threatened?), (ii) internal and external environmental sustainability (mid-to-long term vulnerabilities through feedback loops).</p> <p>Studying territorial capabilities implies an analysis of what is valued by the stakeholders (attributes of concern) and of their dependencies to the outside world.</p> <p>Capabilities enhance adaptive capacity by broadening the solution space of actors.</p>	<p>These are upper-level (meta) frameworks in the sense that different methodologies can be applied to assess each component, including but not limited to MCV.</p> <p>These vulnerability frameworks are action-oriented and generally used to analyze the vulnerability of a system to a particular perturbation (in particular climate change) and to identify ways to reduce it. MCV works the other way around (from system analysis to identification of potential vulnerabilities) and is knowledge-oriented.</p>

			Comparison with the MCV approach (Metabolism analysis for territorial Capabilities and Vulnerabilities analyses)	
Approach	Literature references	Description	Similarities	Differences
Diagnosis of Summer mountain pasture's vulnerability to climate change, developed in the French Alps	Deléglise <i>et al</i> (2019)	Transdisciplinary, 3-step vulnerability analysis: inherent exposure of mountain pastures to climatic hazards based on their physical features, vegetation sensitivity to climatic hazards and changes in practices, adaptive capacities (options for managing mountain pastures, both short-term adjustments and long-term structural adaptations).	<p>Key topic for our case study of Beaufort cheese production in the Maurienne valley.</p> <p>The analysis of the adaptive capacity makes use of quantitative and qualitative information and tackles the complex interactions between stakeholders groups and with the environment.</p>	<p>MCV does not produce any ecological assessment (e.g., on ecosystems exposure or sensitivity to climate change). It can however use such knowledge as inputs and analyze it as a perturbation of the social-ecological system under study (for instance, reflect on the sensitivity of the Beaufort value chain to local fodder production decrease).</p> <p>MCV is not only focused on climate change vulnerability.</p>

			Comparison with the MCV approach (Metabolism analysis for territorial Capabilities and Vulnerabilities analyses)	
Approach	Literature references	Description	Similarities	Differences
Sustainable Livelihood Approach (SLA)	Morse and McNamara (2013)	Individuals own or have access to a portfolio of capitals (human, natural, financial, physical, social), their "livelihood assets", with which they negotiate policies, institutions and processes. They operate within a "vulnerability context" and develop livelihood strategies, which then result in livelihood outcomes. (Kleine 2010)	<p>Both approaches draw on people's potentials and strengths and how they are converted into positive outcomes.</p> <p>Social, economic and environmental aspects are analyzed.</p>	<p>SLA has been developed to study the livelihoods of the poor and is action-oriented.</p> <p>In SLA, the term "capability" is used interchangeably with "assets" or "capital" and is reduced to the ability to acquire resources. Development goals are predetermined (generate more income) in contradiction with Sen's thinking. (Frediani, 2010)</p> <p>In SLA, vulnerability is rather a context than an outcome of the analysis. No direct reference to material and energy flows and to their environmental impacts.</p>

			Comparison with the MCV approach (Metabolism analysis for territorial Capabilities and Vulnerabilities analyses)	
Approach	Literature references	Description	Similarities	Differences
Community resilience assessment (CRA)	Wilson <i>et al</i> (2018), Kelly <i>et al</i> (2015)	CRA assumes that communities are less vulnerable when the social, economic, cultural, political and environmental spheres of activity are more highly structured. Each domain is analyzed according to a set of objective and subjective factors and is assigned a vulnerability score (strong, moderate, weak resilience) which help forming an opinion on the global vulnerability of the community.	<p>Multi-dimensional approaches.</p> <p>Although CRA does not explicitly rely on the concept of territorial capability, practical implementations can result in similar analyses. For instance, according to Wilson <i>et al</i> (2018), "<i>Vent is currently in a weak position to take control over its own development trajectories, and at times of shocks/disturbances the community has to rely largely on external institutions for help, all resulting in self-reinforcing cycles of political weakness</i>".</p> <p>The case study of Vent, a community in the alpine area, by Wilson <i>et al</i> (2018) shares many common features with ours.</p>	<p>In CRA, vulnerability is understood as the antithesis of resilience while MCV uses Turner's and Füssel's definitions where resilience is only one aspect of vulnerability (see above).</p> <p>CRA assesses the vulnerability of communities for each of the five domains separately. MCV divides the territorial system in subsystems of wealth creation and the vulnerabilities of each subsystem emerge from the interaction between the five domains, analyzed through the lenses of metabolism and territorial capabilities.</p> <p>CRA studies appear to develop qualitative rather than quantitative knowledge.</p>

			Comparison with the MCV approach (Metabolism analysis for territorial Capabilities and Vulnerabilities analyses)	
Approach	Literature references	Description	Similarities	Differences
Vienna school of Social metabolism (SM)	Haberl <i>et al</i> (2016)	Human (social) and natural systems coevolve over time and have substantial impacts upon one another. Social metabolism offers a conceptual approach to society-nature coevolution (historical perspective, current development processes and possibilities for future sustainability transitions). Material and energy flows as well as land use link societies with the natural environment. They enable the reproduction of societies' biophysical basis.	<p>SM provides a macroscopic description of the dynamic part (biophysical flows) of societies' biophysical basis (biophysical flows and stocks).</p> <p>For this purpose, MEFA, is a central methodology.</p>	<p>Regarding social aspects, SM focuses on macro-sociology (e.g., demographic, lifestyle trends...). Contrary to MCV, the roles, powers, motivations, constraints of individuals and groups behind metabolism are not investigated.</p> <p>In relation to the above, SM is more quantitative-oriented than MCV.</p> <p>SM does not aim at facilitating action, while MCV is concerned with developing operational knowledge.</p> <p>Unlike SM, which can be applied at local or global scales, MCV is mostly suited to local scales.</p> <p>The analysis of metabolism evolution over time is at the core of SM. While insightful, it is not a critical element of MCV. However, history is important to understand current relationships between actors.</p> <p>Vulnerability is not the focus of SM, even if it objectifies unsustainable trends.</p>

			Comparison with the MCV approach (Metabolism analysis for territorial Capabilities and Vulnerabilities analyses)	
Approach	Literature references	Description	Similarities	Differences
Social-Ecological Systems Framework (SESF)	McGinnis and Ostrom (2014)	A multitier vocabulary is proposed (resource units, resource systems, governance systems, actors, interactions and outcomes, social-economic-political settings, related ecosystems) to describe SES, allowing comparing case studies and theories. It originates from theories like collective choice, common-pool resources, and natural resource management, and has been applied mainly in the area of forests, pastures, fisheries and water management.	Variables described in SESF are relevant to MCV.	SESF is a meta-framework in the sense that it provides a way to organize knowledge about SES and suggests items to investigate but it does not say how this knowledge should be acquired.

			Comparison with the MCV approach (Metabolism analysis for territorial Capabilities and Vulnerabilities analyses)	
Approach	Literature references	Description	Similarities	Differences
Human-Environment Systems Framework (HES)	Scholz and Binder (2011)	<p>HES is used to explore environmental problems related to human activities. It provides guidelines for the description of the structure of human systems and associated environmental systems, as well as for the description of the processes and interactions involved. Interactions occur between components and between nested levels (eg., individuals/groups/society) which have different rationales.</p> <p>HES distinguishes the complementarity between a human system and its environment (which are two exclusive entities) from the complementarity between the material and social dimensions of a system (which are two perspectives to look at the same entity). In HES, both human systems and environmental systems have a material and a social dimension.</p> <p><i>"The human individual is defined by all its living cells and their (inter-)activities. [...] The definition of human systems above the individual is based on the activities of the individuals that can be assigned to this system" (Scholtz et al, 2011).</i> The environment of a human system is the rest of the world (natural but also technological and human environment, e.g., other human beings and social groups) minus what is irrelevant to the human system and to the studied question.</p>	<p>HES and MCV are knowledge-oriented; knowledge can arise from scientific studies and from meetings with stakeholders. The goal is <i>in fine</i> to facilitate action by making actors reflect on these analyses.</p> <p>In HES, MFA is encouraged to conceptualize the material part of environmental systems.</p> <p>Feedback loops between components are analyzed.</p>	<p>The social part of HES is based on decision-making theory (problem, objective, possible strategies, choice) whereas MCV makes use of the (territorial) capability theory to analyze the actors and socio-cultural factors behind the studied metabolism.</p> <p>HES explores potential consequences from current or future decisions taken by human systems thanks to the analysis of the structure and processes of the environment. MCV describes how a subsystem of wealth creation works from its material and social bases, and analyzes potential sources of disturbance.</p> <p>Several notions are explicit in HES and implicit in MCV: short vs. long run feedbacks, sustainability learning and environmental awareness, nested levels of social structures interacting with one another.</p>

			Comparison with the MCV approach (Metabolism analysis for territorial Capabilities and Vulnerabilities analyses)	
Approach	Literature references	Description	Similarities	Differences
Material Flow Analysis coupled with Structural Agent Analysis (MFA-SSA)	Binder <i>et al</i> (2007b)	MFA-SSA is an endeavor to transition from material flow analysis to material flow management. For this, MFA is coupled with SSA, which provides an understanding of the social structures restricting or enabling strategies for managing material flows.	<p>In both MCV and MFA-SSA, actors' actions derive from external factors (social structure and environmental constraints or opportunities) and internal motivations.</p> <p>MFA is central in both cases.</p> <p>SSA is based on Giddens structuration theory in which the social structure is described through rules (moral or cultural context, implicit or explicit regulations) and resources allowing domination of some actors over others (authoritative power, economic power). These dimensions are also explored in MCV although not structured as such.</p>	<p>MFA-SSA is more action-oriented than MCV as it is designed as a problem solving strategy for situations where <i>"several agents with different interests and planning horizons are involved and a combination of strategies is required for achieving the envisioned goals"</i>. (Binder <i>et al</i>, 2007b).</p> <p>SSA provides detailed analysis of stakeholder's groups (power, motivations, constraints, options), and it also analyses how groups interfere. However there is no explicit reference to territorial capabilities, that is the groups' ability to define common goals and ways to develop collective action to achieve them.</p> <p>Vulnerability is not the focus of MFA-SSA.</p> <p>MFA-SSA as such does not study environmental pressures or economic flows, although these features can easily be added.</p>

Table A1 : comparison of the MCV approach developed in this article and other frameworks originating from the fields of vulnerability and sustainability.

A2. Wealth-creation activity: framework short description

A wealth-creation activity presupposes that some resources are used. The use of these resources produces input flows entering the wealth-creation subsystem under consideration, and output flows resulting from the specific operations characterizing this subsystem. Resources are either available within the considered territory, or obtained outside its boundaries; similarly, the production of the subsystem may or not stay within the territory, in particular, when they constitute inputs for other subsystems. The subsystem production creates back-reactions on the resources themselves, with positive or negative effects on the quantity or quality of available resources. Such back-reactions may be voluntary or undesired, as for GHG emissions, for example. We address the material parts of these flows, as well as associated economic flows and environmental issues, in a quantitative way through material flow analysis (MFA) and its various extensions in the next section for a specific subsystem in the Maurienne Valley (Beaufort cheese production).

In practice, this framework can be graphically represented in the following way (after Buclet *et al*, 2015).

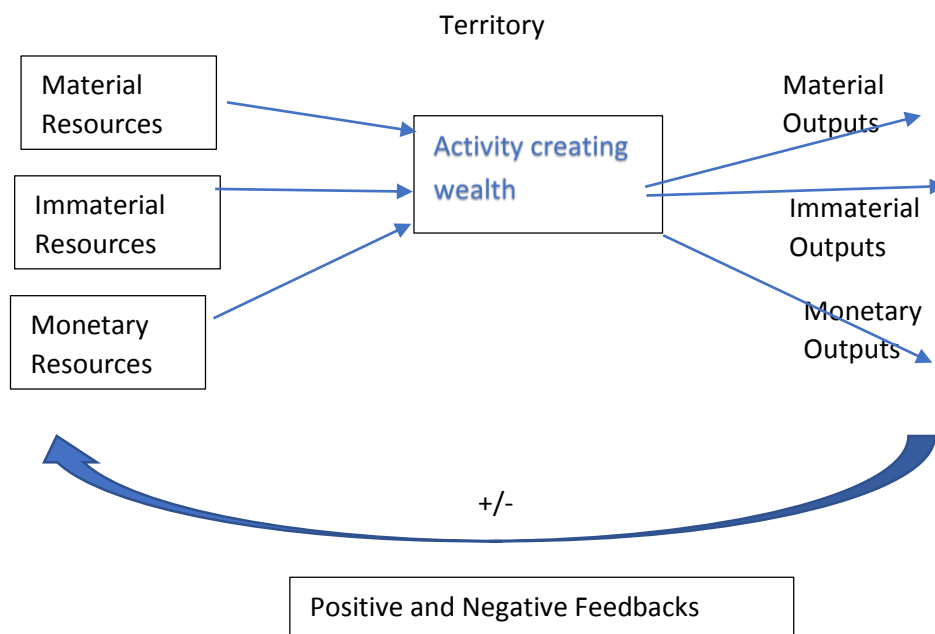


Figure A2: generalized metabolic representation of a wealth-creation activity.

More information can be found in Buclet (2021).

B1. Data sources

Data type	Data analysis		Data source	Data collection method
Quantitative	Material flow analysis	Farm level	<ul style="list-style-type: none"> - Federation for the protection of the Beaufort cheese - Chamber of Agriculture of Savoy - Eleveurs des Savoie - Société d'Économie Alpestre 	<ul style="list-style-type: none"> - Semi-structured interviews - Analysis of available reports - Analysis of technical requirements of the production of Beaufort cheese
		Cooperative level	Cooperatives of the Maurienne Valley	<ul style="list-style-type: none"> - Non-participant observation during general meetings - Analysis of annual reports
	Economic flow analysis	Farm level	Cerfrance	Analysis of the loss and profits statements
		Cooperative level	Cooperatives of the Maurienne Valley	<ul style="list-style-type: none"> - Non-participant observation during general meetings - Analysis of annual reports
	Life-Cycle Analysis	Farm level	Agribalyse	Analysis of the LCA database concerning milk production in French mountainous areas; adaptation of coefficients based on local knowledge (e.g., number of liters of milk per cow)
Qualitative	Stakeholder interplay	Territorial level	<ul style="list-style-type: none"> - Federation for the protection of the Beaufort cheese - Chamber of Agriculture of Savoy - Cooperatives of the Maurienne Valley - Ceraq - Société d'Économie Alpestre - Groupement de développement Agricole (GDA) 	<ul style="list-style-type: none"> - Semi-structured interviews - Non-participant observation during general meetings
	Analysis of territorial capabilities			
	Analysis of territorial vulnerabilities			

Table B1: Quantitative and qualitative methods used in the case study and associated data sources (additional details are provided for MFA et LCA calculation in sections C2 and C3).

In total, 8 non-participant observations and 10 interviews were conducted. The questions addressed during the interviews dealt with the general functioning of the value chain, relationships between stakeholders, perceived difficulties, and quantitative aspects to perform the MFA. This relatively small number of interviews is justified by the fact that many reports already existed on the Beaufort chain. Below is the list of the reports we used.

Reports describing the main features of farms producing milk for the Beaufort cooperative structures of the Maurienne Valley, their vulnerabilities (durability, land property, building renewal) and future perspectives:

- Schoch, M. (2014a). Étude prospective Coopérative des Arves - État des lieux, Chambre d'Agriculture Savoie-Mont Blanc
- Schoch, M. (2014b). Étude prospective Coopérative de La Chambre - État des lieux, Chambre d'Agriculture Savoie-Mont Blanc
- Clavel, C. (2014). Étude prospective Coopérative de Haute Maurienne-Vanoise - État des lieux, Chambre d'Agriculture Savoie-Mont Blanc

Report describing the agricultural sector in the Maurienne Valley, the main features of different agricultural productions, their vulnerabilities and future perspectives:

- Schoch, M. (2015). Intégrer l'agriculture dans le projet de Schéma de Cohérence Territoriale du Pays de Maurienne, Chambre d'Agriculture Savoie-Mont Blanc

Report describing herd size and their hay requirements in comparison with the productivity of forage areas in the Maurienne Valley, with leads to improve feed autonomy in the valley:

- Perrin, F. (2012). L'autonomie fourragère hivernale en zone Beaufort - État des lieux des besoins et des ressources en foin. Réflexions sur l'amélioration de l'autonomie fourragère hivernale, Chambre d'Agriculture Savoie-Mont Blanc

Reports dealing with annual physical and financial statements of Beaufort cooperative structures:

- Annual reports of Beaufort cooperative structures

PDO technical requirement of milk and Beaufort production:

- Ministère de l'agriculture, de l'agroalimentaire et de la forêt, (2015). Cahier des charges de l'appellation d'origine "Beaufort"⁹

C1. Sankey diagrams for material flow analysis of the Beaufort supply-chain

Perimeter of the MFA:

	Included	Excluded
Inputs for fodder and milk production	Water (for livestock, for irrigation), fodder, concentrated feed, grazed biomass, livestock excreta, mineral fertilizers (computed, see below), pesticides (not represented but computed, see below)	Veterinary products (no physical data available, included in the monetary flows in the “livestock expenses”), O ₂ and CO ₂ from breathing (not relevant to our purpose), cereal straw (only included in the LCA using national averages)
Inputs for cheese production (except milk)		Water, embodied materials (neglected)
Outputs of milk production (except milk)	Livestock excreta, air emissions (results from LCA)	
Outputs of cheese production (except cheese)		wastes and air emissions neglected compared to the production stage
Milk	x	
Cheese and other (by-)products	x	

The goal of the MFA is to provide a global view of the main material flows involved (unessential small flows are also included when available). **The purpose is not to implement mass conservation**, for instance, we do not consider livestock breathing and we do not aim to balance the water contents of the flows. On the contrary, the goal of the LCA (see section C3) is to assess environmental pressures originating from any flow (small or large, as small quantities can have big environmental impacts).

CALCULATION DETAILS.

Livestock excreta. Computed based on ratios per type of cow¹⁰.

Grazed biomass. Computed using ratios from Delagarde *et al* (2001).

Fodder consumption, local supply and imports. Fodder need and local supply are estimated by Eleveurs de Savoie (Perrin, 2012). Imports were estimated by Schoch (2014a, 2014b) and Clavel (2014).

Water for irrigation. Only the meadows/pastures of Haute-Maurienne are irrigated. Estimation based on 45 ha irrigated (for Beaufort milk production) and 2000m³/ha¹¹.

Water for drinking. Based on ratios per cow from Massabie *et al* (2013).

Mineral fertilizers. Based on Cerfrance data on fertilizer expenses, we estimated the mineral fertilization of meadows at 8.5 kg N/ha, compared to 42 kg N/ha for organic fertilization. Even if mineral fertilization is low, it is not completely negligible contrary to what came up from our interviews.

Pesticides. Based on Cerfrance data, we estimated pesticides expenditures at 10500€ for the whole milk production of the territory. According to the ministry of agriculture¹², the average price per hectare for one treatment is about 35€. Given there are 3277ha of meadows, we can conclude that only about 9% of the meadows receive one treatment per year.

Milk, cheese and other products. From the annual reports of the cooperatives.

10 https://irda.blob.core.windows.net/media/5339/godbout-2012-dejections_animales-production_2012.pdf

11 Clavel C (2015). Compte-rendu de réunions. Projet de création d'un réseau d'irrigation à Val Cenis. GIDA Haute-Maurienne.

12 <https://agriculture.gouv.fr/lutilisation-des-pesticides-en-france-etat-des-lieux-et-perspectives-de-reduction>

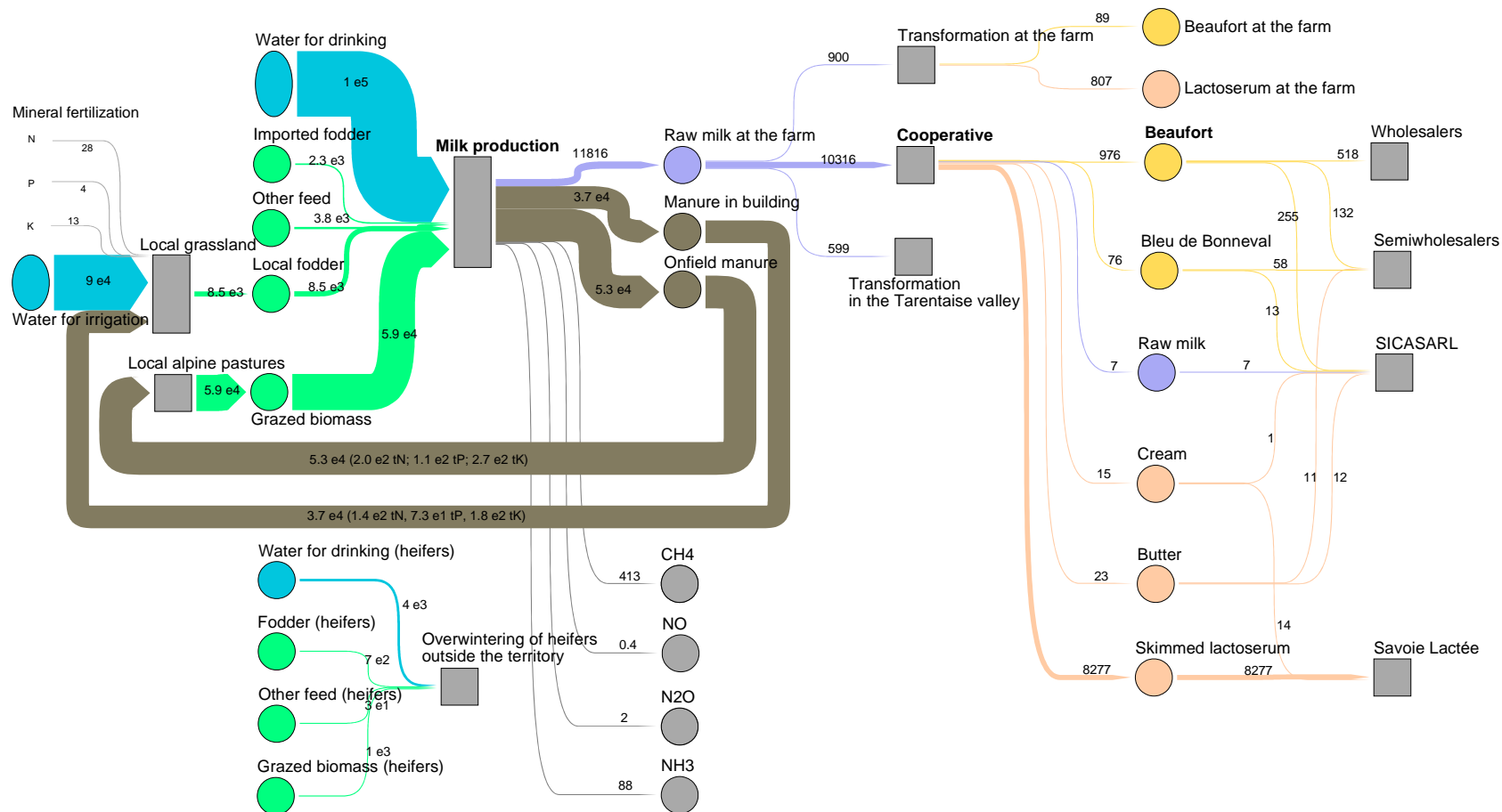


Figure C1a: Material flows of the Beaufort supply chain, expressed in **tonnes (real weight)**. From left to right: inputs (water, animal feed and fodder), animal excreta and milk, cheese and co-products, sales. Such diagrams are read from left to right. Colored bands (mostly horizontal) represent mass flows; the wider the band, the most important the mass flow. Transformation stages are represented by narrow vertical strips. The first transformation to produce milk is due to cow lactation, the other ones are due to various transformation units. We use the scientific notation, e.g., $4.2 \times 10^3 = 4200$. Also, mass (in tonnes) appears inside thick arrows, but outside thin arrows. Color code: light blue = water; brown = animal excreta; green = feed; blue = raw milk; yellow = cheese ; orange = other milk products.

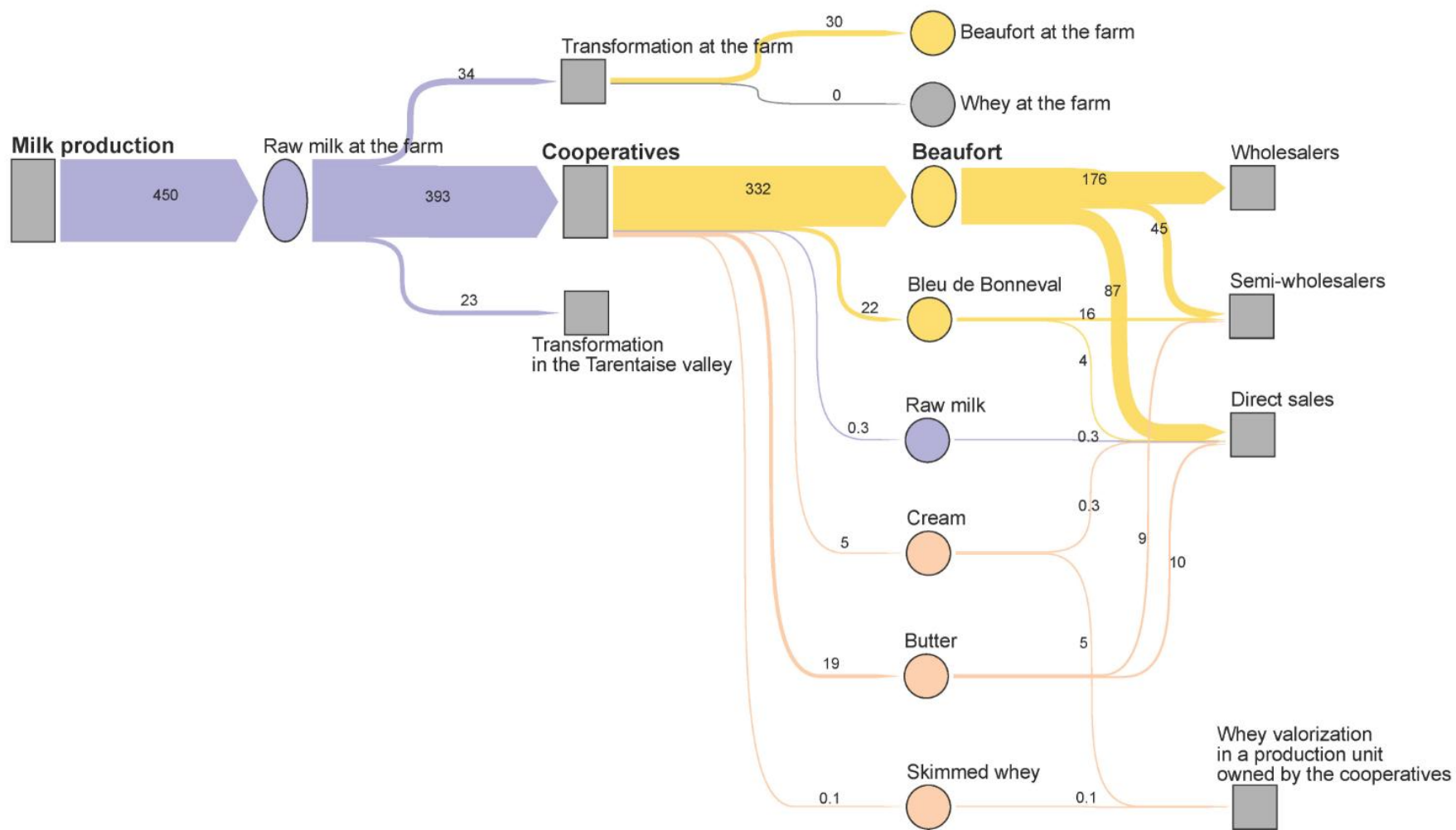


Figure C1b: focus on milk flows, in **fat mass (tonnes)**. As is apparent in Fig. C1a, cheese represents a small fraction of the mass flows. However, cheese keeps most of the fat, and the value added of cheese is in the transformation process. Consequently, a Sankey diagram tracing fat instead of total mass is a much better indicator of where value added lies (see Fig. C4 for monetary flows). Fat mass quantities appear inside thick arrows, but outside thin arrows. Color code: blue = raw milk; yellow = cheese ; orange = other milk products.

C2. Quantified environmental pressures from Life Cycle Assessment coupled to Material Flow Analysis

LCA data traditionally provide aggregated indicators of various sorts, such as impacts on resources, ecosystems, human health, etc. This is not our focus here. Instead, we independently quantify pressures exerted inside and outside of the study area, at each stage of the production of milk (animal feed, excreta management, etc.).

The data in the following tables incorporate both milk and meat production. Based on an economic allocation (proportional to volumes of sales in euros), we are confident that ~90% of these pressures are due to milk production.

The source of quantitative information in the following tables is the Life Cycle Inventory of the Agribalyse database¹³. The methodology applied follows Courtonne *et al* (2016).

			Total (Beaufort milk in Maurienne)			Total per kg of milk				Total per ha						
			Milking cows only	Whole livestock	Unit	Milking cows only	Whole livestock	France (average)	Unit	Milking cows only, fodder land only	Milking cows only, including alpine pastures	Whole livestock, fodder land only	Whole livestock, including alpine pastures	France (average)	Unit	
Inputs and outputs	Process outputs	Milk	11816	11816 t		1.00	1.00	1.00	kg	3606	1142	3606	1142	4400	kg	
		Manure	19834	24476 t		1.68	2.07		kg	6052	1917	7469	2366		kg	
		Slurry	11347	13706 t		0.96	1.16	missing information	kg	3463	1097	4182	1325	missing information	kg	
		Manure (on field)	40521	52979 t		3.43	4.48		kg		3916	16167	5120		kg	
	Process inputs	Agricultural land	3277	3277 ha		0.28	2.77	2.27	m2	1.00	0.32	1.00	0.32	1.00	ha	
		Alpine grassland	7070	7070 ha		0.60	5.98	missing info	m2	2.16	0.68	2.16	0.68	missing information	ha	
		Grazed grass	46309	59649 t		3.92	5.05	1.23	kg	14132	4476	18202	5765		5416	kg
		Fodder crops	8841	11429 t		0.75	0.97	0.51	kg	2698	854	3488	1105		2226	kg
		Concentrated feed	3707	3846 t		0.31	0.33	0.20	kg	1131	358	1174	372		881	kg
		Other feed, minerals	130	130 t		0.01	0.01	0.01	kg	40	13	40	13		37	kg
		Electricity	976	976 MWh		0.08	0.08	0.05	kWh	298	94	298	94		223	kWh
		Heat	4076	4076 GJ		0.34	0.34	0.15	MJ	1244	394	1244	394		638	MJ
		Tap water	114569	143922 t		9.70	12.18	2.85	kg	34961	11073	43919	13909		12552	kg
		Cereal straw	1063	1163 t		0.09	0.10	0.02	kg	324	103	355	112		67	kg

Table C2a: Input and output for milk production in the Maurienne Valley. This table uses LCI (Life Cycle Inventory) data from the Agribalyse database (concentrated feed, other feed, heat, cereal straw), combined with data collected directly from local stakeholders and existing reports (milk, manure, slurry, manure on field, land, grazed biomass, fodder crops, electricity, tap water).

			Total (Beaufort milk in Maurienne)			Total per kg of milk				Total per ha						
			Milking cows only	Whole livestock	Unit	Milking cows only	Whole livestock	France (average)	Unit	Milking cows only, fodder land only	Milking cows only, including alpine pastures	Whole livestock, fodder land only	Whole livestock, including alpine pastures	France (average)	Unit	
Economic allocation of system's impacts to milk (89,5% of impacts)	Direct impacts	Climate change	7526	10142 t CO2eq		0.64	0.86	0.57	kg CO2eq	2297	727	3095	980		2523	kg CO2eq
		Acidification	152	204 t SO2eq		0.013	0.017	0.005	kg SO2eq	47	15	62	20		24	kg SO2eq
		Eutrophication	22	29 t PO4		0.002	0.002	0.001	kg PO4eq	7	2	9	3		3	kg PO4eq
	Indirect impacts	Climate change	5890	7132 t CO2eq		0.50	0.60	0.31	kg CO2eq	1797	569	2176	689		1344	kg CO2eq
		Acidification	67	81 t SO2eq		0.006	0.007	0.006	kg SO2eq	20	6	25	8		25	kg SO2eq
		Eutrophication	31	37 t PO4		0.003	0.003	0.003	kg PO4eq	9	3	11	4		12	kg PO4eq
	Total impacts	Climate change	13416	17274 t CO2eq		1.14	1.46	0.88	kg CO2eq	4094	1297	5271	1670		3867	kg CO2eq
		Acidification	220	285 t SO2eq		0.019	0.024	0.011	kg SO2eq	67	21	87	28		49	kg SO2eq
		Eutrophication	53	66 t PO4		0.004	0.006	0.003	kg PO4eq	16	5	20	6		15	kg PO4eq

Table C2b: Direct and indirect pressures associated to Beaufort production in the Maurienne Valley. Same data source.

	Total (Beaufort milk in Maurienne, whole livestock)	
	Intra-territorial impacts	Extra-territorial impacts
Climate change	83%	17%
Acidification	72%	28%
Eutrophication	74%	26%

Table C2c: Localization of pressures associated to Beaufort production in the Maurienne Valley. Same data source.

C3. Calculation details for income from multi-activity

About 50% of the farmers have winter jobs (Schoch, 2014a; 2014b; Clavel, 2014). The following hypotheses were used to estimate the corresponding income:

- Average of 500 hours of work during the winter season (Sabatté, 2016),
- Average salary of 11.28€/h (Bourgeais, 2017).

D1. Potential detrimental “domino effect”

The figure below is produced from the following considerations.

For an activity with two types of earnings (*earning1* is fixed, *earning2* is variable), let *initial turnover* = *earning1* + *earning2*, and $f = \text{earning2} / \text{initial turnover}$. If *earning2* decreases by $x\%$, the new turnover will be xf (%) smaller than the initial turnover.

For an activity with fixed costs, if the turnover decreases by $x\%$, the associated income decreases by $x / (1-f)$ (%), with f is now the fraction *fixed costs*/*initial turnover*.

One could expect that a 14% decrease in milk production translates into a 14% decrease in sales of milk products and hence in cooperatives’ turnover. With the expression given right above, we in fact estimated a decrease in cooperatives turnover by “only” 13% because 5% of their turnover comes from “other goods and services” not related to milk production.

We then made the hypothesis that the decrease in cooperatives’ turnover is compensated by a decrease in milk price (purchased by cooperatives to farmers). We computed this new price and it resulted in a 15% price decrease.

These expressions applied at the level of the farms, but only part of the farms’ turnover comes from the sales of milk to the cooperatives (54%) and is therefore impacted by a price decrease at the cooperative. A 15% decrease in milk price hence results in a 8% decrease in farms’ total turnover.

Finally, based on Cerfrance data, we estimated that about one half of the turnover of Beaufort farms goes to expenses, hence a decrease of 8% of the farm’s turnover translates into a decrease of 16% of the farmer’s income.

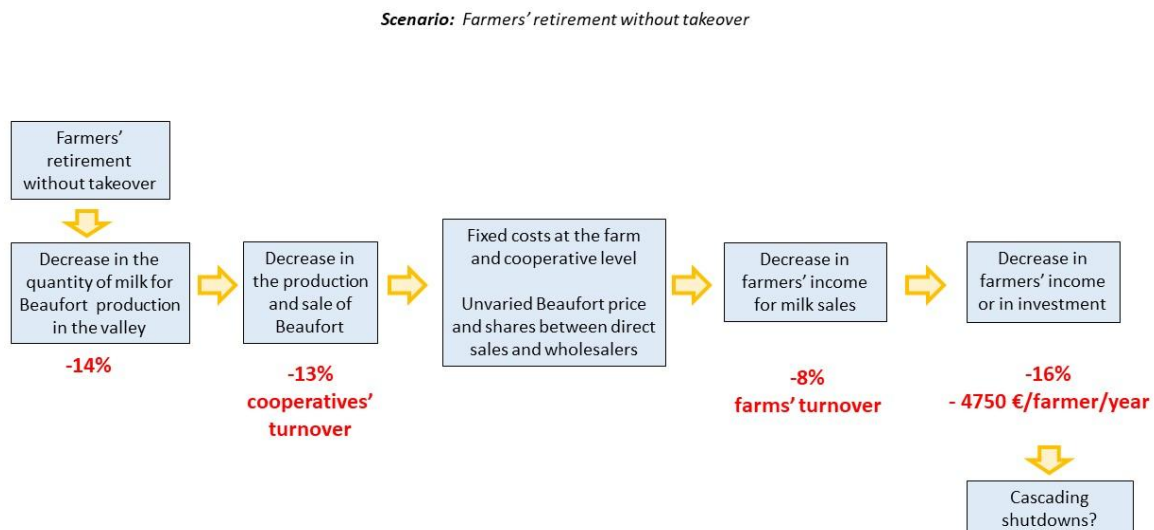


Fig. D1: Scenario of income loss due to a 14% reduction in milk production. This quantity of milk production reduction is estimated on the present demographics of milk producers, over the next decade. Based on the hypothesis that the price of Beaufort does not change.

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