Hy-C-Green project: Evaluation of the economic and environmental impacts of the implementation of a forest biorefinery in the Grand Est region, Project report

Valentin Mathieu

Project Report - Hy-C-Green

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2019 - 2020

Axis 3 of the Hy-C-Green Project: Decision support tools for the implementation of biorefineries in the Grand Est French region.

Writer: Valentin Mathieu, Research Engineer at INRAE, BETA

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01 Introduction

1. Introduction

1.1. From French ambitions for a sustainable energy system to the Hy-C-Green project

The need to move to a low-carbon energy system has never been greater and more pressing (IEA, 2020a; de Coninck *et al.*, 2018). To meet this major challenge, infrastructures such as biorefineries are central to the development of a sustainable energy system (see **Box**). In particular, biorefineries using forest biomass as input - later called “forest biorefineries” - may play a major role to reach this goal. In France, incentives for biorefineries’ development come from various policies. The Law for Energy Transition and Green Growth sets out several objectives in line with global sustainable development ambitions in the field of energy. In particular, Article 43 of this Law states that priority should now be given to the development of advanced biofuels to replace fossil fuels[1]. In the same vein, a bio-economic strategy, a national low-carbon strategy, and a multi-year energy program aim to improve biomass harvest for sustainable development in France[2].

This is because French forests are not harvested at the level of the annual biological growth rate and an additional 20 Mm3/yr is expected to be harvested at a national scale in line with sustainable management (Colin *et al.*, 2016). This additional production of forest biomass presents a real opportunity for the development of clean energy produced from biomass in France.

It is in this context that the Hy-C-Green project takes root. This interdisciplinary research project seeks to sustainably use wood through an integrated thermochemical biorefinery process capable of producing biocompounds and hydrogen at the Grand Est region scale. The forest-wood sector in the Grand Est region is particularly dynamic: it generates more than 55,000 jobs and an annual turnover of more than 8 million euros, and thus represents an important source of economic activity (Lenglet, 2015). But despite a diversified resource and numerous companies, wood is not sufficiently valued in the Grand Est region. The biorefinery appears then as a real development tool for the regional forest-wood sector which allows a better valorization of the hitherto under-exploited forest resource.

1.2. Towards a decision-support tool for a forest biorefinery implementation in the Grand Est region

The Hy-C-Green project echos past French experiences in the energy use of forest biomass. One example is the controversy surrounding the biomass combustion unit at the Gardanne power station. Despite its initial legal authorization to convert a coal unit into a biomass unit and to exploit the local forest resource, its authorization to operate was suspended in June 2017 following administrative appeals filed by local environmental organizations. These appeals have resulted, in particular, from strong criticism regarding the environmental impacts of an additional harvest to supply the biomass unit. The Mède power plant has more recently come under similar pressure. This former oil refinery began its reconversion into a biorefinery in 2016. Its supply plan, based essentially on the import of palm oil, was contested. This controversy was brought before the National Assembly which voted in 2018 to amend the 2019 finance law stipulating that palm oil products are no longer considered biofuels. This amendment came into effect on the 1st of January, 2020. Total's biorefinery thus becomes economically unviable because of the loss of the tax benefit on palm oil products.

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[1] LOI n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte (1), n.d. LOI n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte (1).

[2] Stemming from the Law for Energy Transition and Green Growth, the National Strategy for the Mobilization of Biomass (SNMB) complements France's ambition to develop a decarbonized economy. It particularly targets the energy valorization of biomass and focuses on the mobilization of forest biomass.

These two examples illustrate the importance of a biorefinery unit's location and its supply strategy at a regional level to ensure economic viability and limited environmental impacts. More precisely, two groups of questions arise: First, what are the impacts of the implementation of a forest biorefinery on the existing forest-wood sector[3]? In particular, does it involve competitions with existing industries? Second, what are the impacts on the forest resource? In this vein, one can wonder which origin of the products is desirable and, in the case of a local origin, which perimeter to choose for the harvest.

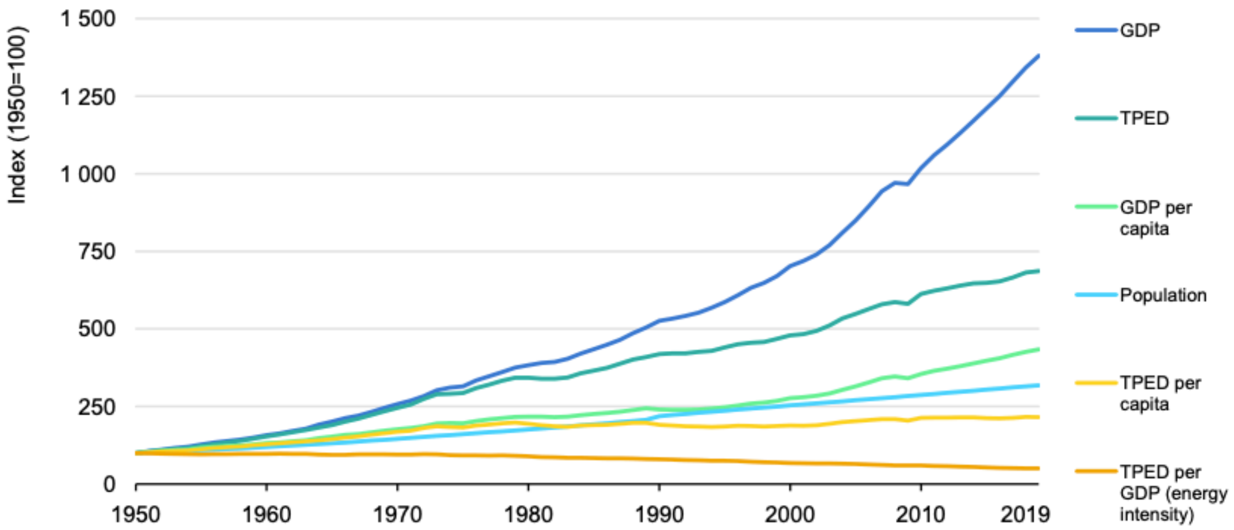
Providing answers to these questions goes beyond the framework of "classical" cost-benefit analysis and usually requires to use Economic-Environment Integrated Models (EEIMs). These models result from the combination of economic models (such as partial or general equilibrium models) and environmental assessment methods (such as the life cycle assessment method) (Beaussier *et al.*, 2019). However, these models are very data-intensive and their geographic resolution is not sufficiently precise to assess impacts at a territory scale. These two reasons prevent us to use them for the project since no economic and environmental data are yet available to calibrate them and since the geographic scope is the region and its territories.

In order to overcome these difficulties, we propose an original modelling framework that combines a qualitative description of scenarios for the implementation of biorefineries and a quantitative assessment of the impacts of such an implementation. The chosen scenarios, as well as their assessment criteria, are mainly based on a literature review and past experiences. We choose to focus on two of these criteria, which are assessed through two spatialized quantitative studies: a study of the spatial structuring of the forest-wood sector and a study of the impact of this sector on the resource through a model of harvesting probability. Finally, we provide a synthesis of the assessment of these scenarios using all the assessment criteria put forward by the literature review.

[3] Note that the company that own the biorefinery unit may not be familiar with the forest-wood sector. That was the case for the Gardanne power station, for instance: E-On was company that entered the forestry sector for the first time.

Box: Forest biorefineries and biomass as promising levers for an energy transition at a global level

In the executive summary of its Energy Technology Perspective 2020 report, the International Energy Agency[4] (IEA) emphasizes the urgency of developing clean energy technologies[5] (IEA, 2020a; de Coninck *et al.*, 2018). All the more so since current pathways on which nations are committed within the Paris Agreement are not sufficient and the largest contributor to greenhouse gas emissions is the energy sector (IEA, 2020a; Bruckner T. *et al.*, 2014). The energy demand is growing as shown in **Figure Box 1**, and will still grow despite a significant - but temporary - decrease in energy demand due to the Covid-19 crisis (IEA, 2020a; IEA, 2020c)[6].



Note: TPED = total primary energy demand.

Figure Box 1: Global total primary energy demand, population and GDP, 1950-2019 (from the Energy Technology Perspectives 2020 report of the International Energy Agency (IEA)). The increase in total primary energy demand seems correlated to economic growth and population growth.

According to the IEA, if "spreading the use of electricity into more parts of the economy is the single largest contributor to reaching net-zero emissions", electricity must be coupled with other types of energy to ensure the total decarbonization of an economy. The IAE's report identifies as promising the use of hydrogen, carbon capture, synthetic fuels, and bioenergy, in tandem with electricity to ensure a sustainable net-zero-emission energy system. Such a system mainly based on those clean energies - instead of actual key fuels like coal, oil, and natural gas - would allow reaching the net-zero emission according to the Sustainable Development Scenario developed by the IEA (IAE, 2020a).

[4] "The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 30 member countries, 8 association countries and beyond." (IEA, 2020a)

[5] We define here clean energy technologies as the technologies that produce energy from renewables, that is, energy with low- or zero-emissions sources.

[6] It should be noted, however, that some deceleration in the rate of growth of global energy demand has occurred in recent years, linked to a decline in global economic growth (IEA, 2020b).

Among the previously mentioned clean energies, hydrogen and carbon capture technologies “are currently at an earlier stage of development”, while “bioenergy remains the single largest category of low-carbon energy sources” today, as shown in **Figure Box 2**.

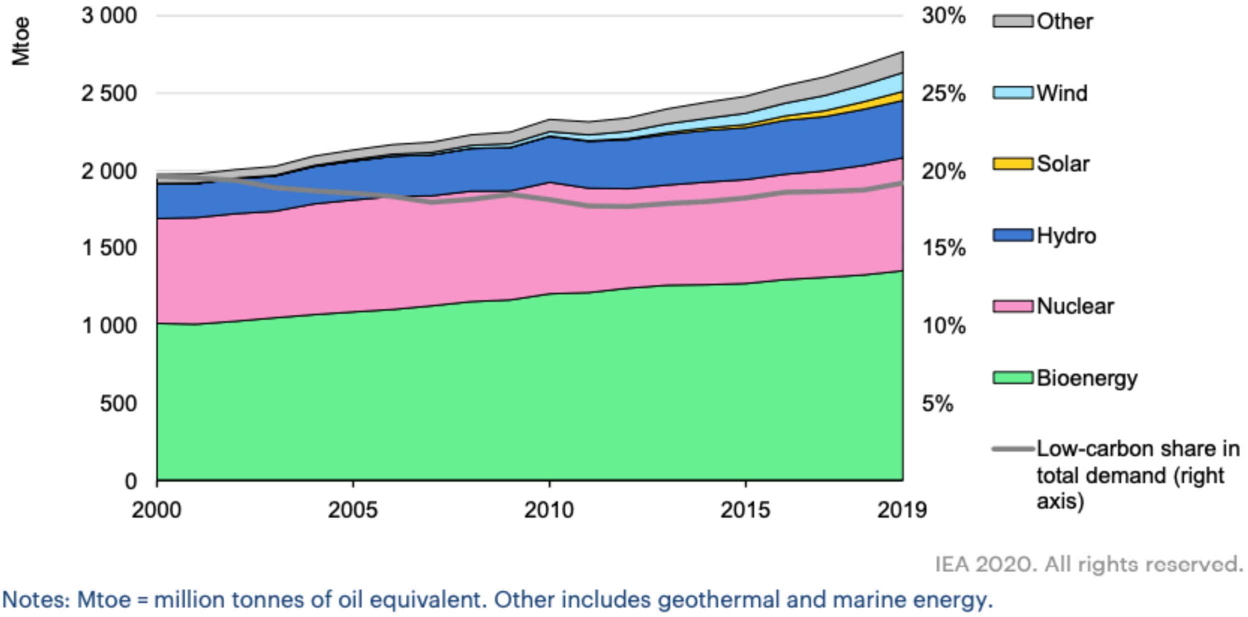


Figure Box 2: Primary demand for low-carbon energy sources, from 2000 to 2019 (from the Energy Technology Perspectives 2020 report of the International Energy Agency (IEA)).

Bioenergy is defined by the IAE as the “energy generated from the conversion of solid, liquid and gaseous products derived from biomass”, where we define biomass as “any organic matter, *i.e.*, biological material, available on a renewable basis”. This definition “includes feedstock derived from animals or plants, such as wood and agricultural crops, and organic waste from municipal and industrial sources”. As previously suggested in **Figure Box 2**, biomass now occupies a major role in “cleaning” the energy system. Its contribution is also expected to become increasingly important with the extension of bioenergy and the development of other clean energy technologies: BECCS technologies (bioenergy with carbon capture and storage) are a key part of carbon capture technologies that rely on biomass and produces negative carbon emissions; hydrogen and electricity can be produced from biomass (IEA, 2020a).

The use of biomass for energy purposes relies on the biorefinery concept, which is considered as the foundation of a future bio-based economy. The IEA defines a biorefinery as “the sustainable processing of biomass into a spectrum of marketable products and energy[7]”. It can thus consider several types of biomass as raw material: biomass from forests, agriculture, aquaculture, as well as various industrial and household residues including wood, crops, organic residues, among others. A biorefinery can then consist of an infrastructure, a process, a plant or even a cluster of infrastructures[8] (de Jong & Jungmeier, 2015). Biorefineries are then expected to contribute to a more sustainable resource supply and an overall reduction in GHG emissions. However, the

[7] It should be noted that even if this report focuses on energy issues, the production of biocompounds by biorefineries are no less important.

[8] Following this definition of a biorefinery, many traditional technologies are in fact already considered as "rudimentary" biorefineries. This is the case of paper mills that convert forest biomass into pulp, for example. Some examples of biorefineries date back to the -100 era (de Jong & Jungmeier, 2015).

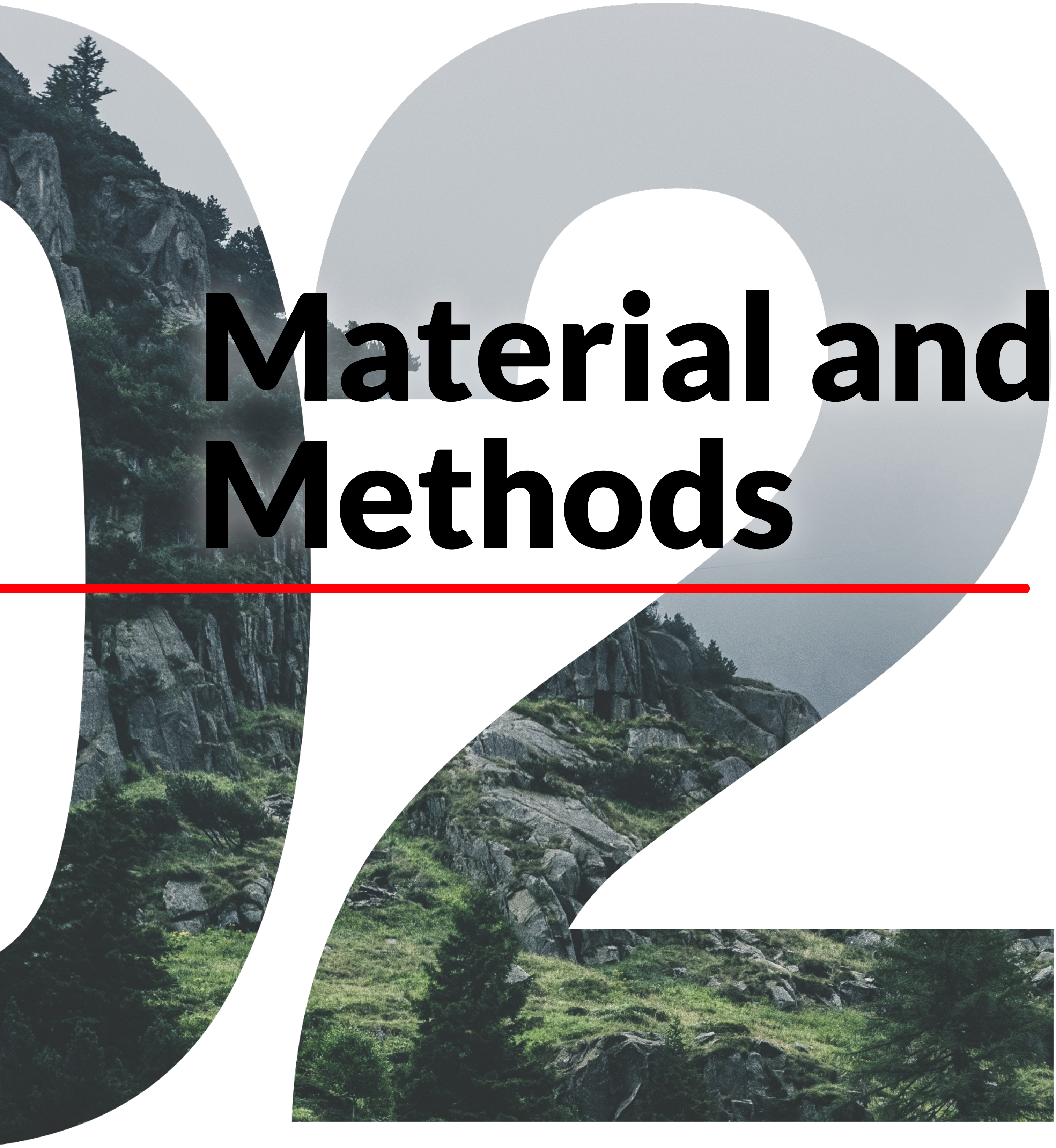
production of biobased products and fuel can also be associated with environmental damage such as land use changes or water eutrophication problems, depending on the biomass used in the biorefinery process (Heinimö *et al.* 2011; Uihlein & Schebek, 2009).

Indeed, as defined above, there is a wide range of biomass types. Among this diversity, lignocellulosic biomass[9] seems to be the most promising (Papini and Simeone, 2010; Uihlein & Schebek, 2009; Antizar-Ladislao & Turrion-Gomez, 2008). Like most usages of biomass to produce energy, the usage of lignocellulosic biomass, mostly forest biomass, can contribute to reducing carbon emissions (Campbell *et al.* 2018; Cambero & Sowlati, 2014; Havlik *et al.*, 2011; Papini et Simeone, 2010) and may lead to less dependence on fossil fuels (Tromborg *et al.* 2013; Bajpai 2013; Havlik *et al.*, 2011; Papini et Simeone, 2010; Uihlein & Schebek, 2009; Antizar-Ladislao & Turrion-Gomez, 2008). Lignocellulosic biomass, however, has other significant advantages: from a logistic perspective, wood is a resource that can be harvested throughout the year and not only during harvest periods (de Jong & Jungmeier, 2015); from an economic point of view, the use of lignocellulosic biomass is becoming a more and more cost-effective alternative to fossil fuels (IEA, 2020a) and can contribute to the development of rural areas (Havlik *et al.*, 2011); from an environmental standpoint, under the hypothesis of sustainable forest management, the environmental impacts associated with the production of lignocellulosic biomass for energy purposes are, *a priori*, lower than those generated with other biomass productions (Moshkelani *et al.* 2013; Havlik *et al.*, 2011).

All these points make the forest biorefinery a prime candidate to meet future energy challenges. Moreover, it presents a real opportunity for the forest-wood sector[10], which is undergoing a structural change in the face of (1) increasing demand for biomass for energy production and (2) decreasing demand for the production of traditional wood products such as pulp and paper (Tromborg *et al.* 2013; Heinimö *et al.* 2011). As such, it represents a relevant lever for regional development.

[9] We define lignocellulosic biomass as the biomass that contains cellulose, hemicellulose and lignin. This category of biomass is mostly represented by wood. It also includes agricultural residues.

[10] We define here the forest-wood sector as the production, processing and sale of wood-based goods and services to the forest resource.



Material and Methods

2. Material and methods

2.1. Development of forest biorefinery implementation scenarios and identification of assessment criteria

In this section, we (1) build qualitative scenarios for the implementation of forest biorefineries in the Grand Est region and (2) identify relevant criteria for assessing such scenarios (notably, those that assess their potential economic and environmental impact(s)). We base our scenarios development and criteria identification on a literature review and insights drawn from comparable French real-life cases, such as those mentioned in the introduction. The literature review has addressed the broad subject of biorefineries and the conditions for their success, focusing especially on the use of forest biomass as a raw material. We first present a synthesis of the literature review before presenting the assessment criteria we selected and before building implementation scenarios.

2.1.1. A summary of the literature review: conditions for the successful implementation of a forest biorefinery

The literature highlights several points of vigilance regarding the success of a forest biorefinery. These points of attention define the framework within which the implementation scenarios take place. They are of three types.

The first point of vigilance focuses on the economic environment in which the forest biorefinery takes place. The economic viability of a forest biorefinery, producing biofuel for example, depends first and foremost on:

(1) **The long-term availability of forest biomass** with the required quality and **at a competitive price** (Cambero & Sowlati, 2014; Antizar-Ladislao & Turrion-Gomez, 2008);

(2) **Transport costs**, which are largely responsible for the cost of the biomass (Tromborg *et al.* 2013);

(3) **Global economic conditions**: oil prices (which influence transportation costs), highly uncertain market prices, competition for biomass, among others; which may hinder the implementation of biorefineries in several economic sectors (Campbell *et al.* 2018; de Jong & Jungmeier, 2015; Tromborg *et al.* 2013).

It also depends on the economic value generated from this biomass, which is determined, on the one hand, by the revenues from products on the market and, on the other hand, by production costs (capital and operating costs)[11]. Most of these points are difficult to control, although strategies may be available to limit the risk of some. For instance, the choice of biorefinery location play a major role in operational costs like transport costs.

The second point of vigilance is that new biorefinery concepts, especially forest biorefinery concepts, are still in the pilot or small-scale demonstration stage: the state of maturity and commercialisation is still far away (de Jong & Jungmeier, 2015), and many technical and economic difficulties still need to be overcome (Tromborg *et al.* 2013; Bajpai 2012; Heinimö *et al.* 2011; Antizar-Ladislao & Turrion-Gomez, 2008). Nevertheless, some processes are already mature enough. For instance, the concept of a multi-input/single-output biorefinery allows to address the biomass-specific fluctuations in terms of price and volume while adapting to market demand. Particularly in the case of the forest biorefinery, technologies that enable a wide range of forest biomass quality to be used will encounter lower prices for the biomass than technologies that are too specific and demanding on the raw material quality. Therefore, flexibility concerning the raw

[11] Generally, products with a relatively high market value are associated with high production costs and *vice versa* (de Jong & Jungmeier, 2015).

material plays an important role in the success of the forest biorefinery unit (Tromborg *et al.* 2013). Also, a greater added value can be generated *via* a co-production concept. For example, the production of molecules, materials, etc. in addition to energy production makes it easier to withstand the competition from fossil fuels, which today dominate the energy sector[12] (de Jong & Jungmeier, 2015). Logistic innovations can also be important. For instance, decentralizing different units (biomass collection, biomass sorting, storage) facilitates multi-input/single-output strategies (de Jong & Jungmeier, 2015): this decentralization strategy can be considered when developing a strategy for implementing a biorefinery.

The third point of vigilance highlights the multiple economic, environmental and social implications of the implementation of a forest biorefinery (Dufossé *et al.*, 2017). A new biorefinery will result in a higher demand for biomass which may cause a competition with the production of other products, such as wood products, paper, etc. (de Jong & Jungmeier, 2015; Papini & Simeone, 2010). The price variation following the implementation of a biorefinery depends on the local context: it may depend on the local availability of raw material, the type of resource considered, or transport and import costs (Tromborg *et al.* 2013). In particular, a large-scale forest biorefinery unit can increase the cost of raw material, thus reducing its profitability (Tromborg *et al.* 2013). On a larger scale, a biorefinery can also have an impact on international and regional dynamics or consumer needs (de Jong & Jungmeier, 2015). Apart from economic impacts, the development of biorefineries can also have profound environmental implications including loss of forest cover, biodiversity, soil productivity, and drinking water availability (de Jong & Jungmeier, 2015; Havlik *et al.*, 2011).

These points of attention give rise to several concrete considerations as to how and where a forest biorefinery should be implemented. A first consideration is its size and capacity, and its location. On one hand, a large size and capacity can lead to a higher production, but, on the other hand, the larger its size, the further away the plant will have to supply itself with biomass. Yet, transporting biomass over long distances can sometimes damage the quality of the raw material and inevitably generates higher operating expenditures (de Jong & Jungmeier, 2015). Those operating costs also depend on the location of the biorefinery. Hence, there exists a trade-off between capital (CAPEX) and operating (OPEX) expenditures in defining the optimal size and location of a forest biorefinery, in order to generate economies of scale (Ong *el al.*, 2020).

A second issue is the supply strategy of the biorefinery unit: will the forest biorefinery source its raw material exclusively locally or will it consider importing raw material? Indeed, the literature tells us that using local biomass can optimize its biofuel production (Antizar-Ladislao & Turrion-Gomez, 2008). However, to increase its production, large-scale biomass imports can be considered (Heinimö *et al.* 2011), thus "delocalizing" the potential impact of production.

A final question concerns the implementation methods themselves: a forest biorefinery can be implemented *ex nihilo* or can be introduced into the forest-based sector by improving or extending pre-existing industrial infrastructures (de Jong & Jungmeier, 2015). These pre-existing structures may come from a sector other than the forest-wood sector (such as a petrochemical refinery with an integrated biomass treatment process) or from the forest-wood sector itself (*e.g.,* pulp and paper industries) (de Jong & Jungmeier, 2015).

[12] These last issues are mainly tackled in the first two research axes of the Hy-C-Green project.

2.1.2. Description of implementation scenarios and selection of assessment criteria

2.1.2.1. Six assessment criteria for evaluating implementation scenarios

From the above, we retain six criteria to evaluate implementation scenarios:

(1) The potential impact of the implementation of a forest biorefinery in terms of competition with pre-existing companies of the forest-wood sector.

(2) The potential impact of the implementation of a forest biorefinery on the forest resource *in situ*.

(3) The production cost of the implementation of a forest biorefinery. Production cost comprises the CAPEX (related to the size and capacity of the forest biorefinery) and the OPEX (related to transport costs).

(4) The origin of the biomass used in the biorefinery, which can be from: (i) harvesting local forest resources, (ii) using recycled wood or wood waste from companies of the forest-wood sector, and (iii) importing raw material; and their respective impact on the resource.

(5) The costs related to the biorefinery's implementation modalities, that is whether the biorefinery will be built *ex nihilo* or whether it will be set up through an upgrading/expansion of a pre-existing company. The considered costs include transaction, opportunity, and capital costs.

(6) Technical and technological feasibility with respect to the biorefinery process.

From these criteria, we decide to focus on the first two, which are directly related to our study objective. While they are put forward in arguments for and against biorefineries, these criteria are rarely evaluated, and, to our knowledge, no study quantifies their magnitude at a regional level. Therefore, we propose, in the second part of this study, a method for approaching these two types of impact through two quantitative studies. Criteria (3), (4), and (5) are mostly covered by the literature, while criterion (6) is addressed by the other research axes of the Hy-C-Green project.

2.1.2.2. Five scenarios for the implementation of a forest biorefinery in the Grand Est region

Our study seeks to compare different forest biorefinery implementation scenarios. The development of these scenarios is based on (1) the literature review carried out above and (2) a press review focused on French news in the fields of the paper or oil industry[13].

Each implementation scenario seeks to meet three implementation objectives defined from the literature review:
1. To minimize the OPEX by being located as close as possible to the exploited resource.
2. To take advantage of pre-existing industrial infrastructure.
3. To be part of a regional development, *i.e.*, to be located in the Grand Est region[14].

Each scenario seeks to best fulfil the implementation objectives according to its own constraints. Notably, the construction of these scenarios does not use any quantitative study that would suggest an optimal location and sizing of a forest biorefinery in the Grand Est region[15]. Thus, scenarios partially - or at least approximately - meet the implementation objectives and are not optimal.

[13] The URL links leading to online sources used are provided as footnotes as the scenarios are built. A list of all URL links is provided in **Appendix I**. These articles were all consulted between 01/01/2021 and 01/07/2021.

[14] Study region of the Hy-C-Green project.

[15] To our knowledge, no such study has yet been published.

For each implementation scenario, the sizing, location, and implementation conditions of the forest biorefinery are fictional and arbitrary. These scenarios are also built with a methodological concern for comparability. Overall, these scenarios are intended to present possible and plausible futures that will fuel a reflection on the implementation of a forest biorefinery in the Grand Est region.

Scenario 1: Implementation of a forest biorefinery *ex nihilo*.

This scenario constitutes the baseline against which the following scenarios will be compared. No particular constraints are considered under this scenario. For the sake of comparison with the other scenarios, we retain the following characteristics:

- **Approximate location**: Golbey / Épinal.

- **Approximate size**: Production of 200,000 t/year of biofuel for approximately 100 to 200 jobs created.

- **Specific points**: Proximity of the Vosges forest resource; use of pre-existing road system of Épinal; large scale project potentially competing with pre-existing industries of the forest and wood sector.

Scenario 2: Conversion of a petrochemical refinery into a forest biorefinery unit.

This scenario is inspired by the example of La Mède oil refinery conversion, located in the South of France, in addition to drawing inspiration from the literature review.

History and characteristics of La Mède biorefinery

Begun in 2015, the conversion of the La Mède oil refinery was intended to create a "world-class French biorefinery"[16] by Total. The new biorefinery began its production in July 2019. Its projected capacity was: 500,000 t/year of biofuel; 60,000 t/year of aviation gasoline; 25,000 t/year of bio-naphtha; and 50,000 t/year of adBlue[17]. In addition to its biofuel production, the biorefinery has its logistics and storage platform and nearby port activity. The conversion project has maintained 250 jobs out of the initial 430 and has not led to geographic mobility: the biorefinery thus has partially retained skills of its initial industrial site.

In this scenario, we consider the conversion of a French oil refinery into a forest biorefinery, on the model of the conversion of La Mède oil refinery.

Looking for a potential candidate among French oil refineries

France counted 8 oil refineries[18] at the end of 2019, including 7 located in metropolitan France and 1 in Martinique. In order of importance in terms of refining capacity (see **Figure 2.1**):

- the Gonfreville L'Orcher refinery (12.5 Mt of refining capacity, operated by Total) ;
- the Port-Jérôme-Gravenchon refinery (12 Mt, operated by Esso);
- the Donges refinery (11 Mt, Total);
- the Lavéra refinery (9.9 Mt, Petroineos);
- the Fos-sur-Mer refinery (6.6 Mt, Esso);
- the Grandpuits refinery (4.9 Mt, Total);
- the Feyzin refinery (5.4 Mt, Total);
- the West Indies refinery (0.8 Mt, SARA).

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[16] https://www.total.com/fr/expertise-energies/projets/bioenergies/la-mede-un-site-tourne-vers-avenir

[17] For information, the oil refinery of La Mède, before its conversion, was producing 750,000 t/year of oil.

[18] https://www.connaissancedesenergies.org/combien-y-t-il-de-raffineries-en-france-et-ou-sont-elles-situees-191219

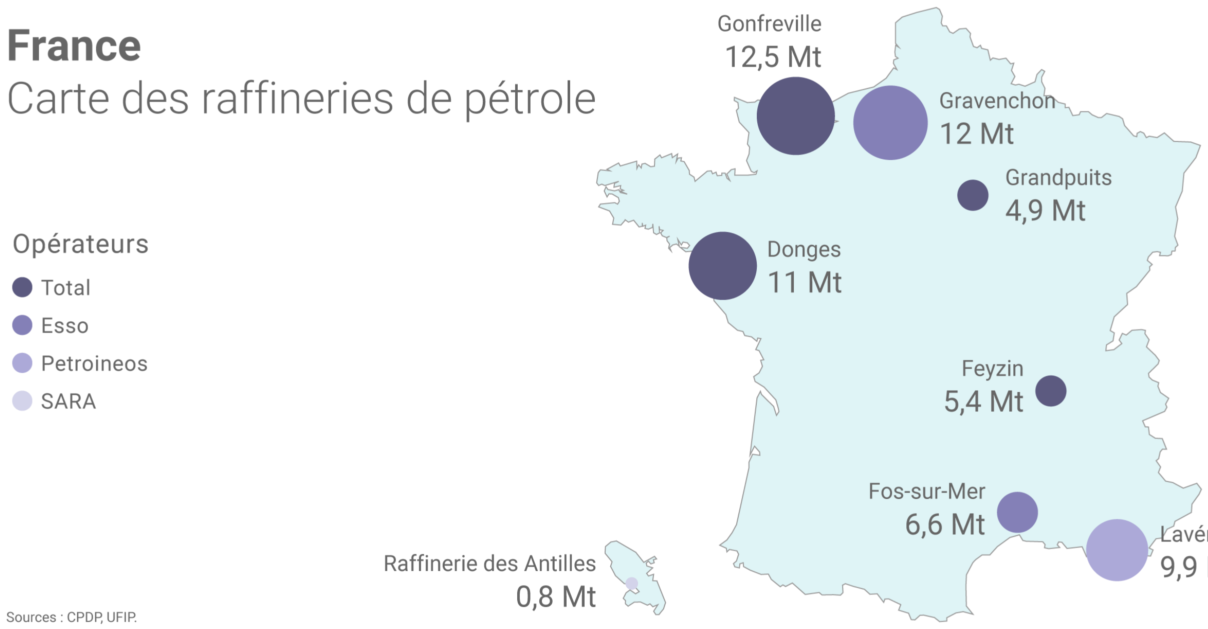

Figure 2.1: Mapping of French oil refineries. The size of the dots is proportional to the refining capacity of the plant and its color differs according to the company owning the refinery. Total has the most refineries in France. Source: www.connaissancedesenergies.org

Recently, 4 refineries were shut down between 2010 and 2013 (Flandres, Reichstett, Berre, Petit-Couronne) in a difficult economic context for the sector[19].

Among all these oil refineries, the refineries owned by Total hold a special position. First, the company has already experienced the conversion of a refinery into a biorefinery (La Mède biorefinery). Second, despite the problems encountered during the first conversion experiment at La Mède, Total is considering a new conversion project: that of the Grandpuits refinery with a projected production of 400,000 t/year of biofuel by 2024 (mainly fuelled by animal fats from Europe and used cooking oils)[20]. And third, Total is also investing in R&D on the conversion of lignocellulosic biomass (notably of forest biomass) through the BioTfuel project[21] (with the intention of a scale-up to the industrial level).

Concerning other companies owning oil refineries in France: (1) either the company focuses on third-generation (algae-based) biofuels (this is the case for Esso), (2) or oil and gas production is a secondary activity and biofuel production consists of low investment (Ineos), (3) or the company's refinery is outside metropolitan France (Sara). We decide then to consider only Total's oil refineries.

[19] https://www.connaissancedesenergies.org/fiche-pedagogique/choc-petrolier

[20] https://www.actu-environnement.com/ae/news/conversion-raffinerie-grandpuits-biocarburant-bioplastique-36176.php4

[21] https://www.total.com/fr/expertise-energies/projets/bioenergies/biotfuel-convertir-residus-vegetaux-carburant

Looking for a potential candidate among Total oil refineries

Total owns 4 oil refineries in France[22] (not including La Mède biorefinery):

- Normandy refinery at Gonfreville-l'Orcher in Seine-Maritime: 12.5 Mt/year;
- Donges refinery in Loire-Atlantique: 11.0 Mt/year;
- Grandpuits refinery in Seine-et-Marne: 4.9 Mt/year (already subject to a conversion project);
- Feyzin refinery in the Rhône department: 5.4 Mt/year.

We can add two Total refineries to this list:
- The Belgian refinery in Anvers[23] with a capacity of 338,000 b/d (approximately more than 1,700,000 t/year). This refineries could potentially be one of the closest refinery to the Grand Est region and its forest resource;
- The former Flandres refinery, which has become a demonstration unit for the BioTfuel project[24,25].

We reduce the list of potential candidates by exclusion. We proceed as follows:

(1) We exclude refineries already subject to a biorefinery conversion project that will not use forest biomass. This is the case of the Grandpuits refinery. In doing so, we exclude the only oil refinery operating in the Grand Est region. This scenario will therefore relate to an oil refinery that will *a priori* be far from the forest resource to be mobilized within the framework of our study.
(2) We exclude refineries that are too far from the Grand Est region, such as the Donges refinery in Loire-Atlantique.
(3) We exclude oil refineries with the largest capacities, such as the Normandy refinery (Total's flagship refinery in France).
(4) We exclude refineries located outside France, such as the Anvers refinery.

Two refineries remain on our list after sorting: the Feyzin refinery and the Flandres refinery. We choose to consider the Flandres refinery for the role it plays in the BioTfuel project[26].

The BioTfuel project's scale-up to industrial scale is expected to produce more than 200,000 t/year of biofuel. To ensure consistency with the R&D project's announcements, we are considering this sizing for scenario 2. The forest biorefinery will not be located as close as possible to its resource (the BioTfuel project is located in the vicinity of Dunkerque) but will have access to the port of Dunkerque, which allows for imports and modulation of the management intensity applied to French forests. Moreover, it is important to note that the BioTfuel project plans to use a mix of inputs (agricultural biomass, forest biomass, fossil fuels...).

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22 https://www.fioulreduc.com/info-fioul/acteurs-fioul/raffineries

23 https://www.total.com/fr/expertise-energies/projets/plateforme-raffinage-chimie/anvers-premiere-plateforme-integree-groupe-europe?gclsrc=aw.ds&&gclid=CjwKCAiA_9r_BRBZEiwAHZ_v1y4W-Z1g3CCXFr2_YQ0XLeeE-10Rpg8Gux7JkLzanAwTjn1TnPkEShoCrK0QAvD_BwE#xtor=SEC-7-%5BEXP%5D-%5BANN%5D---%5BBE%5D--

24 https://www.usinenouvelle.com/article/total-repeint-en-vert-la-raffinerie-des-flandres.N834485

25 https://www.developpement-regional.total.fr/projet-biotfuel-sur-la-raffinerie-des-flandres-inauguration-par-la-ministre-de-lenvironnement

26 https://www.industrie-techno.com/article/carburants-les-biocarburants-de-deuxieme-generation-prets-a-passer-a-l-industrialisation.62803

We then retain the following characteristics for scenario 2:

- **Approximate location**: Dunkerque.
- **Approximate size**: Production of 200,000 t/year of biofuel for approximately 100 to 200 jobs[27].
- **Specific points**: Multi-input biorefinery and access to port infrastructure, allowing diversification of supply; inclusion in a pre-existing R&D project.

Scenario 3: Conversion of a pulp mill into a forest biorefinery unit.

This scenario is the implementation scenario most encountered in the literature. It presents an opportunity for the pulp and paper industry, which is experiencing economic struggles due to the declining demand for paper products. In addition, the industrial processes used by pulp mills are similar to those used by a biorefinery. Setting up a biorefinery by converting a pulp mill is thus, *a priori,* less capital-intensive than an *ex nihilo* implementation. Therefore, converting a pulp mill into a forest biorefinery seems to be a good implementation strategy.

Looking for a potential candidate in the Grand Est region

The third implementation objective stipulates that the forest biorefinery should be located in the Grand Est region, if possible. If we refer only to the nomenclature of French activity (NAF code, detailed in **section 2.2.1.2.**) there is no pulp mill located in the Grand Est region. This nomenclature only considers the main activity of French companies. In other words, that means that no mill in the Grand Est region produces mechanical, chemical, or de-inked pulp as a final product which would be sold to another company for paper production.

However, in some cases, a paper industry may produce its own pulp as an intermediate product for its own paper and/or cardboard production. The production of paper and/or cardboard is then considered as the main activity by the French nomenclature. Nevertheless, these mills may be suitable for conversion into a forest biorefinery, since they have a pulp production line. To find these companies and bypass this “NAF nomenclature bias”, we use the Copacel website[28] to identify companies that produce pulp (of all kinds) in the Grand Est region. Following this method, we find that only one mill is producing pulp in the Grand Est region: Norske Skog Golbey[29].

Characteristics of the mill of Norske Skog Golbey

Norske Skog Golbey paper mill uses as input about 500,000 t/year of recycled paper, plus 250,000 t/year of sawmill chips and thinning logs (60-70% for the former, 30-40% for the latter). The mill is supplied within a 150km radius of Golbey industrial site. 95% of the supply is located in the North-East of France. Its production is 780 t of pulp/d from chips/roundwood and 1200 t of pulp/d from recycled paper. This production corresponds to nearly 4300 km of newsprint per day, *i.e.,* 45 mother reels per day of 40 t. Its annual paper production is thus around 600,000 t. The site employs about 350 employees.

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[27] The rough approximation of a number of jobs that corresponds to a given biofuel production is based on the real case of La Mède biorefinery. That is: 250 jobs for a 500 000 t/year production of biofuel (with a side production of aviation gasoline, naphta, and Adblue).

[28] http://www.copacel.fr/fr/rechercher-un-fabricant.html; Copacel is the French Union of Cardboard, Paper and Cellulose Industries.

[29] https://norskeskog-golbey.com

Projects on the Golbey industrial site

Three recent projects characterize the Golbey industrial site:

(1) The Green Valley Energy project: a group of companies located on Golbey industrial site that focuses on industrial ecology and that is organized around the Norske Skog paper mill[30]. This project focuses on developing a circular economy, bioeconomy, and bioenergy on the Golbey site, and is led by the Norske Skog Group. Norske Skog has already intensively invested in projects that fall within this framework.

(2) The project to increase the production of the biomass cogeneration boiler at the Golbey site (a part of the Green Valley Energy project)[31,32]. This project envisions an increase in production from 12.5MW to 25MW. Norske Skog has invested 160M€ for this project. Currently, the cogeneration boiler consumes about 35 t/h of biomass (*i.e.* about 300,000 t/year). At the end of the project, this biomass consumption should roughly double.

(3) The project to convert a paper production line into a corrugated board production line[33]. This project is motivated by the constant decrease in the price of paper from year to year while the use of packaging board explodes. As a result, the mill's paper production will only be 360,000 t/year (instead of 600,000 t/year) and the mill will produce 550,000 t/year of cardboard. This project is expected to create 25 to 100 new jobs. Norske Skog's investment for this project is 250M€. Production will start in 2023.

It is also planned that Norske Skog's paper mill will stop its supply of sawmill chips and thinning logs by 2023 to focus solely on recycled paper for its paper and cardboard production. 250,000 t/year of wood will therefore no longer be used from 2023 onwards.

In this context, the following project can be envisaged: a conversion of the remaining newsprint production line of Norske Skog's paper mill into a forest biorefinery unit with a re-mobilization of the 250,000 t/year of sawmill chips and thinning logs. A consequent sizing can be envisaged with a production of 200,000 t/year of biofuel and about 200 jobs maintained on the site.

We then retain the following characteristics for scenario 3:

- **Approximate location**: Golbey Green Valley Energy industrial site.

- **Approximate size**: Production of 200,000 t/year of biofuel for approximately 100 to 200 jobs maintained.

- **Specific points**: Proximity of the Vosges forest resource; use of pre-existing industrial infrastructures of Épinal; forest biorefinery located within an industrial ecosystem; acquired skills; relatively low capital investment (transformation of the production chain and not construction *ex nihilo*); already assured supply; dynamism of the site in innovation and innovative projects and proximity of R&D units; pre-existing links with local players such as Grand Epinal, partner of the projects.

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30 https://www.vosgesmatin.fr/edition-d-epinal/2019/11/19/la-green-valley-moteur-economique-de-l-agglo

31 https://www.graphiline.com/article/32708/une-nouvelle-chaudiere-a-la-papeterie-norske-skog-golbey-88

32 https://www.ecologie.gouv.fr/deploiement-des-energies-renouvelables-elisabeth-borne-designe-projets-laureats-dinstallations

33 https://www.vosgesmatin.fr/economie/2020/06/17/golbey-norske-skog-investit-250-m-d-euros-pour-se-convertir-dans-le-papier-carton

Scenario 4: Creation of a small biorefinery unit as an extension of an industry of the forest-wood sector.

This scenario is based on existing cases where a large company in the forest-wood sector (such as a sawmill) creates an extension unit that valorizes its waste (sawdust, wood chips...) into a value-added product (*e.g.*, wood pellet). In this scenario, we consider the forest biorefinery as such an extension unit.

Sine qua non condition and facilitating factor for the implementation scenario 4

In addition to the three implementation objectives common to each scenario, scenario 4 requires an additional condition. That is, the candidate company for scenario 4 must be large enough to (1) have the financial means to invest in an extension unit and (2) mobilize enough biomass or “wood waste” to support this extension unit (although the extension unit would typically be small). Thus, a site where several companies are organized as an industrial ecosystem would facilitate setting up this extension.

A plausible case for this scenario can be derived from scenario 3

We consider the implementation of a small forest biorefinery unit as an extension of the Green Valley Energy site. The interest of the Golbey industrial site for the production of bioenergy is already demonstrated by Norske Skog's investments (the site is already equipped with a boiler that will be further expanded). Moreover, one can imagine that part of the 250,000 t/year abandoned by Norske Skog Golbey could be mobilized again for a small forest biorefinery.

We then retain the following characteristics for scenario 4:

- **Approximate location**: Green Valley Energy's industrial site in Golbey.

- **Approximate size**: Production of 50,000 t/year of biofuel, for approximately 50 to 100 jobs created.

- **Specific points**: Proximity of the Vosges forest resource; use of pre-existing industrial infrastructures of Épinal; forest biorefinery located within an industrial ecosystem; acquired skills; already assured supply; dynamism of the site in innovation and innovative projects and proximity of R&D units; pre-existing links with local players such as Grand Epinal, partner of the projects.

Scenario 5: Implementation of a network of small biorefineries throughout the territory.

This scenario is inspired by the success of small boiler plants that are being set up in rural areas of the Grand Est region ad throughout France[34].

Here we arbitrarily decide to set up a network of small forest biorefineries by following the pre-existing "heat network". In order to satisfy the implementation objectives, we try to position this network as close as possible to the forest resource. We thus consider a group of 4 small forest biorefineries with an annual production of 50,000 t/year of biofuel which mobilizes for all or part of the 250,000 t/year of wood left by the Norske Skog Golbey paper mill.

[34] https://carto.viaseva.org/public/viaseva/map/

We then retain the following characteristics for scenario 5:

- **Number of forest biorefineries**: 4
- **Approximate location**: Saint-Dié-des-Vosges, Sainte-Marie-aux-Mines, Colmar, and Sélestat.
- **Approximate size**: Production of 50,000 t/year of biofuel, for approximately 50 to 100 jobs created.
- **Specific points**: Forest biorefineries are part of a network allowing the shared use of logistic sites (storage warehouses, transport services, etc.) and therefore having a minimal land footprint; the multi-site nature of this network can minimize transport costs (biomass transported to the nearest biorefinery); this forest biorefineries network is located in the Vosges as close as possible to the resource.

2.2. Spatial analysis of the French forest-wood sector and evaluation of its impact on the probability of harvesting

We detail here the materials and methods of two quantitative and spatialized analyses that allow us to assess the two first assessment criteria. Criterion (1) of the impact of setting up a forest biorefinery in terms of competition with pre-existing forest-wood sector companies is addressed in two ways. First, we assume the implementation of a forest biorefinery can exacerbate inter-companies competition under a dual condition, that is: the local annual harvesting level is close to the biological growth rate of the local forest resource, and the density of industries is already high. Second, we assume it can affect competition by modifying the pre-existing spatial structure of the forest-wood sector. **Section 2.2.1.** presents the materials and methods we use to test these assumptions relative to criterion (1).

Criterion (2) of the impact of such an implementation on the forest resource is addressed through the probability that a tree will be harvested. For this purpose, we use a socio-economic model of tree harvesting described in Fortin *et al.* (2019) - called "harvest model" in what follows. In particular, we assume a high density of forest-wood companies and the proximity of the resource to companies able to process it will increase the probability of a tree to be cut and, consequently, the pressure on the resource. **Section 2.2.2.** presents the materials and methods we use to test these assumptions relative to criterion (2).

The following materials and methods are based on the work carried out in Fortin *et al.* (2019) and pursued in Salzet *et al*. (2020). They propose an extension for the part treating the impact of the forest-wood sector on forest resources, *i.e.*, an extension of the harvest model.

2.2.1. Analysis of the spatial aggregation and dispersion of French forest-wood companies

2.2.1.1. From the question of the spatial structure to the spatial analysis of industrial clusters in the French forest-wood sector

The spatial structure of the forest-wood sector has already been studied before. Disciplines such as the economics of proximity or economic geography already explore its multiple dimensions (political, topographical, economic...) (Lenglet, 2018). Paul Krugman's school of the New Economic Geography has also explored agglomeration patterns that structure economic activities (Fujita *et al.*, 1999). Classically, in economic geography, the study of the spatial structure of firms in a given economic sector is based on aggregation or dispersion effects (Kies *et al.*, 2008). These effects can be generated by the heterogeneity of production factors such as employees (*e.g.,* the dynamism of metropolitan areas), capital (Aguilar, 2008), technology, or the availability of primary resources (Aguilar, 2009). We follow this general framework and we choose to explore the agglomeration and/or dispersion of firms of the forest-wood sector.

To our knowledge, few empirical studies exist on the subject (*e.g.*, Kies *et al.*, 2008), but none for the French case. Previous studies of this kind have mostly been conducted at international or national scales (Kies *et al.*, 2008) but rarely at an infra-regional scale (Aguilar *et al.*, 2009). One hypothesis to explain this result is the scarcity of information on firms at this scale. Larger administrative scales, such as the departmental, regional, and national scales, are favored when collecting economic information on French firms. In addition, the sub-regional scale seems to be less strategic when it comes to studying relations between large industrial groups operating on international scales. Nevertheless, the framework of the Hy-C-Green project pushes us to focus on a finer infra-regional scale for our analysis.

Thus, we first propose to study the degree of aggregation of companies of the upstream segment of the forest-wood sector[35] (named "forest-wood companies in what follows) on an infra-regional scale, using spatial econometric methods. In particular, we seek to explain the formation of possible aggregates and formulate the following hypothesis: **firms in the forest-wood sector**

[35] We define the upstream segment of the forest-wood sector as the logging and primary processing industries.

aggregate following homogenous forestry regions' pattern. To test this hypothesis, we rely on homogenous forestry regions called "sylvoecoregions" (SERs) which are grouped in entities called major ecological regions (GRECO). According to the definition given by the French National Forest Inventory (IFN), SERs are territories "where similar conditions prevail from the point of view of forestry production". This encompasses a rather homogenous resource (species, types of management) and homogenous biophysical conditions (climate, soil). Therefore, we stipulate that aggregates of companies in the forest-wood sector would overlap on the SERs and GRECOs, in relation to their biophysical and logistic conditions (resource availability and accessibility, operational road system, homogeneity and quality of raw material, etc.). In other words, we expect SERs that meet favorable conditions for forest resource harvesting to present aggregates of companies of the upstream part of the forest-wood sector.

In a second phase, we go further in our study by focusing on aggregation patterns of three groups of firms: sawmills, logging companies, and pulp industries. Sawmills and logging industries act as an arbitrary baseline that gives perspective to the results we obtain in the case of pulp industries. Pulp industries act as a proxy for the study of forest biorefineries. In fact, no forest biorefineries yet exist in France. As our study describes the pre-existing forest-wood sector, we decided to approach the forest biorefinery by a pulp mill. According to the literature, the processes of both and the type of biomass used are close (de Jong & Jungmeier, 2015), which makes this approximation reasonable and suitable for our study.

2.2.1.2. Spatialized data on companies of the forest-wood sector

The database gathering basic information on the economic activity of French companies is the SIRENE database. In particular, this database contains the standard address of each company, which allows a precise location of the referenced structures. French companies are uniquely identified by the SIREN code and categorized according to their main activity by the nomenclature of French activities' code (NAF code). The spatialized SIRENE database is provided by the French government's Open Data and is geocoded by Christian Quest's scripts[36]. In the framework of our study, the database has been extracted under the July 2018 version. In addition, the database also provides information on the number of employees attached to each company surveyed, among other things.

Our study focuses exclusively on companies in the forest-wood sector. There is currently no unanimous definition of the forest-wood sector (Lenglet and Caurla, 2020), although many are based on the production, processing, and sale of wood and non-wood goods and services related to the forest resource. For the purposes of our study, we restrict this definition by considering only wood production. This restriction leads us to focus on companies in different sections of the nomenclature of French activities[37], namely the sections: 02 Forestry and logging; 16 Woodworking and manufacture of wood and cork, except furniture - craft manufacture of straw and plaiting materials; 17 Paper and cardboard industries. Consequently, the partial reconstruction of the upstream part of the sector (limited to logging companies and the first transformation of wood by sawing) is carried out through the aggregation of precise sub-sections, detailed in **Appendix II**. From this reconstruction results a list of N = 70023 georeferenced companies which, according to the previous considerations, only includes the upstream segment of the forest-wood sector. Within the framework of our study, in a second step, we retain from this dataset specifically logging companies (NAF code 0220Z), sawmills (NAF code 1610A), and pulp industries (NAF code 1711Z). This subset includes N = 20123 companies from the upstream part of the forest-wood sector.

We assume that the organization of the sector respects the principle of atomicity for the companies most closely linked to the resource. This means that these companies are numerous, small, and independent from others so that one company cannot impact the market nor the other companies by an individual decision on its part. This is the case for logging companies, the majority of which have fewer than 20 employees. Therefore, the case analysis can be done with

[36] Open Database License 1.0

[37] Nomenclatures d'activités et de produits françaises, INSEE, available at: https://www.insee.fr/fr/information/2406147

equal weighting for each company. However, this assumption is not verified for industries located at a higher level in the resource value chain, such as sawmills and pulp and paper industries. For this purpose, an exhaustive mapping of sawmills with more than 20 employees, according to the type of timber (softwood, hardwood, or mixed), is carried out[38].

2.2.1.3. Measuring the aggregation and dispersion of forest-wood companies using spatial microeconomics methods

Measuring the spatial aggregation and dispersion of forest-wood companies

Industrial concentration is defined as the measure of the local deviation from the global average in terms of company density per unit area. The measurement of this deviation allows us (1) to measure the degree of aggregation and/or dispersion of the production units and (2) to identify the spatial factors, such as the location of the resource, which explain this deviation. We then refer respectively to local aggregation and dispersion. In order to distinguish distribution patterns, different statistics can be used with the null hypothesis of a uniform distribution over the territory.

Our study is based first of all on the Hotspot & Coldspot analysis which allows to spatially delimit the aggregates of industries based on the G_i^* statistic of Getis-Ord with a fixed radius using the ArcGIS software (version 10.6, ESRI). The resulting G_i^* statistic corresponds to a Z score ($H_0 \sim N(0,1)$) which identifies the state of aggregation. For significantly positive (negative) values of the Z score, the higher (lower) the value of this metric, the stronger (lower) the state of aggregation. This metric is based on the analysis of the local environment compared to the global environment. The G_i^* statistic is expressed as follows:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij}x_j - \overline{X}\sum_{j=1}^{n} w_{ij}}{S\sqrt{\frac{[n\sum_{j=1}^{n} w_{ij}^2] - (\sum_{j=1}^{n} w_{ij})^2}{n-1}}}$$

Where: x_j is the value from observation j; w_{ij} is the spatial weight between observations i and j; and n is the total number of observations. We note: $\overline{X} = \frac{1}{n}\sum_{j=1}^{n} x_j$ and $S = \sqrt{\frac{1}{n}\sum_{j=1}^{n} x_j^2 - (\overline{X})^2}$

This Hotspot & Coldspot analysis is applied to the all dataset of companies with NAF codes: 02, 16, and 17.

The areas of aggregation and/or dispersion of the observed firms are then compared to the spatial distributions of several assumed explanatory factors. The factors considered are the French administrative regions, the SERs, or the GRECOs, the last two corresponding to a territorial division of French territory according to forest production conditions.

[38] We arbitrarily choose the category of sawmills with more than 20 employees to do this mapping for practical reasons: their number is large enough to highlight trends, and small enough to keep the map legible. In addition, this category acts as a baseline in our study.

Descriptive analysis of the spatial clusters of three forest-wood companies groups

In addition, a descriptive analysis of the spatial concentration of given groups of the forest-wood sector companies was carried out using distance-based methods. These methods provide a set of tools for measuring the properties of spatial concentration by topographical measurement, relative to a reference or absolute distribution (Marcon & Puech, 2016).

In the case of the study, we use a topographic measurement: Ripley's K function. This measure allows quantifying the deviations from a supposed distribution observed. Here we assume a homogeneous distribution of companies in the forest-wood sector over the whole territory, following a homogeneous Poisson process (H_0: homogeneous Poisson process). Ripley's K_d function will therefore measure the deviations from this homogeneous Poisson distribution. The size of the aggregates and the radii of dispersion are respectively given by the maxima and minima outside the confidence interval.

We perform this descriptive analysis of spatial concentrations on a subset consisting of three groups of companies corresponding to NAF codes: 0220Z for logging companies; 1610A for sawmills; and 1711Z for pulp industries. These categories are chosen arbitrarily, with the first two acting as a baseline for highlighting the spatial characteristics of the pulp industries' category. We recall that the latter acts as a proxy for a forest biorefinery.

These groups of companies differ notably by their place in the transformation chain (logging companies being upstream; sawmills and pulp industries being further downstream) and the quality of the wood they process (sawmills process lumber, pulp and paper industries process industrial wood). We also detail this analysis for the sawmill category (NAF code 1610A) by decomposing this category into three sub-categories, according to the number of employees (a proxy for sawmill size). We thus perform the descriptive analysis for small (<20 employees), medium (20-50 employees), and large (>50 employees) sawmills[39]. This study allows checking if spatial properties of forest-wood sector companies are differentiated according to (1) the level of one company in the transformation chain, (2) the size of companies (at least in the case of sawmills), and (3) the quality of the wood to be processed.

2.2.2. Estimation of the probability of harvesting a tree by the harvest model

2.2.2.1. A survival model for the study of the impact of forest-wood companies on the forest resource

Focus on the upstream industries of the forest-wood sector raises the question of the impact of those companies and their organization on the harvesting of the forest resource - forestry and primary processing companies being directly dependent on the resource they exploit. In particular, the framework of our study on the potential impact of setting up a forest biorefinery raises the more specific question of the impact of the pulp and paper industries on the forest resource (pulp mills acting as a proxy for the forest biorefinery).

This work on the link between the forest-wood sector and the forest resource is in line with the work of Fortin *et al.* (2019), who propose to estimate a harvest probability using a statistical model known as a "survival model". This model allows us to quantify the effects of global spatialized variables, corresponding to a national scale, and local variables, corresponding to a territorial scale, on the probability of survival of a tree.

[39] We choose the thresholds of number of employees separating small, medium and large sawmills in an arbitrary way, by observing the distributions by class of employees provided by the SIRENE database and the quantiles of this distribution.

The main conclusions obtained by Fortin *et al.* (2019) are:
(1) An increase in the price of wood creates an incentive to harvest forests, in public as in private forests.
(2) This incentive is species-specific with a lower response for the most prized species.
(3) On average, private owners without management plans harvest less. The distinction between public and private forests disappears once management is put in place.
(4) The traditional French administrative regions oriented towards the timber industry (Grand-Est and New Aquitaine regions) do not show a significantly higher probability of harvesting.

In Salzet *et al*. (2020), we propose an extension of the statistical model of survival with proportional chance developed in Fortin *et al*. (2019) by including several complementary explanatory variables of economic nature. The resulting model thus makes it possible to distinguish finely the effect due to spatial heterogeneity of the resource (in a quantitative and qualitative way) from the effect due to regional technical and industrial practices on the forest resource. Furthermore, we question the fourth conclusion of the work of Fortin *et al.* (2019) by focusing this time not on French administrative regions but on SERs and GRECOs. We thus adapt the hypothesis of Fortin *et al*. (2019) by postulating that a higher probability of harvest is expected in certain SERs, such as those of the Landes and the Vosges mountains, in line with the hypothesis formulated concerning the spatial structure of the forest-wood sector.

In what follows, we adopt the method developed in Fortin *et al*. (2019) and suggest an extension of the model developed in Salzet *et al*. (2020) by adding more detail to the economic explanatory variables.

2.2.2.2. Coupling of spatialized data from the national forest inventory and spatialized data of companies of the forest-wood sector

Since 2005, the French IFN has carried out a systematic sampling of metropolitan France and Corsica according to a grid of 1 point every 10 km². Successive campaigns ensure a measurement for all the points at an interval of 5 years. At each node of the mesh, a measurement point is carried out in a zone of 900 m × 900 m tolerance. The measurement protocol is exhaustively described in IGN (2016).

Each measurement point consists of three concentric circles of radii fixed at the same center where trees are measured according to their diameter at chest height (DBH, 1.3m high). Trees are measured on different surfaces according to their DBH as described in **Table 2.1**.

DBH	Measurement radius
7.5 cm - 22.5 cm	6 m
22.5cm - 37.5 cm	9 m
> 37.5cm	15 m

Table 2.1: Hierarchical organization of the sampling plan for sub-surface measurements of variable radius according to diameter.

The measurement taken on each tree consists of taking the circumference at chest height rounded off to the nearest centimeter. Under the assumption of a perfectly circular cross-section, the diameter is deduced by a division by Pi. Moreover, additional observations are added for each measuring point: the presence of a silvicultural treatment over a 5-year period and the slope inclination in particular.

Within the framework of its mission of evaluation of the ligneous resource on a national scale, the IFN carried out from 2010 the second measurement of all the points of the grid resulting from the 2005 campaign. Over a period of 5 years, all the 41,380 measurement points were re-evaluated with an interval of 5 years since the initial measurement. During this second campaign, the cut observation was added to the observations[40].

For our study, measurement points located in protected areas and those where the land use is not wood production were ignored. In addition, points with no commercially usable wood (empty point or with only trees with DBH < 7.5 cm) were not considered. From this first sorting, 40 072 measurement points are obtained. For each point, our study uses the same French IFN measurements as those used by Fortin *et al*. (2019). We also calculate in the same way, from the individual data collected by the French IFN, the basal area variables[41] and the stem density.

We then calculate economic variables by coupling the data from the IFN with those from the SIRENE database. First, we calculate several distances between each inventory point and the nearest companies of the upstream segment of the forest-wood sector according to (1) the type of company (sawmills and pulp industries - NAF codes 1610A and 1711Z), (2) the type of wood sawn in the case of sawmills[42], and (3) the size of the sawmills[43]. Six distance variables are considered: the distance from the inventory point to sawmills with less than 20 employees; the distance from the inventory point to sawmills with more than 20 and less than 50 employees, hardwood or softwood based on the target species[44]; the distance from the inventory point to sawmills with more than 50 employees, hardwood or softwood based on the target species; and the distance from the inventory point to pulp and paper industries. Each distance is expressed as the minimum travel time between two sets of coordinates, taking into account the pre-existing transportation infrastructure. The calculation of these distances is performed by the Open Source Routing Machine (OSRM) R package (Giraud *et al.* 2020).

Second, we estimate the area density of upstream forest enterprises (NAF codes 02, 16, and 17) within the SER to which the inventory point belongs by calculating the ratio between the number of enterprises located in the SER and the surface area of the SER.

[40] A cut is considered to be the felling of at least one tree on the sampled plot. This nomenclature includes thinning and harvesting cuts.

[41] The basal area corresponds to the sum of the cross-sectional areas at 1.30m.

[42] No distinction is made between hardwood, softwood and mixed sawmills with less than 20 employees in accordance with the atomicity principle previously stated B.1.b.

[43] In this work, the size of a company is approached by its number of employees. The choice of the thresholds for the number of employees is made arbitrarily by observing the distribution quantiles of the sawmills by payroll.

[44] For an inventory point where the objective species is resinous, only the distances to small sawmills, medium and large softwood and mixed wood sawmills, and pulp and paper industries are calculated.

2.2.2.3. Cox regression modeling - or "survival model" - for estimating of the probability of harvest

Timber harvest data are in the form of censored time intervals. The date of harvest is not observed precisely, only its occurrence between the two measurements for each point is available. The use of a survival model allows this temporal structure to be taken into account.

It is assumed that the harvest date *T* follows a probability distribution function $F(T \leq t)$. Typically, the probability that the harvesting event did not occur at time t follows a longevity distribution function $S_t = F(T > t) = 1 - F(T \leq t)$. The use of data with interval censoring requires a definition of the probability of occurrence between t_1 and t_2 in the form:

$$P(t_1 < T < t_2) = S(t_1) - S(t_2).$$

If it is found that the masurement point has not yet been harvested at t_1, then the conditional probability of harvesting between t_1 and t_2 is of the form:

$$P(t_1 < T < t_2 | T > t_1) = \frac{S(t_1) - S(t_2)}{S(t_1)} = 1 - \frac{S(t_2)}{S(t_1)}$$

The survival function *S* used in survival models can follow classical parametric distributions such as exponential or Weibull laws. However, Cox regression type models with proportional hazard are preferable to these laws, as they allow to take into account hierarchical spatial effects, *i.e.*, they allow to take into account the effects that may exist between spatially close points, and this at different scales. It is assumed, as has been done by Fortin *et al*. (2019), that in this framework the longevity function is of the form:

$$S(t_i) = exp(h(x_i, \beta) \int_0^{t_i} h_0(t, g_i, \gamma) dt)$$

With x_i and g_i two vectors of explanatory variables of the measurement point i, β and γ are the vectors of parameters for the whole population. The function $h(x_i, \beta)$ corresponds to the "proportional" part of the Cox model, *i.e.*, the part of the model that is independent of time[45]. The function $h_0(t, g_i, \gamma)$ is common to all the measurement points. It corresponds to the basic risk level accumulated over time. The model studied can be rewritten in a discrete form using conditional probabilities:

$$P(t_1 < T < t_2 | T > t_1) = 1 - exp(h(x_i, \beta) \sum_{t_1}^{t_2} h_0(t, g_i, \gamma)) = \pi_i$$

[45] A fundamental assumption of the Cox model is the assumption of a proportional risk. This hypothesis implies that the ratio between the instantaneous risk functions - defined by the product of $h(x_i, \beta)$ and $h_0(t, g_i, \gamma)$ - of any pair of measurement points is independent of time.

2.2.2.4. Model specification: inclusion of ecological, technical and economic explanatory variables

In line with Melo *et al.* (2017), basal probability includes, in its definition, macrovariables that are nationally defined and that can vary over time. The proportional part of the regression, on the other hand, is supposed to take into account regional to sub-regional effects, which are grouped together as local variables. Our work uses the same specification as that described in Fortin *et al*. (2019) for the definition of the basal and proportional parts of the model with the addition of local economic variables.

The macrovariable included in Fortin *et al*. (2019) consists of a proxy of the evolution of timber prices by species in the form of the value evolution of the plot without the occurrence of logging to which is added a random or "natural" mortality effect, which is not linked to the evolution of prices. For this purpose, Fortin *et al*. (2019) use national timber prices in the form of average prices provided by the French National Forestry Office (ONF) for public land over the period 2006-2016. Additional prices for Pseudotsuga menziesii and Populus spp. in plantations and on private land have been obtained from national forest owners' associations. These values are expressed in constant euros. This evaluation is based on a silvicultural treatment with an identified objective species. The effect on the plot corresponds to the overall wood price value plus a specific effect of this species assumed at the time of the inventory. A distinct effect between softwood and hardwood is added to take into account in an integrated manner the differences in silvicultural treatment.

The local variables correspond to specificities linked to ecological and technical determinants, already studied in Fortin *et al*. (2019), to which our study adds economic variables reflecting local specificities. **Table 2.2** provides a list of the local variables used in the model.

For the ecological determinants, we tested: the basal area[46] because, as shown previously (Antón-Fernández & Astrup, 2012; Melo *et al*., 2017; Fortin *et al*, 2019), the occurrence of cutting is positively correlated to it; the stem density because it represents the state of maturity of the trees according to the law of self-thinning or planting; the slope because it influences the accessibility and ultimately the occurrence of cutting (Antón-Fernández & Astrup, 2012; Melo *et al*., 2017; Fortin *et al*., 2019) and corresponds to a proxy of soil fertility in mountainous areas

Regarding technical determinants, the presence of a silvicultural treatment is an important factor in the French case, since forest management is not systematic in the case of private forest holdings. In France, forests of over 25 ha must have a management plan if they are privately owned in order to ensure their management, while all public forests are under this type of regulation. Thus this effect has been distinguished according to the type of owner, public or private. In order to keep the points representative, the IGN keeps secret the exact location of the plots around the measurement point within an area of 900 m × 900 m. Consequently, the type of ownership can only be estimated from data from public forests managed by the ONF available free of charge. The probability of private ownership was estimated by calculating the ratio of the private area within the uncertainty zone divided by the area of this zone. Finally, these traces of management were recorded for each survey.

For economic determinants, we want to test three potential determinants. First, we want to test the distance (approached by time travel measures) between the forest resource and the nearest forest-wood company able to process it. We assume that distance variables would have a negative effect on the harvest probability: the longer the travel time, the smaller the harvest probability is. A second local variable tested is the area density of companies per SER (expressed as #establishment.km^{-2}). We suppose this variable would have a positive effect on the harvest probability: a greater concentration of companies in the SER of an IFN plot would lead to a higher probability of harvesting on this plot. These two variables are detailed previously in **section 2.2.2.2**. A third potential determinant, the regional effect, was added as a random effect. The use of this random effect makes it possible to take into account the spatial correlations between points belonging to the same region. This correlation then makes it possible to take into account

[46] The basal area is the sum of the areas of the tree sections at 1.30m height.

unobservable regional effects (Wienke, 2010) reflecting homogeneity in the local socio-administrative environment. Those economic variables are described in **Table 2.2** and complete the list of explanatory variables used in Fortin *et al*. (2019).

Variable	Description
(X longitude, Y latitude)	Noised location of IFN plots within an area of 900 m×900 m, expressed in the Lambert 93 coordinate system.
ST (m^2)	Basal area, *i.e.*, the sum of the areas of the tree sections at 1.30m height
N (#;ha^{-1})	Tree density per hectare
Slope (°)	Largest raised slope
P(privé)	Probability of private land
e	Target species defined as the species of highest value (Value = wood volume x stumpage price) present at the point of inventory when measured by the IFN.
Dist (min)	Minimum travel times between one inventory point and a company of the forest-wood sector according to: (1) the type of the company, (2) the tree species sawn in the case of sawmills, and (3) the size of the sawmills
$Dens_{SER}$ (#.km2)	Area density of companies under NAF codes 02, 16 and 17 within the plot SER

Table 2.2: Description of the variables associated with each IFN sample plot and used in the model.

2.2.2.5. Statistical tools for Bayesian inference

The parameters of the model presented previously were estimated by Bayesian inference using a Hamiltonian Monte-Carlo algorithm (detailed in **Appendix III**). The characteristics of the priors, which are not informative here, are available in **Appendix IV**. The estimation of the parameters is carried out according to the method proposed by Fortin *et al*. (2019) by *a posteriori* log-likelihood maximization, which can be written as follows:

$$L(X, G, \beta, \gamma) = \sum_{i=0}^{n} [y_i ln(\pi_i) + (1 - y_i) ln(1 - \pi_i)]$$

Where y_i is the binary variable of cut occurrence (0 when no cut is observed, 1 when a cut is observed); X and G are the matrices associated with the explanatory variables at x_i and g_i respectively for all observations; β and γ are the vectors of parameters for the whole population; π_i is the conditional probability of harvesting a tree between t_1 and t_2 knowing that the measurement point has not been harvested at t_1.

This approach is carried out in the R programming environment using Greta software based on the use of Tensorflow (Golding, 2019). The technical interest of Tensorflow is its operation using tensor calculation coupled with machine learning techniques. Thus it allows a simpler parallelization of calculations and a saving in calculation time on matrix multiplication operations. This advantage also allows intensive use of Markov chains by reducing the number of iterations necessary after convergence to sample the posterior. Verification of convergence was carried out using the CODA package (Plummer *et al*., 2006) based on the Split-$\hat{R}$ diagnosis and the effective sample size estimate N_{eff} (Ruppert & Matteson, 2015; Gelman *et al*., 2014).

2.2.2.6. Evaluation of the predictive efficiency of the model

The evaluation of the model fit follows the method used by Fortin *et al*. (2019) and is based on the Akaike Information Criterion (AIC) and the area under the sensitivity/specificity curve using the pROC package (Robin *et al*., 2011).

Results

3. Results

This section first presents and discusses the results of the forest-wood sector spatial analysis study and the harvest probability model in order to address the first two assessment criteria[47]. Second, it evaluates the implementation scenarios with regard to these criteria.

3.1. Spatial heterogeneity of the forest-wood sector as an insight on competition between forest-wood companies

3.1.1. Spatial aggregation and dispersion of forest-wood companies at the national level: a sector structured by the forest resource

3.1.1.1. Spatial heterogeneity of the forest-wood sector at the national scale

The distribution of the forest industries over the metropolitan territory reveals strong spatial heterogeneities.

Figure 1 shows the existence of significant industrial aggregates for the upstream part of the forest-wood sector (corresponding to the NAF codes 02, 16, and 17). Those aggregates are located notably in the Aquitaine region, in the Massif Central mountains, the Jura mountains, and, to a lesser extent, the Vosges mountains (areas colored red in **Figure 3.1**). We identify fifteen significant aggregates ($Gi* > 1.96$ with $p = 0.05$) over the national territory.

It can also be observed that these industrial aggregates are superimposed on a limited number of SERs. This congruence is especially more robust with the SERs with a high concentration of softwoods than with the administrative regions (for the old as well as for the new administrative regions). Indeed, aggregates with the highest values (1% of the highest $Gi*$ values) match very well with particular SERs. Those are the Landes massif (SER: F21) with two clusters of aggregations, the massifs on the western plateaux (SER: G21) and the eastern edge (SER: G41) of the Massif Central, and the massif of the second Jura plateau (SER: E20). The Southern Vosges aggregate (SERs: D11 & D12) has the particularity of bringing together forest areas that are very different in terms of ecology and, ultimately, exploitable resources. The central part of the Vosges aggregate is mainly composed of industries that exploit coniferous trees, whereas the outer ring, which faces the Champagne region, exploits deciduous trees (this distinction is visible on the sawmills distribution map, **Figure 3.2**). Finally, the aggregate in the Paris region corresponds mainly to a set of forest service companies, more than to an industrial aggregate for forestry and resource processing. This observation leads us to assume that the Paris area is a zone of attraction due to its large workforce and economic dynamism.

In addition to the presence of significant areas of aggregation, we observe the existence of areas of dispersion in the forest-wood sector. These zones are of two types. The first corresponds to areas with little woodland where the resource is dispersed (Vendée coastline, SER: A30; and Normandy, SER: A13) potentially subject to maritime imports as suggested by the presence of port infrastructures (this is the case of sawmills importing softwoods, as shown in **Figure 3.2**). The second type is wooded areas with low productivity (Mediterranean zone, SER: J; and Corsican coastline, SERs: K11 and K13) or which are difficult to access (Alps, SER: H; Pyrenees, SER: I; and Corsican mountains, SER: K12).

In **Figure 3.2**, the mapping of sawmills with more than 20 employees shows similar results to those observed previously. The location of sawmills in terms of resources exploited is explicitly distributed according to the forest eco-regions and its dominant wood type (softwood or hardwood). This trend is even more pronounced for large softwood sawmills (> 50 employees)

[47] Criterion (1) the potential impact of the implementation of a forest biorefinery in terms of competition with pre-existing companies of the forest-wood sector; and criterion (2) the potential impact of the implementation of a forest biorefinery on the forest resource.

since they are located in a reduced perimeter (< 150 km) around a softwood massif. On the other hand, a homogeneous network is observed over the national territory for smaller French sawmills (< 50 employees), *i.e.*, there is no significant aggregation or dispersion effect.

In each case, it appears (1) that the forest-wood sector is structured according to the resource on which it depends and (2) that the SERs that show the highest forest productivity already concentrate many companies of the forest-wood sector.

3.1.1.2. Focus on the forest-wood sector in the Grand Est region: a region with strong inter-company competition and a high pressure on the forest resource?

Under the condition that the local harvesting level is close to the biological growth of the local forest resource, we assume the local density of forest-wood sector companies is a good indicator of the degree of inter-company competition: when the forest resource is fully exploited, the greater the density of companies locally, the stronger the competition between companies of the forest-wood sector. A corollary of the above would be: when a tension already exists on the forest resource, the higher the concentration of companies of the forest-wood sector, the higher the pressure on the resource.

As stated above, the Grand Est region has one of the most productive SERs in France: the SERs corresponding to the Vosges mountains (SERs: D11 & D12). These SERs of high forest productivity also presents one area of aggregation of forest-wood companies in the Grand Est region: the Southern Vosges aggregate (see **Figure 3.1**). To determine whether the high density of companies in the Vosges leads to a strong local inter-company competition, we need to assess the forest resource availability in the SERs concerned (SERs: D11 & D12). Here, we approximate the availability of the resource by the flow balance of production forests[48] (excluding poplar groves) calculated by the French national forest inventory (IFN)[49]. The flow balance corresponds to biological production minus timber harvesting and natural tree mortality over a given period. The French IFN provides online access[50] to the forest inventory results (including the flow balance) according to different spatial scales (including the scale of SERs). We find that biological production exceeds timber harvesting and mortality by 1,2 +/- 0,6 Mm3/year in SER D11, and by 0,5 +/- 0,4 Mm3/year in SER D12 over the 2014-2018 period[51]. These positive flow balances indicate that the Vosges forests are under-exploited. According to our assumption, the high density of firms in the Vosges forest-wood sector is therefore not characterised by strong inter-company competition. Conversely, this does not suggests that the Vosges aggregate exert a high pressure on Vosges forest resources.

On the contrary, the Vosges aggregate is rather revealing of a strong dynamism of the Vosges forest-wood sector, in relation to the high productivity of the Vosges forests. This could represent an opportunity for a company to set up in the Vosges forest-wood sector. It could take advantage both of the availability of wood in the Vosges forests and the pre-existing dynamism of the sector without exacerbating competition between companies. We precise this result in the continuation of the spatial analysis of the forest-wood sector (see **section 3.1.2.**).

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[48] The production forest is defined by the French national forest inventory as a land area of at least 50 ares and a width greater than or equal to 20 m where trees with an absolute canopy cover of at least 10% grow and can be used to produce wood. This means that the land must allow wood production without any other use or physical conditions preventing its exploitation (integral reserve, inaccessible area, etc.).

[49] This approximation is questionable on a national scale since the IFN calculations are not strictly limited to managed production forests: unmanaged forests are also considered as contributing to the natural growth of the forest resource. This natural increase in unmanaged forests is not strictly speaking available and should be discarded. However, at the scale of the Grand Est region, the vast majority of forests are public and are therefore managed forests. We thus consider our approximation to be suitable for the purposes of our study.

[50] OCRE tool for accessing the results of the inventory: https://ocre-gp.ign.fr/ocre/afficherAccueil

[51] These are the most recent results available from the IFN. However, the time period covered does not take into account the recent bark beetle crisis affecting the Grand Est region. This sanitary crisis could reduce the flow balance and moderate our comments.

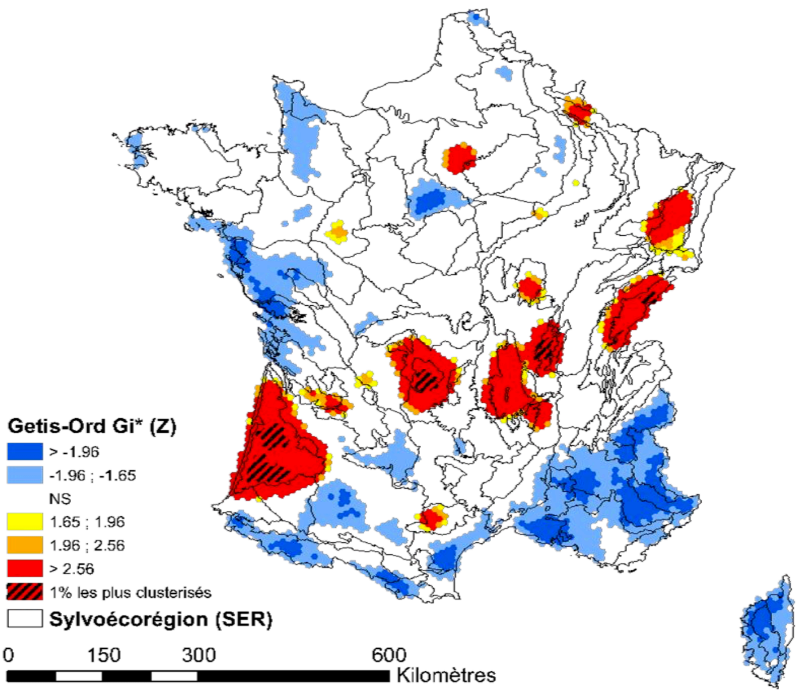

Figure 3.1: Agglomeration of the upstream of the forest-wood sector (NAF codes 02, 16, 17 - INSEE 2018). Observation of a strong congruence with the SERs.

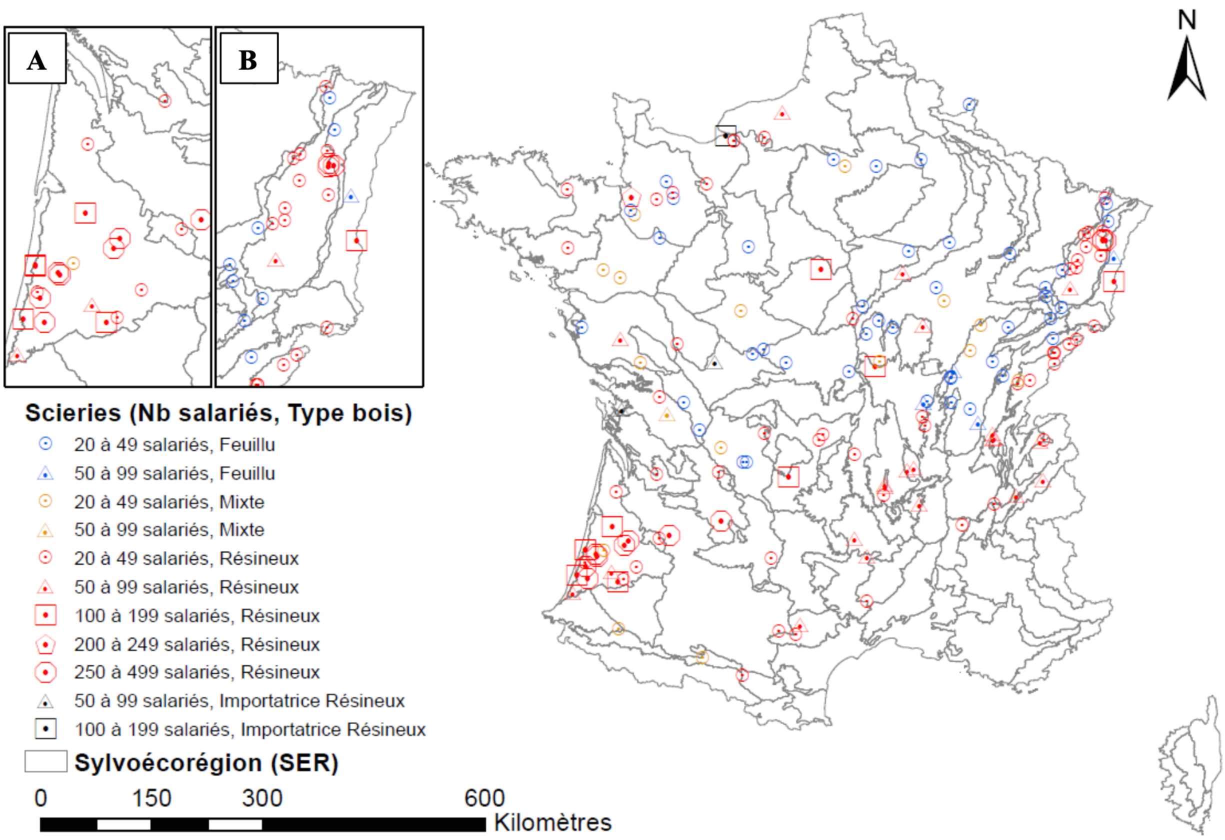

Figure 3.2: Distribution of sawmills by number of employees and type of lumber. Boxe A: zoom on Landais aggregate. Boxe B: zoom on Vosges aggregate.

3.1.2. Spatial structure specificities of forest-wood companies group

3.1.2.1. Differentiation factors in the spatial structuring of forest-wood companies

Here, we detail the results of a spatial concentration analysis of three specific groups of forest-wood sector companies: logging companies (NAF code: 0220Z), sawmills (NAF code: 1610A), and pulp industries (NAF code: 1711Z). In particular, for each category, if aggregates do exist, we determine their average size and the distance between them.

Upstream, for logging operations (NAF code 0220Z), **Figure 3.3** shows the existence of large aggregates of a radius close to 325 km. However, it is impossible to estimate the exact distance between these aggregates in **Figure 3.3** (no local minimum observed). All this figure tells us is that the distance between aggregates of logging companies seems to be greater than 400km. The spatial characteristics of these logging companies clusters are therefore not clear in our study, although those companies seem to agglomerate on a relatively large scale.

Further downstream, the analysis of the spatial distribution of sawmills is also unclear when considering sawmills altogether (NAF code: 1610A). However, a decomposition of the sawmills category according to the number of employees (a proxy for the size of sawmills) allows certain spatial characteristics to emerge. The spatial structure of sawmills in terms of the number of employees, shown in **Figure 3.3** (right-hand column), is to be divided into two groups:

(1) Small sawmill units (< 20 employees) present throughout the metropolitan territory are homogeneously distributed in forest areas and process the resource mostly present in their SER.

(2) Medium (20-50 employees) to large-sized units (> 50 employees) are distributed in aggregates at very short distances (< 30 km) located in softwood SERs. We also observe a distance of about 390 to 410 km between aggregates. This observation is in agreement with the results of **Figure 3.2**.

To sum up, the spatial structure is spatially homogeneous concerning the small units. Aggregation patterns emerge when considering medium and large sawmills in softwood SERs.

The distribution of pulp mills (NAF code: 1711Z) shows aggregation at very short distances (< 5 km, see **Figure 3.3**). It indicates relatively small processing platforms or "industrial clusters”. Those industrial clusters appear to be scattered over long distances (~ 230 km radius).

This spatial analysis of different subcategories of companies suggests that the spatial structure of forest-wood sector companies is at least differentiated according to: (1) the level of companies in the transformation chain (logging companies being upstream; sawmills and pulp industries being further downstream); (2) the size of companies (small sawmills versus medium and large-sized sawmills); and (3) the quality of the wood to be processed (sawmills transforming lumber, pulp and paper industries transforming industrial wood).

3.1.2.2. Completing previous intuitions on the inter-company competition and the pressure on forest resources in the Grand Est region

First, the above shows that the spatial distribution and structuration of companies are different according to the group of forest-wood sector companies considered, in relation to group characteristics (*e.g.* the quality of wood to be processed). This may suggest that a company in the forest-wood sector evolves partly in a closed environment, within its group or category. Thus, interactions between companies in the forest-wood sector could be embodied mainly through interactions between companies in the same category of activity. Sawmills may then not compete with pulp mills. In the specific case of sawmills and pulp mills, this argument is all the more robust since the two categories of companies do not process the same resource: while sawmills mostly process first quality wood (lumber), pulp mills mostly use second quality wood (industrial wood).

Second, according to economic theory (Fujita *et al.*, 1999), agglomeration patterns previously observed can be interpreted as the combination of two economic forces. A first economic force of "agglomeration": the organization of companies into agglomerates presents logistical advantages in terms of transport operations (for supply and sale) and biomass storage, for instance. This first economic force corresponds to a centripetal force, *i.e.*, an attraction that drives companies to agglomerate. A second economic force at work is that of "dispersion": in our case, for a given category of activity, these companies compete for the same resource, which is forest biomass. This competition, linked to the size and needs of these companies, leads to a centrifugal force that pushes agglomerates away from each other. Thus, the distance separating aggregates of companies of the forest-wood sector is somehow a manifestation of a competition between agglomerates of the same category of activity: the greater the competition, the greater the distance separating the agglomerates of the same category of activity.

Comparing the two bottom graphs **Figure 3.3**, it appears that a stronger competition may be hypothesized between medium and large sawmills than between pulp mills: agglomerates of medium and large sawmills are separated by about 400km, while pulp mills agglomerates are separated by about 230km. A possible explanation for this difference may lie in the number of companies of each category: while the number of sawmills exceeded 700 in 2018, the number of pulp mills on the metropolitan territory was less than 10 at the same year[52]. This difference can be seen on maps provided by the FCBA and presented in **Figure 3.4**. The difference in numbers of companies over the French metropolitan area results in a difference in density of companies. The higher density of sawmills on the national territory may lead to a higher demand for lumber, and thus to a relatively higher competition between aggregates.

Those considerations are in line with previous conclusions resulting from the analysis of the forest-wood sector spatial structure at the national level. Indeed, if the concentration of forest-wood companies in the Grand Est region is essentially due to a high concentration of sawmills (as suggested by **Figure 3.2**), the economic environment may not be so competitive for the implementation of a forest biorefinery.

It is nevertheless important to note that this does not mean that competition between pulp mills is weak. Their low number at the national level, coupled with an industrial wood resource about half as important in terms of volume harvested than that of lumber[53], may suggest a highly competitive environment[54]. Besides, what **Figure 3.3** shows is that despite the low number of firms in this category (reflected by a large confidence interval in **Figure 3.3**), the spatial structure of pulp mills is still very pronounced. The emergence of a new pulp mill - in our case, the emergence of a new forest biorefinery - can thus disrupt this existing spatial structure and can consequently generate/suffer strong competition for/from other pre-existing firms, in particular: the Norske Skog Golbey pulp mill in the Grand Est region.

As a reminder, we address the assessment criterion related to the impact on inter-companies competition by how the implantation of a new company may modify the pre-existing spatial structure of the forest-wood sector, for a given category. Thus, according to its modalities, the implementation of a forest biorefinery may modify the spatial structure of the pulp mill group of companies, and would then have an impact on inter-pulp mills competition.

[52] According to “Enquête Annuelle de Branche - Exploitation forestière et Scierie 2018” conducted by Agreste: https://agreste.agriculture.gouv.fr/agreste-web/methodon/S-Prod.%20Exp.%20forestière%20%202018/methodon/

[53] Source: Memento FCBA 2020 - https://www.fcba.fr/wp-content/uploads/2020/10/memento_2020.pdf

[54] This could also be explained by an overall lack of profitability of the pulp production activity. This explanation seems relevant according to the literature.

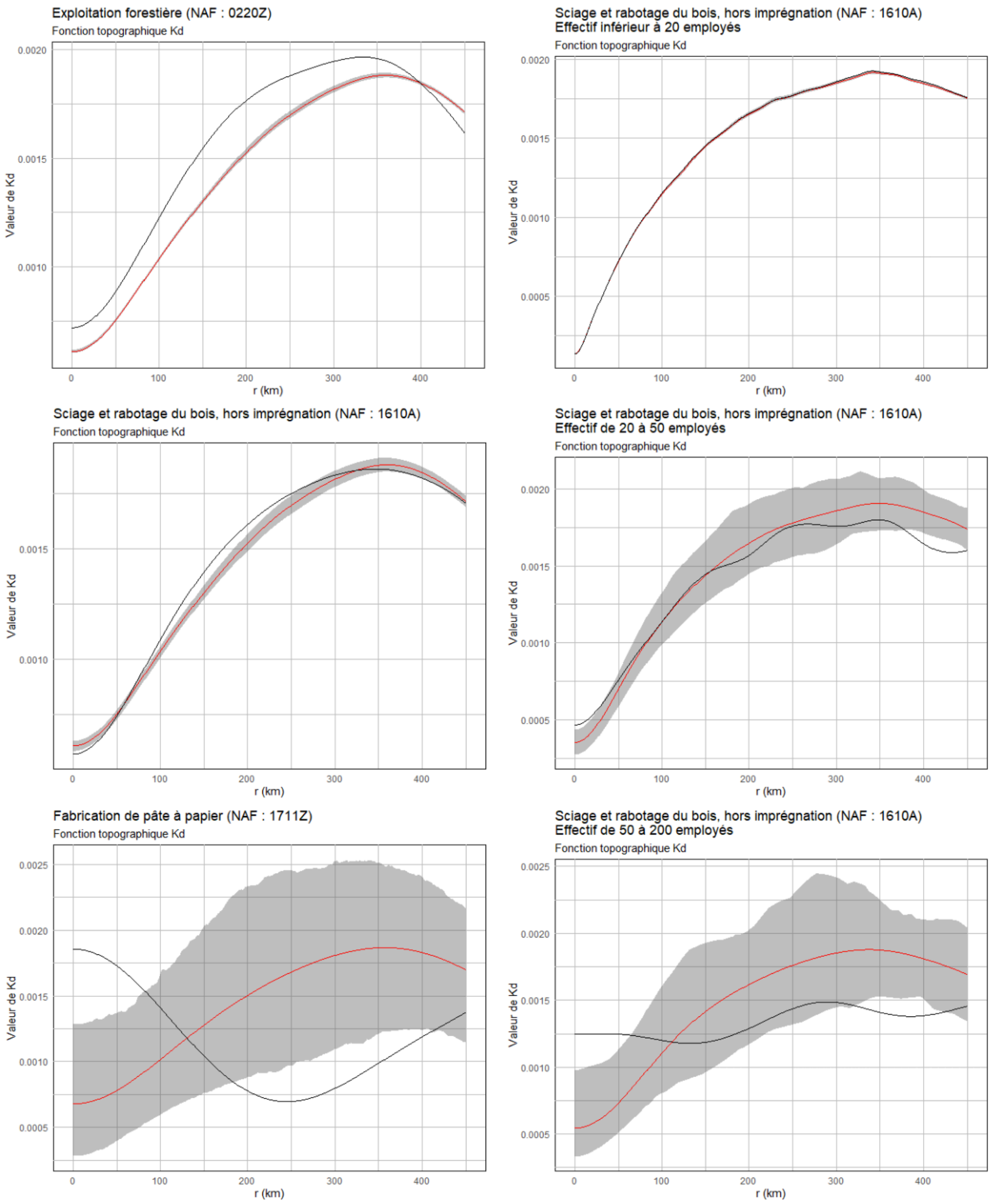

Figure 3.3: Results of the topographic function Kd for the main sectors of the forest-wood sector (NAF codes 0220Z, 1610A, and 1711Z). Reading: the K_d curves, in black line, located above (below) their confidence intervals, represented as shaded area, detect a phenomenon of spatial concentration (dispersion). The confidence intervals are generated according to 1000 simulations.

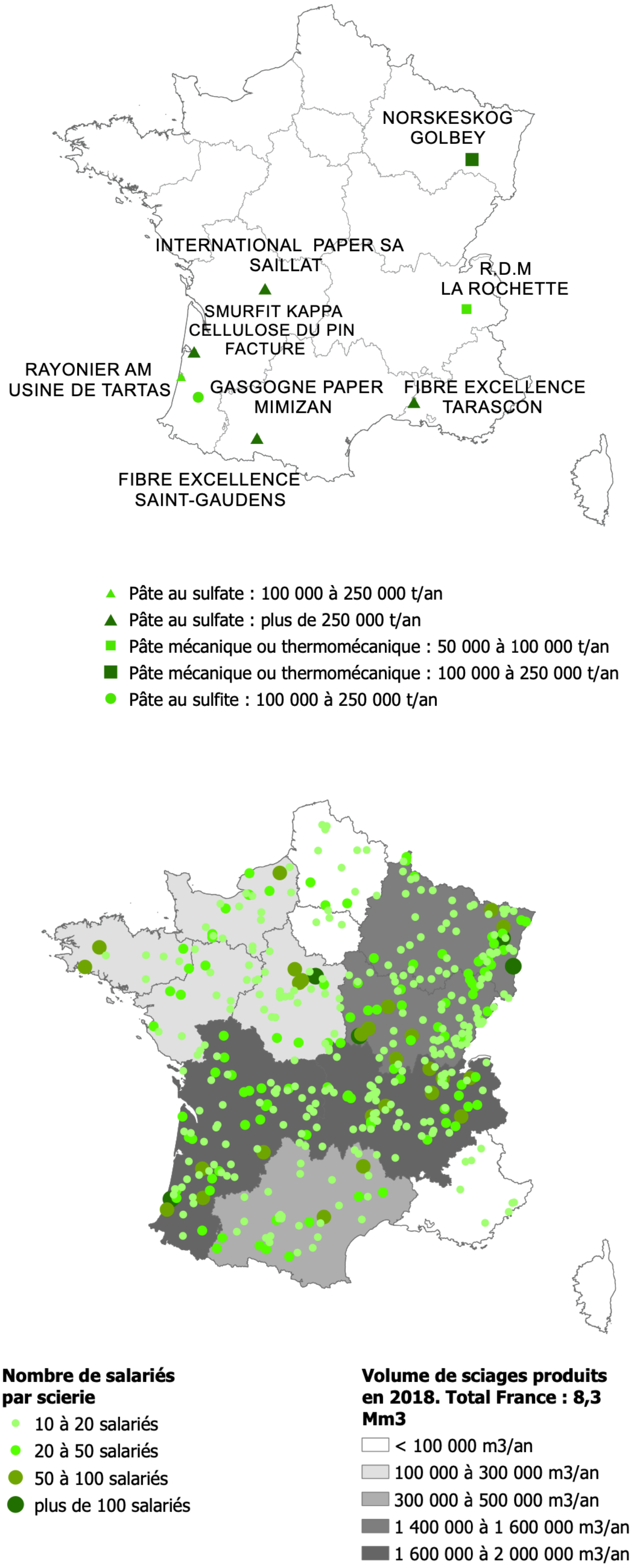

Figure 3.4: Location of French mills that produces cellulose pulp (top) and sawmills (down). Source: Memento FCBA 2020.

3.2. Results of the survival model and the impact of the forest-wood sector on the forest resource

3.2.1. Model adjustment results at the national level: significance of economic variables

The fitted model can be written as follows:

$$(1): P(t_1 < T < t_2) = 1 - exp(h(x_i, \beta)\sum_{t_1}^{t_2} h_0(t, g_i, \gamma))$$

For the i-th plot:

$$h_0(x_i, g_i, \gamma) = exp(\vec{G}_{Macrovariables} \times \vec{\alpha}_{Macrovariables}) = exp(\alpha_0 + (\alpha_1 + \alpha_{2,res} + \alpha_{3,e,i}) \times Value_{e,i,t})$$
$$h(x_i, \beta) = exp(\vec{X}_{Ecological} \times \vec{\beta}_{Ecological} + \vec{X}_{Technical} \times \vec{\beta}_{Technical} + \vec{X}_{Economic} \times \vec{\beta}_{Economic} + \beta_{9,r} + \beta_{10,SER})$$

With:

$$\vec{X}_{Ecological} \times \vec{\beta}_{Ecological} = \beta_1 \times BA_i + \beta_2 \times \frac{BA_i \times N_i}{1000}$$

$$\vec{X}_{Technical} \times \vec{\beta}_{Technical} = \beta_3 \times Slope_i + (\beta_4 + \beta_5 \times Manag_i) \times P_{priv,i}$$

$$\vec{X}_{Economic} \times \vec{\beta}_{Economic} = \beta_{6,type,size} \times Dist_{sawmill,type,size,i} + \beta_7 \times Dist_{pulp,i} + \beta_8 \times Dens_{ind,SER,i}$$

$$\beta_{9,r} \sim N(0,\gamma) and \beta_{10,SER} \sim N(0,\omega)$$

Where: $Value_t$ is the standing value of the target species *e* in year t according to French National Forest Office prices; *BA* is the basal area ($m^2.ha^{-1}$); N is the stem density ($\#.ha^{-1}$); *Slope* is the slope (%); *Manag* is the binary variable where the value 1 indicates the presence of traces of development in the interval of 5 years, 0 otherwise; P_{priv} is the probability that the measurement point is located on private land; $Dist_{sawmill,type,size,i}$ is the minimum travel time between a plot i and the closest sawmill according to the type and size of the sawmill; $Dist_{pulp,i}$ is the minimum travel time between a plot i and the closest pulp mill; $Dens_{ind,SER,i}$ is the density of companies per SER per unit area ($\#.km^{-2}$); *i* is the index of measurement points; *res* is the index of a softwood species; *e* is the index of the target species; *r* is the index of the administrative region; γ the intra-regional variance-covariance; and ω the intra-SER variance-covariance[55].

The adjusted values of the parameters are available in **Table 3.1**. Modelled probabilities for the period 2005-2010 and with sliding bounds to the period 2011-2016 are available spatially in **Figure 3.5** and by SER in **Figure 3.7**. The spatial decoupling between the 5-year cumulative basal risk and the impact of local factors is available in **Figure 3.6**.

[55] Since $BA_i \times N_i$ values are generally large, a scaling factor of 10^{-3} has been added to avoid computational problems during adjustment.

Parameter	Mean value	Credibility interval 95%
α_0	-3.8698667	[-4.7794087 ; -3.056858]
$\alpha_{1,RefOak}$	1.73662x10^{-2}	[0.0136723 ; 0.021223]
$\alpha_{2,res,RefFir}$	4.02316xx10^{-2}	[0.0275026 ; 0.052145]
$\alpha_{3,Beech}$	4.35250x10^{-2}	[0.0359659 ; 0.051403]
$\alpha_{3,Spruce}$	-8.668x10^{-4}	[-0.0035786 ; 0.001918]°
$\alpha_{3,DouglasFir}$	-1.01180x10^{-2}	[-0.0137675 ; -0.006194]
$\alpha_{3,ScotsPine}$	9.5755x10^{-3}	[0.0009839 ; 0.017814]
$\alpha_{3,MaritimePine}$	3.10261x10^{-2}	[0.0234829 ; 0.038439]
$\alpha_{3,Poplar}$	3.12531x10^{-2}	[0.0213142 ; 0.041087]
$\alpha_{3,Coppice}$	1.157674x10^{-1}	[0.0920427 ; 0.140018]
β_1 (BA)	5.047166x10^{-1}	[0.4612482 ; 0.548858]
β_2 (BA x N)	-5.28035x10^{-2}	[-0.0671760 ; -0.037718]
β_3 (Slope)	-1.60788x10^{-2}	[-0.0177978 ; -0.014335]
β_4 (P_{priv})	-6.497339x10^{-1}	[-0.7167803 ; -0.582020]
β_5 (Manag and P_{priv})	5.048232x10^{-1}	[0.4310672 ; 0.574930]
$\beta_{6,small}$ (sawmill with less than 20 employees)	-1.66093x10^{-2}	[-0.0592954 ; 0.025754]°
$\beta_{6,softwood,medium}$ (softwood sawmill with more than 20 but less than 50 employees)	-5.94555x10^{-2}	[-0.1226667 ; 0.001189]°
$\beta_{6,hardwood,medium}$ (hardwood sawmill with more than 20 but less than 50 employees)	-9.84596x10^{-2}	[-0.1481401 ; -0.045796]
$\beta_{6,softwood,large}$ (softwood sawmill with more than 50)	-8.82888x10^{-2}	[-0.1468534 ; -0.016147]
$\beta_{6,hardwood,large}$ (hardwood sawmill with more than 50)	-4.61426x10^{-2}	[-0.1072490 ; 0.014316]°
β_7 (pulp mill)	-9.82572x10^{-2}	[-0.1744246 ; -0.020615]
β_8 (Companies density per SER)	2.091162x10^{-1}	[0.1637282 ; 0.258703]
$\beta_{9,r}$	3.659402x10^{-1}	[0.2309895 ; 0.596701]
$\beta_{10,SER}$	1.888859x10^{-1}	[0.1512141 ; 0.232714]

Table 3.1: Distribution of posteriors after estimation by Bayesian inference (°: 0 included in the interval, that means the result is not statistically significant).

The maps in **Figure 3.5** show the area distribution of the occurrence of harvesting and the modeled 5-year harvest probability of harvesting per IFN plot. We can see that the probabilities converge towards the frequencies, *i.e.*, that the estimates of harvest probabilities from the model are consistent with the values of occurrence of harvesting from the IFN data.

Adding the distance variables (minimum travel times between an IFN plot and the closest sawmills and pulp mill) as an extension of the work of Salzet *et al*. (2020) leads to a decrease in the AIC of 140 (a decrease of 680 compared to the model of Fortin *et al*. (2019)). The explanatory power of the model is therefore slightly better.

As a reminder, the main conclusions obtained by Fortin *et al.* (2019) are:
(1) An increase in the price of stere of wood creates an incentive to harvest forests, in public as in private forests.
(2) This incentive is species-specific with a lower response for the most prized species.
(3) On average, private owners without management plans harvest less. The distinction between public and private forests disappears once management is put in place.
(4) The traditional French administrative regions oriented towards the timber industry (Grand-Est and New Aquitaine regions) do not show a significantly higher probability of harvesting.

As it is the case in the work of Salzet *et al*. (2020), the first three conclusions remain valid in this extension of the model.

However, **Figure 3.5** shows, in particular, that there is a higher density of occurrence of harvesting in SERs with aggregates of forest-based enterprises (see **Figures 3.2 and 3.5**). This trend is well transcribed in the model with a concentration of high harvesting probabilities (10th quantile, *i.e.*, the 10% highest probabilities) in resinous SERs with industrial aggregate(s).

In addition, in **Figure 3.6**, the risk decomposition between basal risk and the proportionality factor shows that:

(1) Basal risk accounts for resource availability for harvesting. This risk is related to the characteristics of national demand. Thus the regional disparities visible are the differences in species between the northern and southern half of the country (Mediterranean species being less in demand).

(2) The proportionality factor of the risk is spatially structuring because it shows that a large part of the resource is not available despite demand. Local cutting factors result in the formation of privileged exploitation zones corresponding to the division into SERs.

Like Salzet *et al*. (2020), we conclude that the fourth conclusion in Fortin (2019) is to be revised following the division of the forest-wood sector according to the SERs. It appears in **Figure 3.7** that strong regional disparities within the new Aquitaine lead to an underestimation of the level of cutting. The observation made here is that there is a correspondence between the industrial aggregate zones/SERs and the important harvesting areas.

Concerning the value of the parameters, we find similar results to those obtained in Fortin *et al*. (2019) and Salzet *et al*. (2020). Among other things, as it is already observed in Fortin *et al*. (2019) and Salzet *et al*. (2020), we note the significant effect on the probability of harvesting a tree of particular variables such as: the basal area; the probability that the inventory point is on private property; the presence of forest management operation; and the density of companies of the forest-wood sector within a SER.

With regard to the economic variables of interest, the value of the parameter corresponding to the enterprise density variable is positive. This confirms the previous hypothesis that a high enterprise density within a SER will locally increase the probability of harvesting. In addition to the work carried out in Salzet *et al*. (2020), our study proposes a decomposition of the economic variable of distance to firms by considering (1) sawmills and pulp industries, (2) the type of wood sawn by the sawmill, and (3) the size of the sawmill. We observe that the effect of distance is significant only for certain categories, namely: hardwood sawmills of medium size, softwood sawmills of large size, and pulp industries. In other words, the distances to small sawmills, medium size softwood sawmills, and large size hardwood sawmills have not a significant effect on the probability of a tree to be harvested. Regardless of the category considered, the value of the parameter associated with the distance variable is negative. Thus, the greater the travel time between the inventory point and the nearest company that is capable of harvesting the resource, the lower the probability that a tree will be harvested. This result confirms our hypothesis. Among the statistically significant distance variables, distance variables relative to medium-sized hardwood sawmills and to pulp and paper industries categories present the most negative parameter values, while the distance variable relative to large softwood sawmills present a significant but less negative parameter[56]. This means that the decrease in the probability of a tree being cut due to an increase in the travel time between the resource and a given forest-wood company will be relatively higher in the case of medium-sized hardwood sawmills and pulp mills than in the case of large softwood sawmills. Medium-sized hardwood sawmills or pulp mills, therefore, have an effect on the resource that is rather located in their close surroundings, while large softwood sawmills have a relatively greater influence on a more distant resource that implies longer travel times. In other words, for the same travel time to the nearest company, a large softwood sawmill is more likely to cut a tree than a medium-sized hardwood sawmill or a pulp mill.

[56] This comparaison is only relevant because the input data, *i.e.,* the travel time data, are of the same nature. Thus, the distance variables become comparable with each other, but cannot be compared with explanatory variables such as the density of enterprises within the SER, for example.

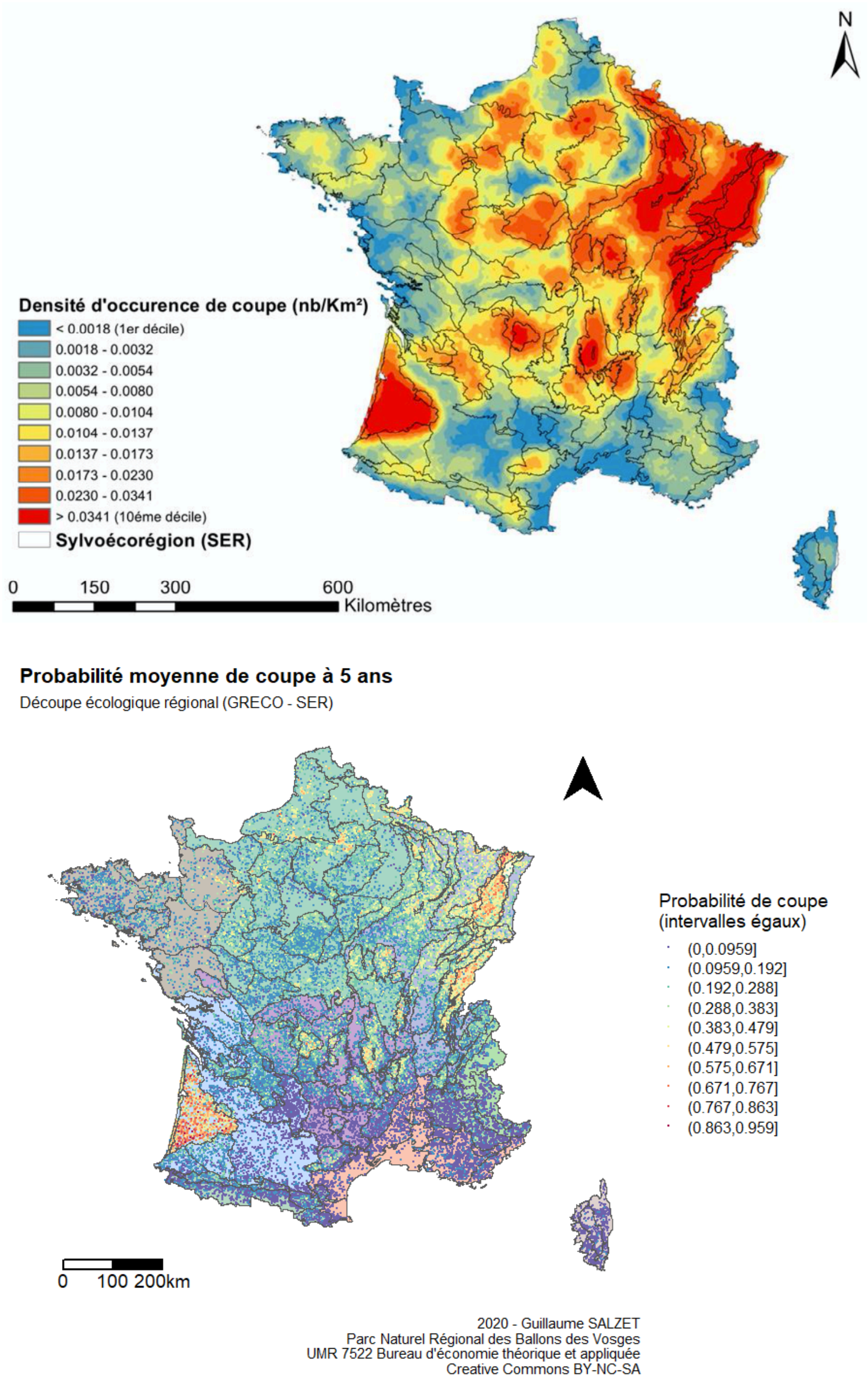

Figure 3.5: Spatial distribution of harvest occurrences (top) and modelled 5-year harvest probability per IFN plot (bottom). Background color: GRECO. The density of cut occurrence is derived from a Gaussian core with a radius of 30 km.

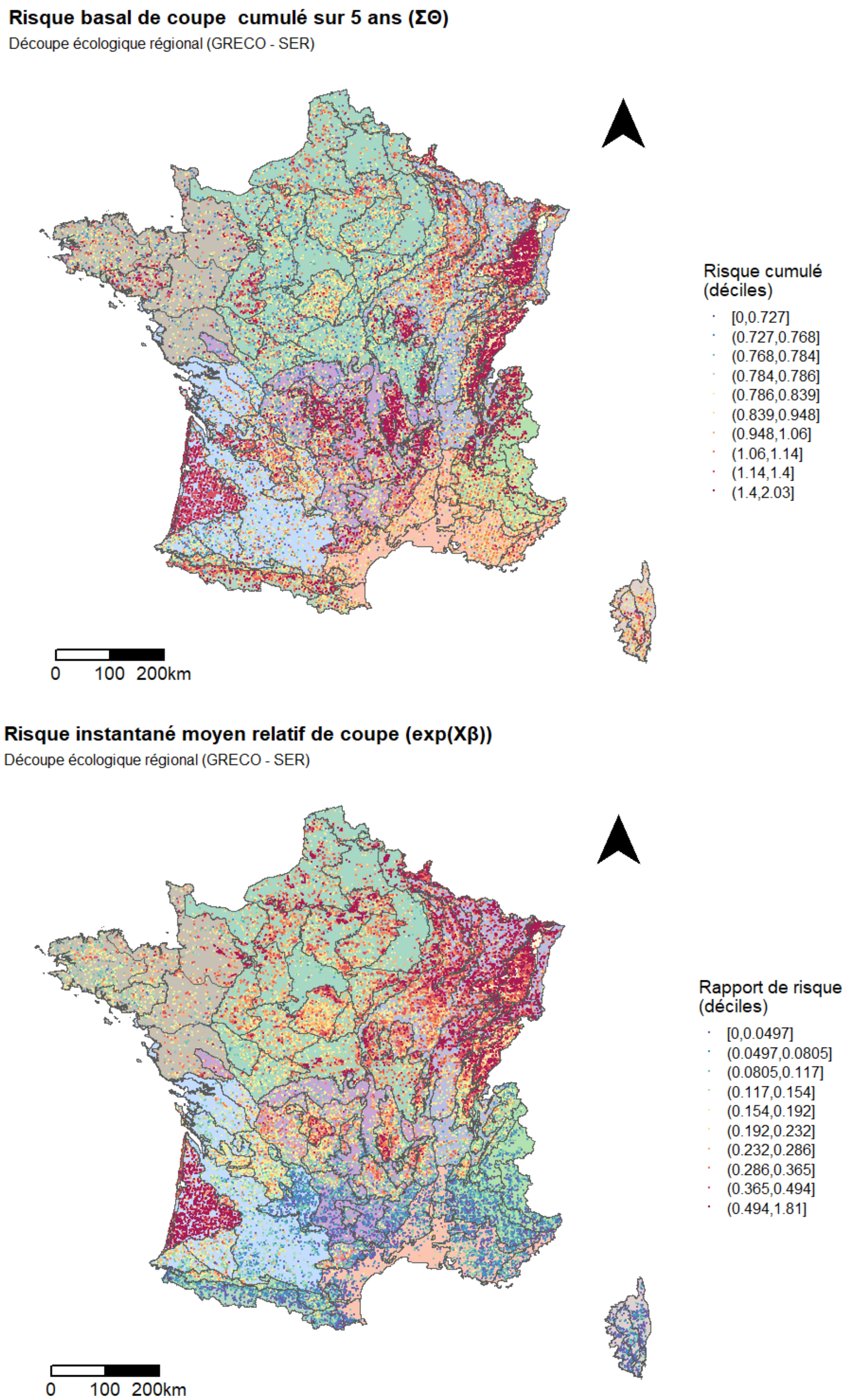

Figure 3.6: Decomposition of the risk of cutting according to macrovariables (top) and local variables (bottom). Background color: GRECO. The basal cutting risk is accumulated over a 5-year period.

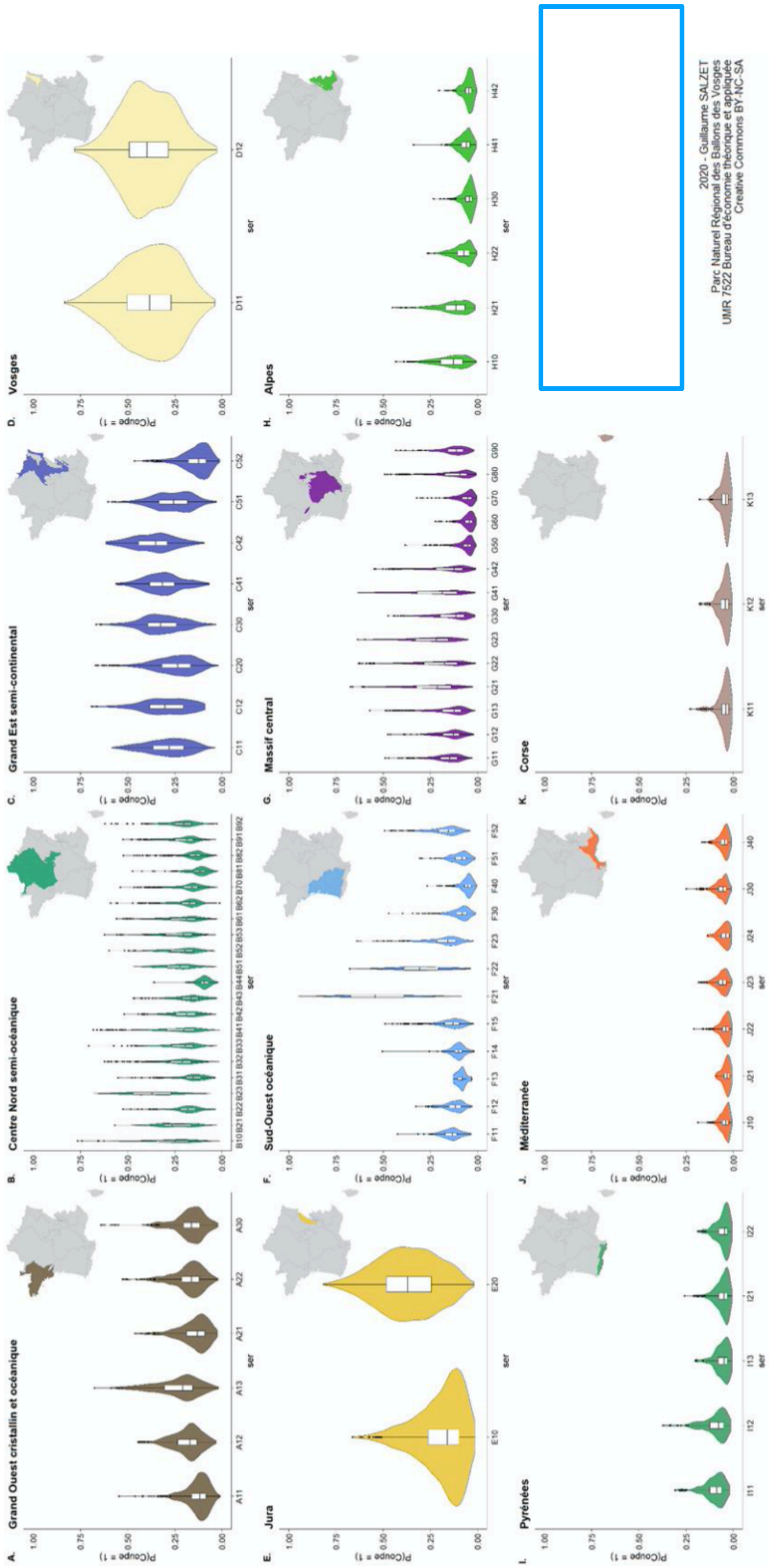

Figure 3.7: Distribution of harvesting probabilities modelled by regional ecological decoupling (color: GRECOs, division: SERs).

3.2.2. Focus on the forest-wood sector in the Grand Est region: insights on the potential impact of the implementation of a forest biorefinery on forest resources

The potential impact of the implementation of a biorefinery is captured in the survival model by two proxy variables: the density of companies within the SER of the measurement plot and the travel time to the pulp and paper industry[57].

If we look more closely at the case of the Grand Est region, we can see that it is a region where the industry density per SER is among the highest in France: adding one more company like a forest biorefinery will have a positive marginal effect on the effect of company density over the probability of harvesting. Thus, according to its modalities, the implantation of a forest biorefinery will mechanically (at least slightly) increase the probability of harvesting, and thus the pressure on the regional forest resource.

The effect of distance from the pulp mill could be analyzed using **Figure 3.8**. **Figure 3.8** compares four maps: the map of estimated harvesting probabilities for the Grand Est region, and the travel time maps for the three categories of firms that have a significant effect on the probability of harvesting (*i.e.*, the distance effect for pulp industries, the distance effect for medium-sized hardwood sawmills, and the distance effect for large softwood sawmills). As expected, the distance effect alone cannot explain the current probabilities that a tree will be cut down: other factors have a significant explanatory role (see **section 3.2.1.**). Nevertheless, it is possible to notice the local influence of sawmills on the concentration of high logging probabilities on the map of the Grand Est, as for example in the North of the Vosges massif. Thus, within the Vosges massif agglomerate, the probability of harvesting seems to be mainly explained by the presence of large softwood sawmills.

This observation echoes previous considerations, notably the results in **Figures 3.2 and 3.5**. It must also be noticed that the travel time to the nearest pulp mills seems to have a small impact on the probability of harvesting in the Grand Est region[58]. In other words, these results suggest that the pressure on the forest resource in the Grand Est region is mainly linked to a high concentration of sawmills. Thus, if the effect of pulp mills on the harvest probability is significant at the national scale, it does not currently seem to be significant at the regional scale corresponding to the Grand Est region. This observation is then consistent with the discussion in **section 3.1.2.2.**, reinforcing the argument that, because sawmills and pulp mills use a different raw material and evolve in their own category of companies, the economic environment would not be so competitive for the implementation of a forest biorefinery.

However, there is nothing to indicate that the *ex nihilo* implementation of a forest biorefinery in the Grand Est region, which does not have pulp mills according to the NAF classification, would have no impact on the resource. First, an inconsistency in our argumentation reveals a methodological bias in our study. Indeed, the NAF classification does not consider the Norske Skog Golbey as a pulp mill, *i.e.*, a mill that produces cellulose pulp, while it does. The contribution on the harvesting probability of the distant variable relative to pulp mills in the Grand Est region is expected to increase when considering the Norske Skog pulp mill. Second, the survival model presented above demonstrates that the time travel to the nearest pulp mill has a significant impact on the forest resource. Regardless of the location of the forest biorefinery, this suggests that the probability of harvesting nearby trees should increase, reflecting an increasing pressure on the resource. Lastly, despite the effort to detail the effects of distance according to the size of the companies, the results do not allow to conclude on the actual effect of the size of a company on the forest resource.

[57] As a reminder, we consider pulp and paper mills as a good proxy for a forest biorefinery.

[58] This is mainly explained by the fact there is no pulp mill in the Grand Est region according to the NAF classification.

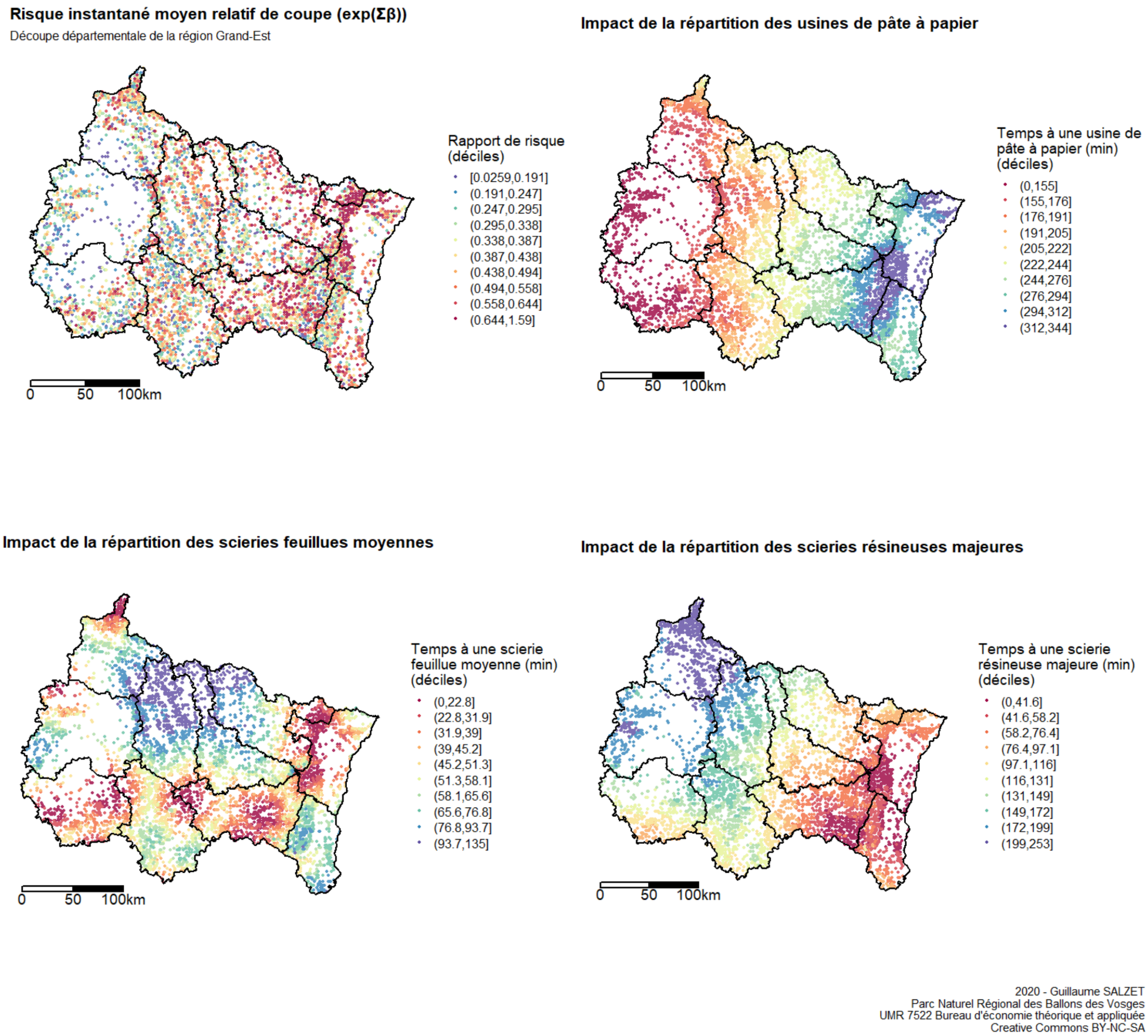

Figure 3.8: Maps representing the risk of a tree to be cut and the significant time travel effects retained in the model fit, in the Grand Est region.

3.3. Evaluation of implementation scenarios according to the two first assessment criteria

3.3.1. A synthesis of the contribution of previous quantitative studies of the forest-wood sector to the assessment of implementation scenarios.

Previous sections show that a high density of forest-wood industries characterizes the Grand Est region. This specificity results in a potentially strong competitive environment, a strong economic dynamism of the sector, and a significant pressure on the resource.

In this section, we assess each scenario according to two assessment criteria. As a reminder, criterion (1) corresponds to the potential impact of the implementation of a forest biorefinery in terms of competition with pre-existing companies of the forest-wood sector. To address this criterion, we made two assumptions. First, we assumed the implementation of a forest biorefinery could exacerbate inter-companies competition under a dual condition, that is: the local harvesting level is close to the biological growth of the local forest resource, and the density of industries is already high. We showed in **section 3.1.1.** that only the second part of this dual condition was met and that the local harvesting level has not reached the biological growth of the local resource. Thus, the forest-wood sector of the Grand Est region is therefore not characterized by strong sectoral competition but, on the contrary, by a strong dynamism - especially in the Vosges mountains. No pre-existing regional competition between forest-wood companies could then apparently be exacerbated by the implementation of a forest biorefinery in the Grand Est region. Second, we assumed the implementation of a forest biorefinery can affect competition by modifying the pre-existing spatial structure of the forest-wood sector. We showed in **section 3.1.2.** that the spatial distribution and structure of forest-wood companies are differentiated by categories of companies, in relation to their characteristics, *e.g.* the kind of wood that is to be processed. Interactions between companies are then partly embodied within a given category of companies (and not only between companies of different categories). We concluded the implementation of a forest biorefinery is likely to create competition by modifying the spatial structure of the pulp and paper industry category. On the contrary, it is unlikely that a biorefinery would compete with a sawmill. Therefore, criterion (1) is approximated by the disturbance the implementation of a forest biorefinery cause on the spatial structure of the pulp and paper industry category.

Criterion (2) corresponds to the potential impact of the implementation of a forest biorefinery on the forest resource, which is approximated by the probability of harvesting. We assumed a high density of forest-wood companies and the proximity of the resource to companies able to process it will increase the probability of a tree to be cut and, consequently, the pressure on the resource. **Section 3.2.** validates those assumptions and shows that: (i) increasing the industry density will increase the pressure on the forest resource and (ii) that the closer an industry is to the resource, the more likely it is to be harvested (at least for certain industry categories). More precisely, the analysis of the influence of the travel time to the closest company shows that: (1) pulp mills have a significant effect on the probability of harvesting, suggesting that the implementation of a forest biorefinery will have a significant impact on the regional forest resource; and (2) depending on the size of the company, the effect on the probability of harvesting may or may not be significant. Since pulp mills are all large in size, this size effect is not identifiable for this category. This last point may complicate the analysis of scenarios where different sizes of biorefineries are considered.

3.3.2. Qualitative assessment of scenarios for the implementation of a forest biorefinery in the Grand Est region according to two assessment criteria

In this section, we assess each implementation scenario considered with respect to assessment criteria (1) and (2), and using the results previously presented. This assessment is reported in **Table 4**, where a score between 1 and 5 is assigned to the different scenarios for each of the two assessment criteria. The grade "1" corresponds to "very strong impact", the grade "2" corresponds to “strong impact", the grade "3" corresponds to “medium impact", the grade "4" corresponds to “low impact”, and the grade "5" corresponds to "very low impact". A short rationale for the scores assigned to each scenario and for each criterion is provided below with a reminder of each scenario’s characteristics.

Scenario 1: Implementation of a forest biorefinery *ex nihilo*.

Main characteristics:

- **Approximate location**: Golbey / Épinal.
- **Approximate size**: Production of 200,000 t/year of biofuel for approximately 100 to 200 jobs created.
- **Specific points**: Proximity of the Vosges forest resource; use of pre-existing road system of Épinal; large scale project potentially competing with pre-existing industries of the forest and wood sector.

This scenario acts as a baseline scenario to which we compare the other implementation scenarios. This scenario scores 1 for each criterion. Indeed, setting up a forest biorefinery *ex nihilo* in Épinal, close to the Norske Skog Golbey pulp mill, would, *a priori,* strongly modify the spatial structure of the pre-existing pulp mills. Moreover, this scenario places the forest biorefinery at a relatively short distance from the Vosges forest resource and would lead to a marginal increase in the density of companies within the Grand Est region: this would result in an increase of the pressure on the nearby forest resource.

Scenario 2: Conversion of a petrochemical refinery into a forest biorefinery unit.

Main characteristics:

- **Approximate location**: Dunkerque.
- **Approximate size**: Production of 200,000 t/year of biofuel for approximately 100 to 200 jobs.
- **Specific points**: Multi-input biorefinery and access to port infrastructure, allowing diversification of supply; inclusion in a pre-existing R&D project.

This scenario involves building the biorefinery on a pre-existing petrochemical refinery, that is, the old Flandres petrochemical refinery as part of the BioTfuel project. While different from the baseline scenario, this scenario acts conceptually in the same way as the latter for the first assessment criterion. Indeed, converting a petrochemical refinery is equivalent to setting up a forest biorefinery *ex nihilo* as it would, *a priori*, modify the spatial structure of the pre-existing pulp mills. However, as this scenario places the forest biorefinery in Dunkerque, that is, outside the Grand Est region and far from the pulp mills located in the metropolitan area, it scores slightly better than the previous scenario with regards to criterion (1). Furthermore, in scenario 2, the remote location of the forest biorefinery does not lead to a marginal increase in the density of companies within the Grand Est region, and would not much increase the pressure on the Grand Est forest resource that is far away. Coupled with a multi-input supply strategy and the access to port infrastructure that allows for importation, the impact on the Grand Est forest resource should score even lower. Thus, this scenario scores respectively 2 and 4 for criterion (1) and criterion (2).

Scenario 3: Conversion of a pulp mill into a forest biorefinery unit.

Main characteristics:

- **Approximate location**: Golbey Green Valley Energy industrial site.
- **Approximate size**: Production of 200,000 t/year of biofuel for approximately 100 to 200 jobs maintained.
- **Specific points**: Proximity of the Vosges forest resource; use of pre-existing industrial infrastructures of Épinal; forest biorefinery located within an industrial ecosystem; acquired skills; relatively low capital investment (transformation of the production chain and not construction *ex nihilo*); already assured supply; dynamism of the site in innovation and innovative projects and proximity of R&D units; pre-existing links with local players such as Grand Epinal, partner of the projects.

For this scenario, contrary to scenario 2, the pre-existing company that is converted into a forest biorefinery (that is, Norske Skog Golbey pulp mill) is already part of the forest-wood sector: the density of companies of the forest-wood sector within the Grand Est region would then remain unchanged. Moreover, since forest biorefineries and pulp mills, *a priori*, exploit the same type of raw material, use similar processes, and are similar in structure, the implementation of the forest biorefinery would be done in a harmonious way within the pre-existing spatial structure of the pulp and paper industries. The demand for the resource would vary only marginally: the raw material initially valorized by Norske Skog Golbey in pulp would be valorized in bioenergy and biomaterials, without significant increase of the needs of the industrial unit, and without changing the type of raw material used. The biorefinery unit would also have access to wood waste from the Golbey industrial ecosystem for supply. The overall picture, therefore, suggests that this scenario will have a very low economic and environmental additional impact compared to the present situation, leading to good scores for both assessment criteria.

Scenario 4: Creation of a small biorefinery unit as an extension of an industry of the forest-wood sector.

Main characteristics:

- **Approximate location**: Golbey Green Valley Energy industrial site.
- **Approximate size**: Production of 50,000 t/year of biofuel, for approximately 50 to 100 jobs created.
- **Specific points**: Proximity of the Vosges forest resource; use of pre-existing industrial infrastructures of Épinal; forest biorefinery located within an industrial ecosystem; acquired skills; already assured supply; dynamism of the site in innovation and innovative projects and proximity of R&D units; pre-existing links with local players such as Grand Epinal, partner of the projects.

This scenario is relatively similar to scenario 3 in that the forest biorefinery unit is established from a pre-existing company in the forest-wood sector. However, it is not a matter here of converting an industry into a forest biorefinery but of building the forest biorefinery unit as an extension of a company of the forest-wood sector, in this case: Norske Skog Golbey pulp mill and, more globally, the Golbey Green Valley Energy industrial site. No major change in the spatial structure of companies in the forest-wood sector is observed, so the impact in terms of inter-company competition would probably be minor and similar to that of scenario 3. Nevertheless, the construction of such an extension would probably generate an increase in terms of demand for wood compared to scenario 3. Indeed, if the forest biorefinery is built as an additional unit of the Golbey industrial ecosystem, it can ensure its supply partly by exploiting the Vosges forest resource. This may lead to greater pressure on the resource. However, this additional pressure would, *a priori,* be lower than the one considered in the baseline scenario, since the biorefinery unit can use both industrial wood and sawmill wastes from the Golbey industrial ecosystem (sawdust, shavings...) for the production of high value-added products. This scenario, therefore, receives the same score as scenario 3 for assessment criterion (1), and a slightly lower score of 4 for assessment criterion (2).

Scenario 5: Implementation of a network of small biorefineries throughout the territory.

Main characteristics:

- **Number of forest biorefineries**: 4
- **Approximate location**: Saint-Dié-des-Vosges, Sainte-Marie-aux-Mines, Colmar, and Sélestat.
- **Approximate size**: Production of 50,000 t/year of biofuel, for approximately 50 to 100 jobs created.
- **Specific points**: Forest biorefineries are part of a network allowing the shared use of logistic sites (storage warehouses, transport services, etc.) and therefore having a minimal land footprint; the multi-site nature of this network can minimize transport costs (biomass transported to the nearest biorefinery); this forest biorefineries network is located in the Vosges as close as possible to the resource.

This scenario is probably the most difficult to assess, as its modalities differ considerably from those of the current situation we observe: there exist no small pulp mills nor small forest biorefineries today. Nevertheless, the spatial structure analysis of the different categories of companies of the forest-wood sector brings us some elements of reflection for the assessment of this scenario with regards to criterion (1). Indeed, on one hand, no pattern of spatial structure is observed in the case of logging companies, all of which are small in size, and small-scale sawmills: these companies are spatially distributed homogeneously and randomly over the whole territory. It is, therefore, likely that the implementation of a network of “small enough” biorefineries would have a low impact on the spatial structure of companies of the forest-wood sector, as no particular spatial structure is observed for small companies of the forest-wood sector that are studied in our work. On the other hand, this conclusion should nevertheless be considered with caution, since no real case of small pulp mills (considered as a reasonable proxy for a forest biorefinery) exists today in France, and as our study is not exhaustive and only consider a few categories of companies. Moreover, the spatial structure analysis shows that medium-sized sawmills (those of more than 20 employees but less than 50 employees) and large sawmills (those of more than 50 employees) are well structured. The transfer of conclusions from the analysis of companies from categories other than pulp mills is then more than delicate, as we cannot assess if the approximative size of the biorefineries units considered in this scenario corresponds to rather a “small size” or a “medium/large size” for a pulp mill or a forest biorefinery. It is nevertheless reasonable to say that this biorefinery network would not directly compete with the sawmills present in the region, as these two categories use a different type of raw material. For those reasons, we can’t attribute a score for this scenario with regards to criterion (1).

The same cautious reasoning can be applied to the impact on the forest resource, with small firms having no significant impact on the probability of harvesting if one considers the distance variables of the survival model. However, establishing a network of enterprises can substantially increase the regional density of enterprises of the forest-wood sector, leading to greater pressure on the resource. Moreover, as the network is directly implemented in the vicinity of the Vosges forest resource, the pressure on the forest resource should increase due to proximity to the forest resource. These considerations lead to a medium score of 3 with regards to criterion (2).

Scenarios	Score criterion (1)	Score criterion (2)
Scenario 1	1	1
Scenario 2	2	4
Scenario 3	5	5
Scenario 4	5	4
Scenario 5	-	(3)

Table 3.2: Scores of the different scenarios of implementation of a forest biorafinery in the Grand Est region according to the two first assessment criteria. Scores go from 1 (“very strong impact”) to 5 (“very low impact”). Scores in parentheses are uncertain scores and should be considered with caution.

04 Discussion

4. Discussion

In this section, we seek to put what precedes into perspective by considering not only two assessment criteria but all of the criteria selected. As a reminder, the six criteria retained to evaluate the implementation scenarios are the following:

(1) The potential impact of the implementation of a forest biorefinery in terms of competition with pre-existing companies of the forest-wood sector.

(2) The potential impact of the implementation of a forest biorefinery on the forest resource *in situ*.

(3) The production cost of the implementation of a forest biorefinery. Production cost comprises the CAPEX (related to the size and capacity of the forest biorefinery) and the OPEX (related to transport costs).

(4) The origin of the biomass used in the biorefinery, which can be from: (i) harvesting local forest resources, (ii) using recycled wood or wood waste from companies of the forest-wood sector, and (iii) importing raw material; and their respective impact on the resource.

(5) The costs related to the biorefinery's implementation modalities, that is whether the biorefinery will be built *ex nihilo* or whether it will be set up through an upgrading/expansion of a pre-existing company. The considered costs include transaction, opportunity, and capital costs.

(6) Technical and technological feasibility with respect to the biorefinery process.

Criteria (1) and (2) have already been analyzed in detail in the results section. We here assess criterion after criterion each scenario based on the literature review, for criteria (3) to (6). The assessment of each scenario with respect to criteria (3) to (6) will complete the assessment carried out previously regarding criteria (1) and (2). This synthesis aims to deliver a global vision on the relevance of each implementation scenario.

4.1. Qualitative assessment of implementation scenarios with respect to criterion (3) to (6)

4.1.1. Qualitative assessment with respect to criterion (3): the production cost of the implementation of a forest biorefinery

The balance between CAPEX and OPEX determines the production cost of a biorefinery and, therefore, its profitability. The larger a biorefinery is, the higher its capital cost, but the more it can benefit from economies of scale. Conversely, the larger the biorefinery, the higher its OPEX: i to meet its needs, the biorefinery must source its biomass from far away. This leads to substantial transportation costs, hence a strong OPEX. In the end, the size and location of the biorefinery condition the CAPEX and OPEX, and then the production cost. Depending on the abundance and the direct access to a nearby resource, a biorefinery can generate more or less operating costs, *i.e.*, more or less OPEX (Ong *et al.*, 2020).

Usually, the trade-off between CAPEX and OPEX is addressed through detailed techno-economic studies. Here, we do not intend to provide such a study and will not numerically estimate those costs for each scenario. Rather, we provide a rough estimate of how each scenario should score according to the approximative size of the forest biorefinery, its approximative location, and the specificities of the scenario.

Regarding the CAPEX, scenarios 1, 2, and 3 consider a biofuel production of 200 000 t/y, which corresponds to a large size forest biorefinery and significant economies of scale, while scenario 4 considers medium-size biorefineries of a 50 000 t/y capacity, which corresponds to lower economies of scale. Scenario 5 considers a network of 4 forest biorefineries of a 50 000 t/y capacity. The biorefineries network hence has an overall capacity of 200 000 t/y and should incur similar economies of scale than those of scenarios 1, 2, and 3. If we now take into consideration scenario specificities, scenario 2 and 3 particularly stands out as they incur a lower initial capital cost due to the conversion of a pre-existing company[59] for equivalent economies of scale than those of, *e.g.*, scenario 1.

Regarding the OPEX, the size of forest biorefineries considered in scenarios 1, 2, and 3 would imply a large supply radius, thus leading to significant transport costs. On the contrary, supplying small forest biorefineries as those considered in scenarios 4 and 5 would result in a smaller supply radius and lower transport costs. When considering the approximative location of the forest biorefinery, all scenarios place the forest biorefinery in the vicinity of the Vosges forest resource, except scenario 2. Scenario 2 sets up a forest biorefinery in a sparsely wooded region (North of France[60]) and then should incur high transport costs due to its remote location. This last consideration should nevertheless be moderated by the fact that the access to Dunkerque port infrastructure, in addition to a multi-input supply strategy, should allow the biorefinery to considerably mitigate its transport costs of woody biomass. Lastly, in scenarios 2 and 3, the explicit use of wood waste from forest-wood companies nearby by the forest biorefinery should lead to lower transport costs too.

Taking all these considerations into account, scenarios 3 and 5 score the highest, scenario 4 scores well, and scenarios 1 and 2 score medium.

4.1.2. Qualitative assessment with respect to criterion (4): the supply strategy and its impact

Criterion (4) focuses on the supply strategy of the forest biorefinery. In particular, three modes of supply are differentiated in the literature: local wood supply; import of foreign wood; use of wood waste from pre-existing forest-based enterprises. Overall, each scenario can consider each supply strategy, and in particular a supply mode based on wood waste. This assessment criterion is therefore perhaps the least discriminating of the assessment criteria.

Regardless of the scenario, a great deal of flexibility is left to the choice of the balance between local supply and imports: all mixes are possible. It should be noted that these two modes of supply each generate an impact on the resource. This impact can be very localized in the case of an exclusively local supply or relocated abroad in the case of a supply strategy based solely on imports. On a local scale, therefore, importing wood can reduce the local impact of the forest biorefinery, but on a global scale, the balance is more or less the same, regardless of the balance between the two modes of supply considered.

Therefore, we decide to focus our attention on how easy it is for the forest biorefinery to use wood waste from pre-existing companies in the forest-based sector. This last mode of supply allows conceptually to decrease the impact on the resource, whatever the scale considered. A given scenario will then score high if it particularly and explicitly emphasizes the use of wood waste from pre-existing forest-wood companies, in an “industrial ecosystem" perspective.

Hence, scenario 4 stands out particularly, as it explicitly considers setting up synergies between the pre-existing companies of Golbey Green Valley Energy industrial site and the biorefinery unit (considered here as an extension unit of Golbey industrial site). In the same vein, scenario 3 of the conversion of Norske Skog Golbey pulp mill into a forest biorefinery intends to keep a similar supply strategy to that of the pulp mill, which implies a smaller but significant share of wood waste in the supply than in scenario 4. For this reason, we, therefore, decide to give a very good score to scenario 4 and a good score to scenario 3, while giving an average score to other scenarios.

[59] Namely, the Flandres petrochemical refinery in scenario 2 and the Norske Skog pulp mill in scenario 3

[60] Source: Memento FCBA, using IFN data - https://www.fcba.fr/wp-content/uploads/2020/10/memento_2020.pdf

4.1.3. Qualitative assessment with respect to criterion (5): the costs related to the biorefinery's implementation modality

Criterion (5) considers three types of biorefinery implementation: *ex nihilo* implementation, conversion of a pre-existing industry, or extension of a pre-existing industry. Our scenarios cover all of these modalities. In particular, the literature identifies several advantages/disadvantages for each modality. Overall, it emerges that the modalities of conversion or extension of a pre-existing industry present more advantages than the *ex nihilo* implementation modality. Indeed, these two modalities have in common that they take advantage of pre-existing, operational, and mature infrastructures. Hence, not considering the conversion or extension of a pre-existing industry incurs an opportunity cost. This consideration particularly highlights scenarios 2, 3, and 4 compared to scenarios 1 and 5. Following the same reasoning, we can also argue that scenario 5 benefits from the pre-existing heat network structure and scores slightly better than scenario 1.

Two other advantages are observed in the case of the conversion of a pre-existing industry. First, building on the pre-existing infrastructure reduces the cost of capital. Second, whether it is the conversion of a petrochemical refinery or a pulp mill, skilled labor is available directly after conversion. Then, there exists an opportunity cost of not converting a pre-existing petrochemical refinery or pulp mill into a forest biorefinery. Thus, in terms of the assessment criterion (5), scenarios 2 and 3 stand out, while scenario 4 seems to have, *a priori*, slightly more advantages than scenarios 1 and 5 which both emerge *ex nihilo*.

Scenarios 2, 3, and 4 can be differentiated another way, however. Scenarios 3 and 4 have in common that the converted or expanded industry already belongs to the forest-wood sector. Thus, the forest biorefinery can also benefit from sector-specific skills already available in the pre-existing industry: access to a network of professionals of the sector, knowledge and information on the resource already exploited by the company, pre-existing contracts and partnerships, pre-existing supply chain... This implies lower costs of transaction, or more precisely: lower search and information costs; lower bargaining and decision costs; and lower policing and enforcement costs (according to the typology of transaction costs proposed by Dahlman in Dahlman, 1979). Scenario 2, on the other hand, has an environmental specificity: the production of bioenergy replaces the production of fossil fuels. Thus, the conversion of the petrochemical refinery into a forest biorefinery has a strong substitution effect, which is virtuous from an environmental point of view and leads to a positive externality (or social benefit). Finally, the literature raises a point concerning scenario 3: the conversion of a pulp mill into a forest biorefinery can economically revitalize the company. Indeed, pulp mills have been experiencing financial difficulties for several years due to a drop in demand for their products and their low added value. Converting these "dying" industries into a forest biorefinery thus represents an economic opportunity and, conversely, not converting these companies somehow implies an opportunity cost.

From these considerations, it appears that the scenario receiving the highest score is scenario 3, followed by scenarios 2 and 4 which score lower. Scenarios 1 and 5 scores respectively very low and low on the assessment criterion (5).

4.1.4. Qualitative assessment with respect to criterion (6): technical and technological feasibility

It is difficult to assess scenarios from the perspective of criterion (6). Indeed, little information and experience feedback is available yet on the exact process used by the forest biorefinery under consideration. Moreover, the scenarios do not explicitly take into consideration the process used to convert wood into bioenergy and biocomposites. However, if we reason with regard to the degree of freedom left by each scenario concerning technical and technological aspects, it appears that scenario 3 is the one that leaves the least freedom concerning the process since it is based on the pre-existing infrastructures of Norske Skog Golbey pulp mill. These structures can only be adapted within a certain limit. Scenario 3, according to this criterion, therefore score medium. In contrast, scenarios 1, 4, and 5 score well, leaving total freedom regarding the design of the biorefinery unit. Lastly, scenario 2 stands out particularly, as it is a part of the R&D project BioTfuel: technological and technical feasibility is an integral part of scenario 2, which leads us to score it the highest.

4.2. Synthesis: global assessment of each scenario for the implementation of a forest biorefinery in the Grand Est region

The scores obtained for each scenario and according to each assessment criterion are recorded in **Table 4.1**.

Averaging these scores to identify which scenario scores the best on average would make little sense. However, **Table 4.1** allows us to identify the strengths and weaknesses of each scenario, within the limits of the available data. Indeed, it is important to note that some assessment criteria, like criteria (3) and (6) for instance, are difficult to address as they stand. They are ultimately approached through a rough approximation and may be addressed more precisely with complementary studies.

It is nevertheless interesting to note that without the assessment of scenarios by criteria (1) and (2), some scenarios seem conceptually relevant, but once criteria (1) and (2) are taken into account their relevance diminishes. This is the case, to some extent, for scenarios 1 and 2, which are directly inspired - and, therefore, very close - to real cases. On the contrary, considering criteria (1) and (2) makes less conventional scenarios like scenarios 3 and 4 all the more relevant. Although it cannot be properly assessed in our study, scenario 5 also seems to be relatively relevant, despite the uncertainties in its assessment regarding criteria (1) and (2).

Scenarios	Score criterion (1)	Score criterion (2)	Score criterion (3)	Score criterion (4)	Score criterion (5)	Score criterion (6)
Scenario 1	1	1	3	3	1	4
Scenario 2	2	4	3	3	4	5
Scenario 3	5	5	5	4	5	3
Scenario 4	5	4	4	5	4	4
Scenario 5	-	(3)	5	3	2	4

Table 4.1: Scores of the different scenarios of implementation of a forest biorefinery in the Grand Est region according to all assessment criteria. Scores go from 1 (“very strong impact”) to 5 (“very low impact”). Scores in parentheses are uncertain scores and should be considered with caution.

05

Conclusion

5. Conclusion

Our research work has aimed to qualitatively assess several scenarios for setting up a forest biorefinery in the Grand Est region. These scenarios, as well as the assessment criteria used, were based on the literature and insights drawn from comparable real-life cases. Among the 6 assessment criteria we identified, two criteria were of particular interest to us: (1) the potential impact of the implementation of a forest biorefinery in terms of competition with pre-existing companies of the forest-wood sector; and (2) the potential impact of the implementation of a forest biorefinery on the forest resource. In order to assess the implementation scenarios according to these two criteria, we used two quantitative descriptive analyses: an analysis of the spatial structure of the forest-wood sector and an analysis of the impact of the sector on the forest resource through a harvest probability model. These studies allowed us to approach these two assessment criteria in an innovative way and to carry out a relevant assessment of the implementation scenarios with respect to these two criteria. An overall assessment of each scenario, according to all the assessment criteria, was carried out based on the descriptive studies and the literature. The overall approach provides a conceptual tool to assist in the reflection on the implementation of a forest biorefinery in the Grand Est region.

Nevertheless, it is crucial to understand the scope of this study. Our analysis is a tool for reflection, in that we draw lessons from existing and past experience (the current French forest-wood sector) to help us reflect on future developments. But a limitation may lie to base our analysis on the pre-existing as no past experience on the implementation of a forest biorefinery yet exists in France. We, therefore, have to go through some "detour" paths in order to address this difficulty. These detours have led us to consider pulp mills as a proxy for a forest biorefinery. Despite the proximity in terms of process or supply of these two types of industry, this approximation has obvious limits: the products of a forest biorefinery are different from those of a pulp mill, they do not belong to the same markets, and do not bring the same added value to the raw material. Besides, all French pulp mills are large industrial sites, which makes it difficult to assess a scenario that considers small biorefineries. The number of pulp mills in France is also low, which may limit the observations, although the results obtained in our studies are significant. Another limitation of our study may lie in its early stage in the progress of the Hy-C-Green project: the design, the process, and the location of the forest biorefinery have not yet been decided. We rather took this limitation as an opportunity that has given us a great degree of freedom in the construction of our implementation scenarios. However, there is no doubt that our work will find complementary conclusions in the concrete technical-commercial analyses carried out otherwise within the Hy-C-Green project.

From this point of view, our work can provide more material for reflection if it is deepened. More details can be brought to the study of the spatial structuring of the forest-wood sector, notably through the descriptive analysis of other categories of companies than the three selected. Some NAF classification biases could also be avoided. Concerning the study of the probability of harvesting, several refinements such as taking into account other modes of transport other than road transport, taking into account the questions of imports and exports, or the consideration of larger time series, are all promising avenues to take our descriptive study further. Although the lack of data did not allow us to do so, a preliminary study of the heating network - in connection with the latest biorefinery implementation scenario - would make a significant contribution to our study. To complete the panorama drawn up by our work, it would also be necessary to take into account the downstream part of the process. Finally, as regards the study of the economic and environmental impact of setting up a forest biorefinery, our assessment criteria can be approached from other perspectives: employment, pollution linked to transport, or the impact on prices and markets.

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Appendices

Appendix I: List of URLs links used to build implementation scenarios by order of appearance in the text

(1): https://www.total.com/fr/expertise-energies/projets/bioenergies/la-mede-un-site-tourne-vers-avenir

(2): https://www.connaissancedesenergies.org/combien-y-t-il-de-raffineries-en-france-et-ou-sont-elles-situees-191219

(3): https://www.connaissancedesenergies.org/fiche-pedagogique/choc-petrolier

(4): https://www.actu-environnement.com/ae/news/conversion-raffinerie-grandpuits-biocarburant-bioplastique-36176.php4

(5): https://www.total.com/fr/expertise-energies/projets/bioenergies/biotfuel-convertir-residus-vegetaux-carburant

(6): https://www.fioulreduc.com/info-fioul/acteurs-fioul/raffineries

(7): https://www.total.com/fr/expertise-energies/projets/plateforme-raffinage-chimie/anvers-premiere-plateforme-integree-groupe-europe?gclsrc=aw.ds&&gclid=CjwKCAiA_9r_BRBZEiwAHZ_v1y4W-Z1g3CCXFr2_YQ0XLeeE-10Rpg8Gux7JkLzanAwTjn1TnPkEShoCrK0QAvD_BwE#xtor=SEC-7-%5BEXP%5D-%5BANN%5D---%5BBE%5D--

(8): https://www.usinenouvelle.com/article/total-repeint-en-vert-la-raffinerie-des-flandres.N834485

(9): https://www.developpement-regional.total.fr/projet-biotfuel-sur-la-raffinerie-des-flandres-inauguration-par-la-ministre-de-lenvironnement

(10): https://www.industrie-techno.com/article/carburants-les-biocarburants-de-deuxieme-generation-prets-a-passer-a-l-industrialisation.62803

(11): http://www.copacel.fr/fr/rechercher-un-fabricant.html

(12): https://norskeskog-golbey.com

(13): https://www.vosgesmatin.fr/edition-d-epinal/2019/11/19/la-green-valley-moteur-economique-de-l-agglo

(14): https://www.graphiline.com/article/32708/une-nouvelle-chaudiere-a-la-papeterie-norske-skog-golbey-88

(15): https://www.ecologie.gouv.fr/deploiement-des-energies-renouvelables-elisabeth-borne-designe-projets-laureats-dinstallations

(16): https://www.vosgesmatin.fr/economie/2020/06/17/golbey-norske-skog-investit-250-m-d-euros-pour-se-convertir-dans-le-papier-carton

(17): https://carto.viaseva.org/public/viaseva/map/

Appendix II: List of NAF codes selected for the forest-wood sector (in French)

Division	NAF	Activité
02 Sylviculture et exploitation forestière	0210Z	Sylviculture et autres activités forestières
	0220Z	Exploitation forestière
	0230Z	Récolte de produit forestiers non ligneux poussant à l’état sauvage
	0240Z	Services de soutien à l’exploitation forestière
16 Travail du bois et fab. d'art. en bois et en liège sauf des meubles. Fab. art. vannerie et sparterie	1610A	Sciage et rabotage du bois, hors imprégnation
	1610B	Imprégnation du bois
	1621Z	Fabrication de placage et de panneaux de bois
	1622Z	Fabrication de parquets assemblés
	1623Z	Fabrication de charpentes et d'autres menuiseries
	1624Z	Fabrication d'emballages en bois
	1629Z	Fabrication d'objets divers en bois ; fabrication d'objets en liège, vannerie et sparterie
17 Industrie du papier et carton	1711Z	Fabrication de pâte à papier
	1712Z	Fabrication de papier et de carton
	1721A	Fabrication de carton ondulé
	1721B	Fabrication de cartonnages
	1721C	Fabrication d'emballages en papier
	1722Z	Fabrication d'articles en papier à usage sanitaire ou domestique
	1723Z	Fabrication d'articles de papeterie
	1724Z	Fabrication de papiers peints
	1729Z	Fabrication d'autres articles en papier ou en carton

Appendix III: Description of the HMC algorithm

The Hamiltonian Monte-Carlo (or hybrid Monte-Carlo) algorithm is a particular type of Markov chain by Monte-Carlo that allows to limit autocorrelation in posterior chains and thus to accelerate convergence, even for models with many parameters (which is the case in this study). What limits autocorrelation in the parameter chain is the ability to sample almost the entire parameter space, and not just the fraction of the parameter space near the last values of the chain.

The operation of the algorithm for proposing a new parameter vector can be described by analogy with a mechanical system. For example a ball on a surface whose height would be the posterior likelihood of the posterior. The ball does not undergo friction: the sum of the potential energy, related to the height of the ball, and its kinetic energy, related to its speed, is preserved in time. The initial position of the system is the last parameter vector of the Markov chain. The HMC algorithm then simulates a trajectory of the system from a random initial impulse, and stops for a predetermined length of the trajectory. The position of the system at the end of the trajectory gives the new proposed parameter vector.

Tiré de (Piponiot-Laroche, 2018).

Appendix IV: Definition of the *priors* and obtention of the *posteriors*

All priors have been parameterized as non-informative priors such as:

$$\forall j \in [\![0,10]\!],\ j \sim N(0,10);\ \forall k \in [\![0,2]\!],\ \forall e \in [\![0,8]\!],\ k,e \sim N(0,10),\ \gamma \sim \log N(0,1),\ \omega \sim \log N(0,1)$$