WORKING PAPER

Sectoral, resource and carbon impacts of increased paper and cardboard recycling

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Recycling is emerging as an alternative to extraction in many industries and one of the corner stones of the circular economy. In this paper, we assess the role of paper and cardboard recycling on the forest sector, both from an economic and carbon perspective. For that purpose, we model this recycling industry within our forest sec- tor model, in order to relate it to other wood products. As the forest sector has an important potential for climate change mitigation, this model allows us to assess the effects on the resource and the carbon balance of the forest sector. We show that these results are strongly linked to the hypothesis of substitution or complementarity between recycled and wood-pulp.

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KEYWORDS

Forest sector | Recycling | GHG Emissions | Bioeconomic model

1 Introduction

1.1 Context and motivations

Recycling plays a central role in the development of a circular economy. This lever for developing a more sustainable economic model is based on the idea of escaping the linear "extract-consume-throw away" logic. The objective is to "close the loop", among other things by turning end-of-life materials into economic inputs. Recent developments of the concept have spurred academics and politicians to approach this issue. Studying the underlying dynamics of the development of recycling in a circular economy brings to consider the different externalities linked to resource extraction and disposal. Historically, resource depletion and waste accumulation have been the principal motivation for the development of a circular economic model, mainly through recycling programs. However, recent developments led to a more holistic approach of environmental issues, as local and global pollution have become a focal point of environmental studies. The study of the circular economy is now strongly connected to climate change challenges, as a redefinition of our linear economic model could have impacts on greenhouse-gas emissions (GHG) (ADEME and FEDEREC, 2017; UNEP, 2019; ADEME, 2019).

This paper focuses on the specific case of paper and cardboard recycling in France. The sector is indeed very well developed, with 66% of the production coming from recovered waste (ADEME and Bio by Deloitte, 2017). Besides, the paper pulp industry is directly connected to the global forest sector, which plays a crucial role in climate change mitigation. Unlike other recycling sectors like metals or plastics, there is little to no substantial difference in GHG emissions between recycled and wood-pulp industrial process (ADEME and FEDEREC, 2017; ADEME, 2019). Besides, complex cascading impacts on the resource and other wood products suggest unclear economic and environmental impacts of paper and cardboard recycling. Our objective is to assess the effect of recycling by expending the usual scope of the study to the forest sector. The main goal here is to investigate wether climate change mitigation mechanisms of the forest sector offset or not the small difference in climate impact between recycling and virgin pulp.

Our contribution here is the sectoral analysis of a recycling industry and its impacts in terms of GHG emissions. Instead of a standard accounting for GHG displacements using the LifeCycle Assessment methodology (LCA), we also use an Integrated Assessment Model (IAM)(the French Forest Sector

Model - FFSM++)[1] providing prospective scenarios of the French forest sector. Using an IAM allows us to account for the whole forest sector with a bioeconomic perspective, including dynamic mechanisms. Different economic hypothesis on the new recycling branch as well as a carbon accounting module allows us to give the climate impact of increased recycling at different scopes.

1.2 Related literature

The economic literature tackled the topic of recycling very early with a focus on social costs associated to waste accumulation and resource depletion, in order to find an optimal level of pollution (Hoel, 1978; Smith, 1972). Later on, a few papers invested the topic of pollutant emissions and recycling, with a dynamic scope like Huhtala (1999) and Lafforgue and Lorang (2020) or a static micro-economic approach with Acuff and Kaffine (2013). These theoretical papers often isolate costs as the main barrier for development of a recycling industry. However, another central question when dealing with a recycled product, is the substitution with virgin material, especially for paper and cardboard.

The econometric literature highlights this issue of substitution, although studies do not appear to give a clear-cut result. Lee and Ma (2001) show that recycled and wood-pulp could be substitutes, however they find very low values for cross-elasticities that are not statistically significative. Some studies also show complementarity between inputs, with pulp industries hardly substituting materials in their transformation process (Lundmark and Olsson, 2015; Lundmark and Söderholm, 2003). A literature review from Mansikkasalo et al. (2014) shows that we can find variations between countries, that could be driven from technological differences. They also show that inputs can be substitutes or complements. Those heterogenous results can be explained by the wide diversity of products within the paper and cardboard industry. Beyond purely market reasons, these results can also be addressed by examining technical difficulties of swapping inputs in pulp production processes (ERPC, 2015). These considerations encouraged us to explore different scenarios where recycled and wood-pulp could be complementary or substitutable products. This question of substitution is actually a crucial point yet to be addressed in the circular economy literature. An undesirable

[1] https://ffsm-project.org/wiki/en/home

scenario would be that recycling contributes to circular economy by creating a rebound effect in production when recycled products poorly substitute to others or even are complements, thus fulfilling an unsustainable goal (Zink and Geyer, 2017).

Beyond these investigations on substitution, econometric studies show low values for price elasticities of the demand for recycled pulp (Deadman and Turner, 1981; Edgren and Moreland, 1990; Lee and Ma, 2001). This low value is also found for the supply of recycled pulp (Mansikkasalo et al., 2014). However, differences can be found between the several use of transformed pulp, showing the difficulty to compute a composite value describing recycled pulp markets (Lundmark and Olsson, 2015; Lundmark and Söderholm, 2003). A key parameter describing recycled pulp markets is the level of substitutability with, in this case, other wood products. Early studies tackle this question showing that wood-pulp is a complement to solid-wood (Newman, 1987).

These econometric considerations aside, GHG displacement factors of paper recycling have often been studied with strong economic assumptions. Early assessments from Byström and Lönnstedt (1997) do not show that increased recycling could be environmentally friendly, while only taking into account the pulp sector. One paper from Merrild et al. (2009) gathers estimations on GHG emissions for different recycling technologies. By extending the analysis to the boundaries of the forest resource, they are able to take into account sequestration and substitution mechanisms. However, they assume substitution with wood-pulp and that unused wood is consumed for energy as a substitute for fossil fuel. They get then a high environmental performance of recycling, without taking into account the complexity of cascading effects in the forest sector. On the other hand, a French study from ADEME and FEDEREC (2017) uses LCA[2] without feedbacks and competition in the rest of the forest sector. By comparing GHG emissions of virgin and recycled production, including avoided end-of-life, their static analysis concludes that paper and cardboard recycling emits the same or even more than producing wood-pulp. This study is extended in ADEME (2019) and finally shows GHG gains when adding assumptions on wastepaper anaerobic degradation. Finally, an Input/Output model applied to the dutch case by Nakamura (1999) shows decreases in emissions while taking into account wide inter-industry effects, but not economic effects, being a quantity based

[2]ISO 14040 and ISO 14044

model.

Including the forest sector in the analysis of the GHG impact of wood products recycling seems crucial as its relationship with climate change mitigation is consequential. It draws on two different mechanisms we take into account in this study. First, sequestration relies in the growth of forests in order to capture additional carbon and reduce GHG concentration. It depends strongly on climatic factors of the forest, thus varies around the world and is likely to be affected by ongoing and future climate variations (Cook-Patton et al., 2020). In addition to this environmental factor, management practices of the forest are also central as strategies on collected and replanted biomass can have significant impacts (Lobianco et al., 2016a). Second, the substitution mechanism consists in using wood instead of other products in industrial process. The GHG balance is impacted through different activities including replacing fossil fuel energy with fuel-wood, using less energy for manufacturing forest products instead of non-wood products as well as storing carbon in products (Sathre and O'Connor, 2010; Churkina et al., 2020).

These observations incited us to study the carbon impact of recycling while considering market interactions in the global forest sector. Such a study is carried out with an integrated assessment model representing the dynamic evolution of the french forest sector. A similar model, the Global Forest Products Model, already shows that recycling has little impact on other wood products, however it does not compute GHG displacement factors (Buongiorno et al., 2003). A study on a smaller scale by Pieratti et al. (2019) using multi-criteria decision analysis with circular economy principles underlines under-optimal management practices for a single forest, while the global GHG balance is positive thanks to fossil fuel substitution. However they do not examine the specific effect of recycling. D'Amato et al. (2020) stress that LCA assessments of forest-based economy, while they very often include climate change impacts, lack waste and circularity considerations.

Our model here, FFSM++, has provided a wide stream of literature regarding long-term assessments of the sector, with market, resource or climate outlooks. Introduced by Caurla et al. (2010), it already produced results on the introduction of climate change mitigation policies and their possible crossed-effects (Caurla, 2012; Caurla et al., 2013a,b). Climate impacts and risk aversion are also a useful scope for long-term assessments of the French forest dynamics, with Lobianco et al. (2016b) showing overall stability of the volume stocks. Finally, FFSM++ also allows the observation of substitute products, with the introduction of crossed-elasticities (Caurla et al., 2013b;

Petucco et al., 2019). We present here an extension of this model that links pulp production to waste accumulation and recycling.

1.3 Outline

The remaining of this paper is structured as follows. Section 2 presents the extension we added to FFSM++ and the simulation strategy to analyse recycling. Section 3 describes the impact of increased recycling in the model, with a focus on carbon at different scales of the sector. Section 4 concludes.

2 Adding a paper recycling loop to a forest sector model

2.1 Modular structure of FFSM

FFSM is designed to explore the dynamics of markets and resources, as well as policies and their economic and environmental impacts[3]. Each year, the model computes prices and quantities for different primary and secondary wood products based on a Samuelson (1952) spatial equilibrium. This way, trade of products is represented on the national level, using prices in different regions, as well as on the international level, using Armington (1969) substitution model. Sauquet et al. (2011) investigate this last point with the FFSM framework, on the specific product sawnwood. This economic model is completed by a resource module representing the dynamics of the forest sector, and a carbon accounting module in order to assess the emissions balance of the sector. Carbon accounting consists in reporting sequestration mechanisms (through wood products, inventoried and extra forest biomass) and emissions (direct forest operations, energy and material substitution for transformed wood products with coefficients from the already existing literature) described in detail in Lobianco et al. (2016a).

The dynamic recursive structure of FFSM is described in Figure 1, where previous year harvest and forest dynamics gives the availability of the resource to the market module. The detailed description of the market module is given by Figure 2, with a supply in primary products upstream (roundwood and industrial wood) and a demand in products of first transformation

[3] See Caurla (2012) for a full description of the model, and `https://ffsm-project.org/wiki/en/doc/home#published_articles` for any further extension.

downstream. The interface between production and consumption consists in the transformation industry, with an input-output logic (see Figure 2).

The addition of a recycling loop consists here in the creation of a pair of primary and transformed products. Recovered waste of the previous year (from both recycled and virgin pulp consumed in the model) is reprocessed into recycled pulp, linked to the demand in wood-pulp through complementarity or substitution.

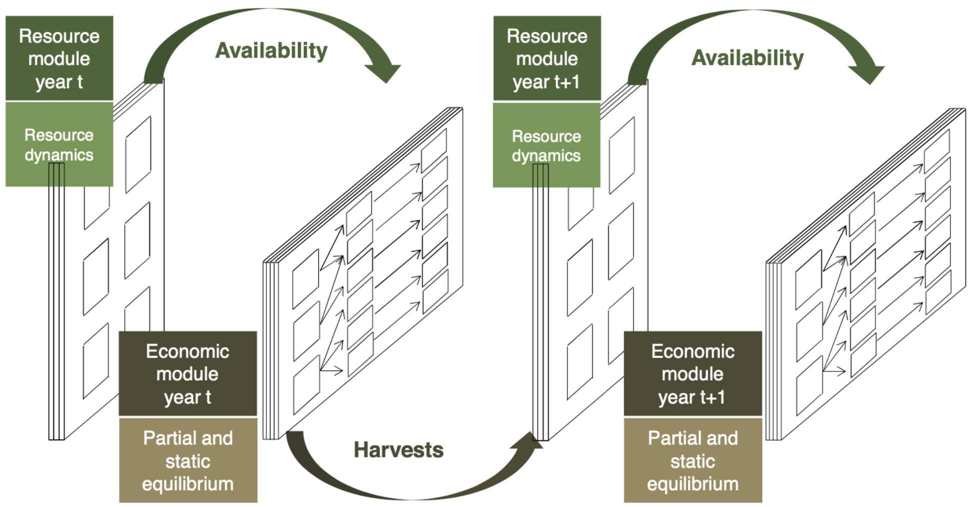

Figure 1: Recursive structure of FFSM

2.2 Dynamics of pulp recycling

The regional demand for recycled pulp is similar to demands for other transformed products introduced in FFSM (Caurla et al., 2010), expressed as a composite demand $D_{recy,i,t}$ (for region i at year t) with a substitution between foreign and local shares of the total demand. Besides the recursive dependency with supply and prices, we introduce a cross elasticity between the recycled pulp and wood-pulp:[4]

[4]See Caurla et al. (2013b).

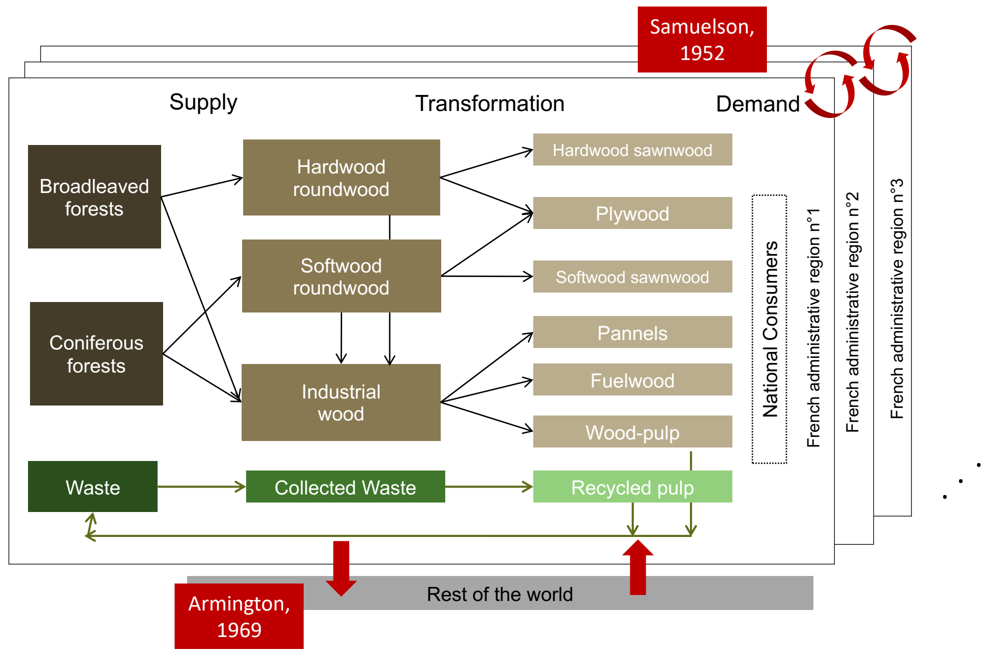

Figure 2: Products structure of FFSM

$$D_{recy,i,t} = D_{recy,i,t-1} \left(\frac{\tilde{P}_{recy,i,t}}{\tilde{P}_{recy,i,t-1}} \right)^{\sigma_{recy}} \left(\frac{\frac{\tilde{P}_{recy,i,t}}{\tilde{P}_{pulp,i,t}}}{\frac{\tilde{P}_{recy,i,t-1}}{\tilde{P}_{pulp,i,t-1}}} \right)^{\eta_{recy,pulp}} \tag{1}$$

Where

- σ_{recy} is the price elasticity of demand;
- $\tilde{P}_{recy,i,t}$ is the price of composite recycled pulp, in region i at year t;
- $\tilde{P}_{pulp,i,t}$ is the price of the substitute (or complementary) product, wood-pulp in region i at year t;
- $\eta_{recy,pulp}$ is the cross elasticity of demand.

A similar and symmetric cross-elasticity $\eta_{pulp,recy}$ in the demand function for wood-pulp is introduced.

We also introduce a composite supply of recovered waste $S_{waste,i,t}$ [5] depending on its price and the stock of waste paper and cardboard that could be recovered for recycling purposes:

$$S_{waste,i,t} = S_{waste,i,t-1} \left(\frac{\tilde{P}_{waste,i,t}}{\tilde{P}_{waste,i,t-1}} \right)^{\epsilon_{waste}} \left(\frac{W_{i,t}}{W_{i,t-1}} \right)^{\beta_{waste}} \tag{2}$$

Where:

- $\tilde{P}_{waste,i,t}$ is the price of composite recovered waste paper and cardboard, in region i at year t;
- $W_{i,t}$ is the volume of waste cardboard and paper that can be recovered;
- ϵ_{waste} is the price elasticity of supply;
- β_{waste} is the stock elasticity of supply.

From the dispersive use of material and the technological limits associated to recycling and recovery, stock $W_{i,t}$ is a share of the total pulp (from wood and recycled) that has been produced at $t-1$. Following a common assumption in literature concerning recycling of resources, we do not account for the duration of use of the pulp produced that would produce lagged effects in the model (Palmer et al., 1997; Huhtala, 1999). This means that each year, paper is produced, consumed and then recycled or disposed of the following year.

$$W_{i,t} = \gamma_{i,t}(D_{pulp,i,t-1} + D_{recy,i,t-1}) \tag{3}$$

Where:

- $\gamma_{i,t}$ is the share of pulp (recycled and wood) consumed in region i at year $t-1$ that can be recovered in region i at year t;
- $D_{pulp,i,t-1}$ is the demand in wood-pulp in region i at year $t-1$;
- $D_{recy,i,t-1}$ is the demand in recycled pulp in region i at year $t-1$;

[5] see Caurla et al. (2010) for the detailed construction of the composite supply of primary products

Recovered waste paper and cardboard are transformed by a recycling industry at a constant cost of production c_{recy} for each unit of recycled pulp produced. This costs enters in the surplus expression, as the model is solved through a static Samuelson spatial equilibrium maximizing the surplus function (detailed at length in Caurla (2012)).

2.3 Calibration and simulations strategy

The model is run through a numerical solver with a calibration relying on previous calibrations detailed in the FFSM literature (Caurla et al., 2010; Caurla, 2012). Values on supply and demand parameters come from sectorial analysis of the French forest sector (Lenglet et al., 2017; Montagné and Niedzwiedz) and the recycling sector (Copacel, 2016; ADEME and Bio by Deloitte, 2017). Price elasticities of supply and demand come from the relative literature mentioned above (Lee and Ma, 2001; Buongiorno et al., 2003; Mansikkasalo et al., 2014).

As the literature shows conflicting results for the cross-elasticity between recycled and wood-pulp, three cases are designed with different values to examine the sensitivity to this parameter. As there seems to be a common consensus toward low values (Lee and Ma, 2001; Lundmark and Olsson, 2015), we introduced low substitution ($\eta = -0,2$) and low complementarity ($\eta = 0,2$) between transformed products. A third case is also explored with an optimistic hypothesis on substitution, considering a high negative cross-elasticity ($\eta = -1$). As we do not investigate asymmetries between those products, we use the same crossed elasticity $\eta = \eta_{recy,pulp} = \eta_{pulp,recy}$. The paper and cardboard industry encompasses a wide variety of different products, which creates various types of substitutability/complementarity between virgin and recycled pulp. Thus the elasticity we use should be understood as synthetic indicator of those many types of relationships for the various products within the industry.

GHG emissions linked to the transformation activity of the pulp industry are included in the carbon balance module. Based on the LCA analysis of ADEME and FEDEREC (2017), we assign to the recycling sector emissions of collection, sorting and avoided end of life. Besides, there is a difference between cardboard and paper recycling (cardboard pollutes more): we take into account this difference by creating a weighted coefficient relying on the share of French production, around 40% paper and 60% cardboard (ADEME and Bio by Deloitte, 2017; Lenglet et al., 2017). The resulting GHG coefficients are 350 kg CO_2e/t for wood-pulp and 530 kg CO_2e/t for recycled pulp.

Our objective in this paper is to assess the effect of paper recycling on the forest sector, and especially its GHG balance. To this end, we test four scenarii with different recycling intensities: a baseline, lower increase in recycling, medium increase and higher increase. For these increases we use the proxy of the transformation cost c_{recy}, as shown in Table 1. This change in costs of the recycling process can come from different sources: a technological breakthrough making the recycling technology broadly available (Lafforgue and Rouge, 2019) or policy choices focused on subsidizing recycling (Palmer et al., 1997) As explained above, we set out this simulation in three different cases: low complementarity, low substitutability and high substitutability, and we compare scenarii with `baseline`.

Scenario name	`baseline`	`low`	`med`	`high`
c_{recy} (€/m^3)	70	50	30	10

Table 1: Tested recycling scenarii

3 Impact of paper recycling on the carbon balance

The model is solved numerically over a period of 67 years (from 2013 to 2080). It computes supply/demand/prices of products, as well as resource dynamics and a detailed carbon accounting. In the following part, yearly results, averaged over the simulation period, are given.

3.1 Impacts on the pulp industry

What we observe for the pulp sector is the direct impact on production, given a cost reduction. This impact is direct for the recycling industry, and indirect for wood-pulp. The wood-pulp industry is indeed affected through the cross-elasticity between the two products, with a higher demand in the case of complementarity, a lower with substitution. However, in any case, this absolute change in wood-pulp demand is smaller than the absolute increase of demand for recycled pulp. This is illustrated in Table 2 showing the

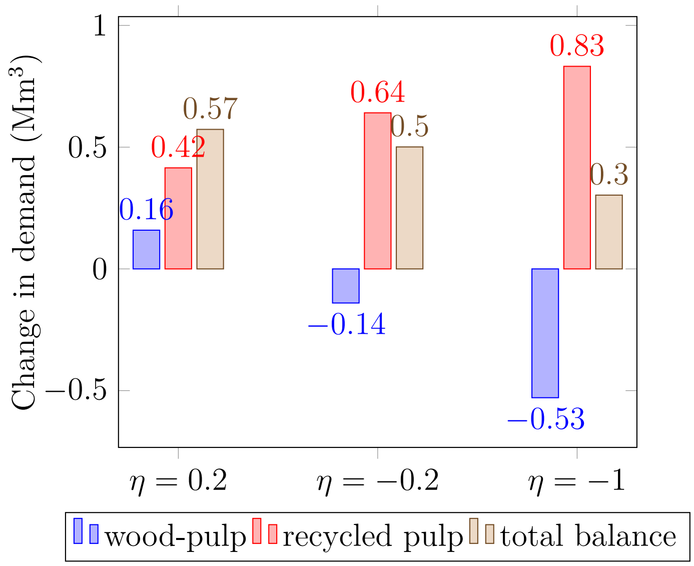

Table 2: Changes in demand for pulp between `baseline` and `med` for substitutability ($\eta < 0$) and complementarity ($\eta > 0$) in 2030

evolution in demand for pulp between `baseline` and `med` in 2030. For this reason, Table 3 shows that emissions in the pulp industry are always higher with a cost reduction: increased recycling prevails. Besides, from the same reasoning, we show that when increasing substitution (from $\eta = -0,2$ to $\eta = -1$), leads to a smaller emissions difference.

Scenario	`low`	`med`	`high`
Emissions variations ($MtCO_2$) of the transformation industry			
$\eta = 0,2$	0,140 (+4%)	0,231 (+6%)	0,315 (+8%)
$\eta = -0,2$	0,127 (+3%)	0,225 (+6%)	0,315 (+8%)
$\eta = -1$	0,105 (+3%)	0,192 (+5%)	0,265 (+6%)

Table 3: Changes in emissions linked to transformation in the pulp industry (compared with scenario `baseline`) - yearly average for 2013-2080

One interpretation of complementarity comes from paper and cardboard industries introducing fixed proportions of wood-pulp and recycled pulp in their transformed products, according to the use and the level of quality they look for. There is indeed a lower quality of the fiber for each recycling process, thus imposing a limit of cycles and use (ERPC, 2015). With this hypothesis, recycling fosters the demand for wood-pulp. In contrast, when products are substitutes, introducing recycled pulp implies a stronger competition for wood-pulp, thus decreasing the quantities. High substitution also reflects technical possibilities, where recycled pulp has an equivalent quality and consumption pattern as wood-pulp.

The purpose of our analysis here is to go beyond this straightforward economic result of higher direct GHG emissions. Structural links between the pulp industry and the rest of the forest sector are expected to induce economic and carbon impact when recycling is more prevalent. These results will figure out wether the wood sector can alleviate the increased climate impact of the pulp industry.

3.2 Impacts on other forest products

The structure of the model, depicted in Figure 2, shows the link between the pulp industry and the rest of the forest products sector. Wood-pulp is indeed a transformed product of industrial wood, also used for pannels manufacturing and energy purposes. This induces a competition for the resource (the primary product). For this reason we can expect an effect of increased recycling on those products. At a wider scale, industrial wood competes with round-wood primary products for the forest resource. We can also expect an impact on these products. However, results from the work of Buongiorno et al. (2003) lead us to suspect very small effects in terms of relative changes in supply and demand of wood products.

Table 4 shows very small relative effects on the wood products. Fuel-wood which is in direct competition with the pulp industry for primary industrial wood shows higher impacts (from $-0,14\%$ to $0,4\%$), while sawnwood shows negligible impacts. These products also follow the effect of substitution and complementarity of the two sources of pulp. Besides we have to assess the climate impact that derive from these economic impacts. It regroups material and energy substitution related to the use of wood products, as well as emissions linked to forest exploitation (forest operations and transport). As emissions of forest operations are negligible compared to energy and material substitution they are not be displayed in Table 5[6]. While they remain low in terms of relative changes, these sequestration mechanisms can potentially

[6]Unlike Table 3 where we show GHG emissions amounts, we produce in Table 5, 6 and 8 GHG substitution and sequestration, where a negative sign means more emissions, and a positive sign more mitigation.

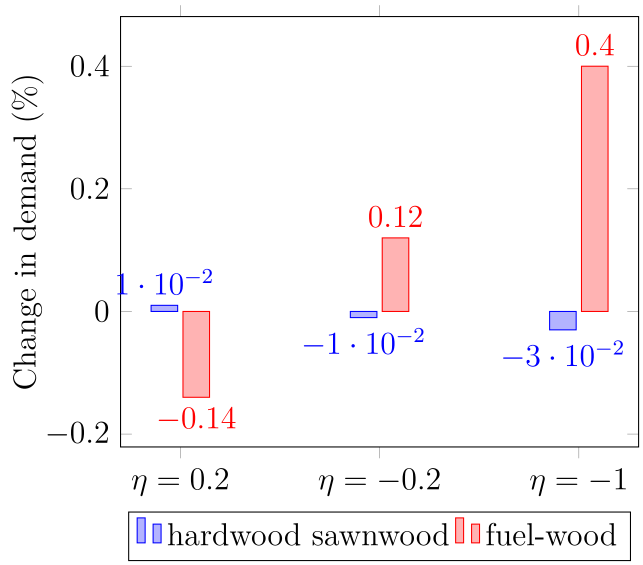

Table 4: Relative changes in demand for other wood products between `baseline` and `med` in 2030

offset additional emissions of pulp transformation. This is especially true for energy substitution, derived from the differences in fuel-wood usage. It does not compensate higher emissions from transformation detailed above, but when pulps are substitutes they amount 10% of the emissions variation. However, when pulps are complementary products, sequestration is lower, thus deepening the negative climate impact of pulp recycling.

Scenario	`low`	`med`	`high`
Energy substitution ($MtCO_2$)			
$\eta = 0,2$	-0,012 (-0,08%)	-0,019 (-0,14%)	-0,030 (-0,18%)
$\eta = -0,2$	0,010 (+0,07%)	0,017 (+0,12%)	0,023 (+0,16%)
$\eta = -1$	0,033 (+0,23%)	0,055 (+0,39%)	0,072 (+0,51%)
Material substitution ($MtCO_2$)			
$\eta = 0,2$	-0,004 (-0,01%)	-0,006 (-0,02%)	-0,008 (-0,03%)
$\eta = -0,2$	0,003 (+0,01%)	0,005 (+0,02%)	0,007 (+0,03%)
$\eta = -1$	0,009 (+0,04%)	0,016 (+0,06%)	0,022 (+0,09%)

Table 5: Changes in carbon substitution for other wood products (compared with scenario `baseline`) - yearly average for 2013-2080

3.3 Impacts on the forest resource

The specification of resource impacts relies first on inventoried and non-inventoried biomass (branches and roots), as well as wood products (however this last one is negligible in terms of absolute values). We see from Table 6 that in the case of complementary pulp products, effects on stocks exacerbate the negative climate effect of increased recycling. Substitution in contrast leads to higher sequestrated carbon with up to a $1,5\%$ increase in the most optimistic case (high substitution $\eta = -1$ and scenario `high`).

Scenario	`low`	`med`	`high`
Carbon sequestration pool ($MtCO_2$)			
$\eta = 0,2$	-0,143 (-0,2%)	-0,232 (-0,3%)	-0,310 (-0,4%)
$\eta = -0,2$	0,141 (+0,2%)	0,245 (+0,4%)	0,336 (+0,5%)
$\eta = -1$	0,453 (+0,7%)	0,781 (+1,1%)	1,027 (+1,5%)

Table 6: Changes in carbons stocks (compared with scenario `baseline`) - yearly average for 2013-2080

Changes for the forest resource are also reflected in landscapes evolutions, as increased recycling has impacts in terms of forest management after some decades. Results for the volume of resource in Table 7[7] are coherent with results on carbon stocks for the sector, with an increase when substitutes

[7]Note that we do not display results for lands covered with a mix of conifers and broadleaves.

and a decrease when complements. We can notice that this increase (resp. decrease when $\eta = 0,2$) mainly concerns the broadleaved cover. Changes in forest areas are also noticed. While the overall forest cover remains stable in France with no evolution in total, the ratio of species evolves with more broadleaves (resp. less when $\eta > 0$) and less conifers (resp. more). These results are in relative values limited, reflecting the overall stability of the forest sector. However these landscape impacts can lead to modifications in terms of ecosystem services from the forest sector, with an overall reduction in some cases (Gamfeldt et al., 2013).

	Broadleaves	Conifers	Total
Forest areas (Mha)			
$\eta = 0,2$	-1,980 (-0,02%)	1,730 (+0,04%)	0 (0%)
$\eta = -0,2$	1,749 (+0,02%)	-1,595 (-0,04%)	0 (0%)
$\eta = -1$	5,853 (+0,07%)	-5,420 (-0,14%)	0 (0%)
Forest volumes (Mm^3)			
$\eta = 0,2$	-6,318 (-0,20%)	-1,695 (-0,18%)	-9,106 (-0,19%)
$\eta = -0,2$	5,264 (+0,17%)	1,297 (+0,14%)	7,441 (+0,16%)
$\eta = -1$	17,637 (+0,57%)	5,121 (+0,55%)	26,012 (+0,56%)

Table 7: Changes in forest volumes and areas between `baseline` and `med` in 2070

3.4 Global carbon impact on the forest sector

Results on sequestration described above combined with changes in GHG emissions give the total CO_2 balance of the forest sector. Reduced sequestration with complementary pulp products lead to important diminutions in the global balance, as we find a reduction between $0,299$ and $0,660$ $MtCO_2$/year (Table 8). On the other hand, with low substitution ($\eta = 0,2$) we find an equilibrium between additional emissions and sequestration, with slightly positive values for the carbon balance, although negligible compared with the use of other values for elasticity η. This effect is indeed higher when we examine the optimistic case of a high substitution between pulps, up to $0,8\%$ of the total carbon balance of the French forest sector for scenario `high`.

While these global results are relatively small for the scale of the forest sector, it shows the central role of substitutability and complementarity to understand the environmental impact of paper recycling. With complementarity, reduced recycling costs and thus increased production of pulp overall (as shown in Table 2) leads to a higher usage of the virgin resource, coupled with increased forest utilization. On the other hand, substitution between pulps leads to lower forest exploitation, then higher sequestration compensating emissions of the pulp industry. It is interesting to notice that the forest sector only alleviates an increased carbon impact of the recycling sector when added recycled products are substitutes to wood-pulp. Besides, this is true for both substitution mechanisms (Table 5) and sequestration mechanisms (Table 6).

Scenario	`low`	`med`	`high`
Global carbon balance ($MtCO_2$)			
$\eta = 0,2$	-0,299 (-0,3%)	-0,489 (-0,5%)	-0,660 (-0,6%)
$\eta = -0,2$	0,027 (+0,03%)	0,041 (+0,04%)	0,050 (+0,05%)
$\eta = -1$	0,390 (+0,4%)	0,660 (+0,6%)	0,857 (+0,8%)

Table 8: Changes in global GHG balance (compared with scenario `baseline`) - yearly average for 2013-2080

4 Conclusion

With this work, we contribute to the already existing literature focusing on recycling of wood products. The question of wether recycling has a positive or negative carbon impact is crucial when issues relative to climate change and circular economy are more and more prominent. Based on the present situation of the French forest sector, we examine what would be the impact of increased recycling, simulated through a cost reduction in the sector. The use of FFSM enables us to have a broader perspective for the climate impact. The market module and the recursive structure expands a standard LCA analysis with both economic impacts on other wood products sectors and variations in carbon substitution and sequestration.

First, we show the expected impact of recycling on wood-pulp industry. Expected qualitative results regarding the complementarity or substitution of both products are found, with respectively a positive or negative impact on demand. Beyond this economic outcome, GHG emissions of the pulp sector are always increasing, thus raising the question of their possible mitigation through the rest of the forest sector.

Second, we find small effects on other wood products. This is expected as the economic model combines small price-elasticities of products competing for timber resources and small cross-elasticities between virgin and recycled. The model produces small changes for transformed products from industrial wood (such as fuel-wood and pannels), with a higher demand when pulp recycling is a substitute (and vice versa when complements). However this effect is negligible for other wood products such as sawn wood and plywood. This involves small effects on carbon substitution mechanisms (material and energy).

Finally, our study of global carbon sequestration highlights small relative effects overall (between $0,4\%$ and $0,8\%$ in the additional carbon balance of the sector). However in terms of absolute evolution of the net sequestration potential, we observe a positive impact when considering substitution in the pulp industry, and a negative impact when considering complementarity. The already existing literature on the econometrics of paper and cardboard recycling shows that strongly substitute products would be a very optimistic scenario, while low complementarity is a more realistic one. Our results show that the development of recycling (and more generally of a circular economy) relies on the substitutability of natural capitals to be environmentally efficient (here virgin and recycled capitals)(Ayres, 2007).

This sectoral analysis on the economic and carbon impacts of paper and cardboard recycling should be pursued with further investigation, including sensitivity analysis of other parameters in the model, such as recovery rates and the introduction of policies promoting recycling or a lower carbon footprint.

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