Sectoral, resource and carbon impacts of introducing recycling in a forest sector

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Abstract

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 sector 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 market effects of paper and cardboard recycling as well as 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.

Keywords— Recycling; Forest sector; Bioeconomic model **JEL classifications**— Q23, Q53, Q54, L73

1. Introduction

1.1. Context and Motivations

The concept of a circular economy has emerged as an important topic of research during the last decade. It is in fact regarded as a central piece for the redefinition of a more sustainable economic model. One of the corner stone of this topic is the development of recycling, on order to escape from the linear "extract-consume-throw away" logic. The study of its underlying dynamics calls for a global approach taking into account the different externalities linked to resource extraction, recycling and disposal. Historically, waste accumulation and resource

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scarcity have been the main motivations for developing a circular model of our economies. More recently, local and global pollution like greenhouse-gas emissions drew more and more concern, directly linking the circular economy and climate change issues. During the last decades, mostly developed countries engaged in expanding recycling activities through policies (tax and subsidies) and technological progress. However, recycling remains a costly choice, rarely preferred over extraction.

In this context, the paper and cardboard industry has an important role, as the corresponding resource, forest, is directly linked to climate change: it has an important mitigation potential and climate change has an effect on the availability of the resource. Besides, the industry produces important amounts of waste each year (9Mt in France in 2014, according to ADEME[1]), while in the case of France, 66% of the production comes from recovered waste. Moreover, this industry is integrated into the global forest sector, motivating a more holistic study that includes other wood products and usages, in order to properly assess the effect of paper and cardboard recycling.

Our contribution in this paper is to consider the impact of paper and cardboard recycling on forest sectors, both from an economic and carbon point of view. Our study will be based on the French forest sector, thus relying on a wide literature based on the already developed French Forest Sector Model (FFSM++ version).[7][1] FFSM++ is an integrated assessment model providing prospective scenarios of the French forest sector. Its recursive dynamics simulates every year the amount of wood products produced, consumed and prices. International and regional trade of different forest products are considered and combined to forest management considerations. It also accounts for carbon emissions and sequestration, giving the impact on climate of the different activities of the sector. For the purpose of this study,we integrate recycling of paper and cardboard to the previous FFSM++ model.

1.2. Literature

Motivations for recycling have been tackled by the economic literature from the 70s, as authors would highlight its role to reduce waste volumes and the pressure on natural resources: Smith [24] studies the trade-off between private costs (labor, material) and social costs (waste accumulation, resource depletion) that come into play when recycling is an alternative to ex-

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

tracting from the virgin resource. Several model of the literature of polluting resources tackle this issue in order to determine optimal economic paths.[12][21] This theoretical framework is useful to guide the study of specific products, such as wood products in our case.

As far as the paper and cardboard sector is concerned, substitution between waste and wood-pulp appears to be a key element when determining the effect of recycling. Technological process induces a lower quality of input after each recycling loop: the loss of quality raises the question of sustainability as a limited amount of cycles can occur, depending on the type of product that is manufactured.[10] Low elasticities of substitution can be found for waste and wood-pulp by Lee and Ma,[13] while in the Swedish case, Lundmark et al. show complex interactions between the two products, with often a complementarity between the two.[17] Different articles also show small price elasticities for paper waste.[8][9][18] These results imply that price-based mechanisms have little effect to reduce paper waste accumulation and promote the use of recycled input. Besides, in the case of complementary products, while recycling could be promoted, it would not have a major effect on the resource. At the same time, Berglung and Söderholm show that recovery rates are determined mainly by long term economic indicators such as GDP and demography.[3] This is consistent with the use of an exogenous recovery rate by Buongiorno in his global forest sector model.[4] With this hypothesis, he shows that more recycling in the US has little effect on other wood products, but reduces paper world prices thus increasing demand of paper and cardboard worldwide. Our study also includes different wood products, as described in Lenglet and al.[14]

While for many industrial sectors there are unambiguous positive environmental effects of substituting recycling to extraction, the case of paper and cardboard is more complex. In their life-cycle assessment,[11] Federec and ADEME compute a neutral or worse climate impact of recycling paper and cardboard in France. This is due to the energy use of the recycling process itself, as well as the use of fuel-wood in the wood-pulp sector. Merrild and al. also highlight the impact of downstream emissions,[19] however they show important GHG emissions savings when extending the analysis to avoided emissions: avoided standard paper production and assuming that forest wood is instead used for energy purposes. These contrary results suppose strong assumptions regarding substitutions effects, and are highly dependent on energy sources for the different industrial activities of the sector. The paper and cardboard industry can yet play an important role in the ecological transition, from replacing other materials like plastic, to its recycling potential and strong ties to the forest sector which is a major player for climate change mitigation.[23] Besides, studies like Pieratti and al. show that forest management has potential for improvement as far as sustainability is concerned.[20] This local analysis points out optimizations that tend to reduce GHG emissions, and complete a wider analysis by Lobianco and al. on the french forest sector indicating mitigation potential despite the impacts of climate change on the sector itself.[15] For this reason, using a wide calibrated model can add a new perspective on the environmental impact of paper and cardboard recycling, by including economic theory to support potential substitution effects on the whole forest sector.

The French Forest Sector Model (FFSM) used here for our analysis has already produced a wide stream of literature regarding long-term assessments of the sector, from its original version FFSM 1.0[7] showing the impact of fuel-wood policies when a payment for carbon sequestration is introduced. The model was completed by modules accounting for long term forest management[16] and carbon emissions, with an effect of worldwide emissions on the dynamic of the forest and the accounting of local emissions and sequestration. The model is an useful tool to examine the effect of different policies with conflicting effects such as a carbon tax with a fuel-wood policy.[6] However, FFSM++ did not consider the recycling industry, which is especially important for pulp products. Therefore we present here an extension of the model, that links virgin wood-pulp to recycled one.

2. Modelling recycling within a forest sector model

2.1. The French Forest Sector Model

As described in Caurla and al.[7] and Caurla[5], FFSM was designed to explore the dynamics of markets and resources, as well as policies and their economical and environmental impacts. Each year, the model computes prices and quantities for different primary and secondary wood products based on a standard surplus maximization. Besides, trade of products is represented on the national level, using Samuelson spatial price theory with different regions,[22] as well as the international level, using Armington substitution model.[2] This economic model is completed by a resource module representing the forest sector, and a carbon accounting module in order to assess the emissions balance of the sector.

In order to take into account paper and cardboard recycling, we add a pair of primary and secondary products representing the recycling loop: respectively recovered waste that can be sold either worldwide or to national recyclers, and processed waste (called here recycled pulp) that is a substitute to wood pulp.[2]

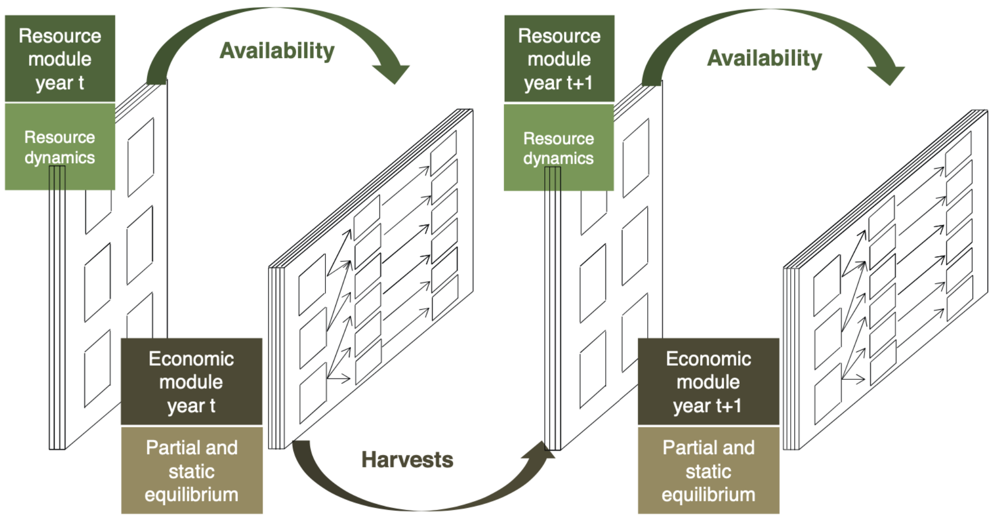

Figure 1: Recursive structure of FFSM

2.2. *Introducing recycled paper in FFSM++*

The introduction of recycling into FFSM++ requires to add both demand for recycled pulp and supply of waste paper and cardboard.

2.2.1. *Demand for recycled pulp*

Regional demand for recycled pulp, with a substitution between local and international according to Armington theory, is expressed:

$$D_{recy,i,t} = \left[\left(1 - b_{D_{recy,i}}\right) LD_{recy,i,t}^{\frac{\varphi_{recy,i}-1}{\varphi_{recy,i}}} + b_{D_{recy,i}} M_{recy,i,t}^{\frac{\varphi_{recy,i}-1}{\varphi_{recy,i}}} \right]^{\frac{\varphi_{recy,i}}{\varphi_{recy,i}-1}} \quad (1)$$

Where:

- $D_{recy,i,t}$ is the demand for composite recycled pulp, in region i at year t;
- $LD_{recy,i,t}$ is the demand for recycled pulp produced in France in region i at year t;

[2]There is a more extended discussion to have on whether wood pulp and recycled pulp are substitutes or complementary, on technical and economical aspects, as explained in different articles such as Lundmark and al.[17][13][18]. For this purpose we introduce an elasticity of substitution between those two products, as explained below.

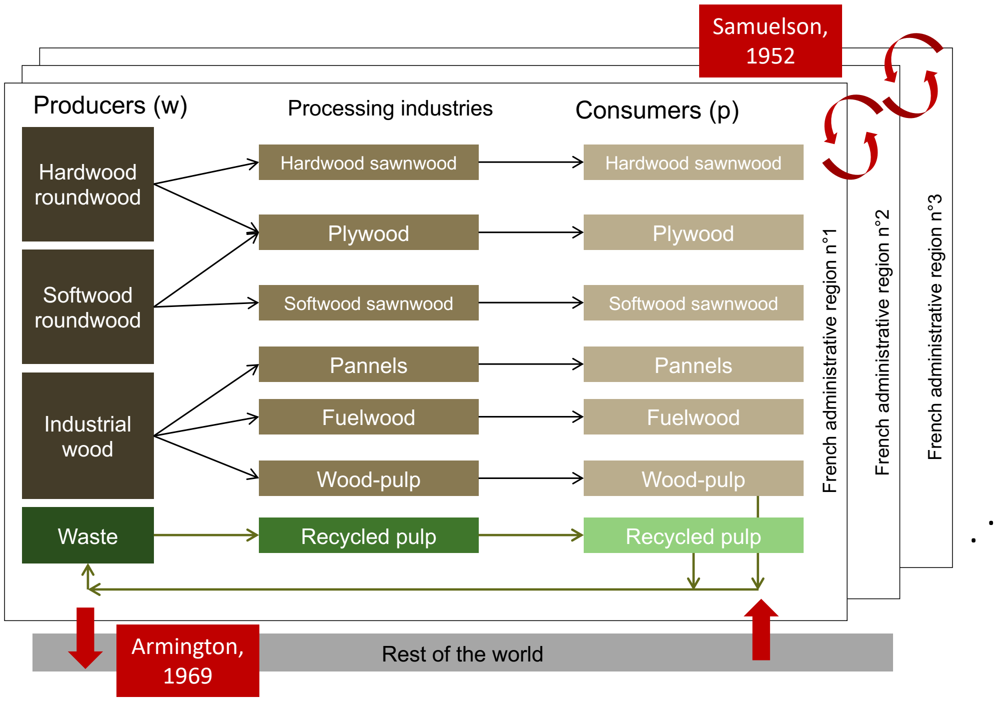

Figure 2: Products structure of FFSM

- $M_{recy,i,t}$ is the demand for recycled pulp produced abroad, (meaning the amount of imports of recycled pulp), in region i at year t;
- $\varphi_{recy,i}$ is the elasticity of substitution between recycled pulp produced in France and recycled pulp produced abroad;
- $b_{D_{recy,i}}$ is a constant parameter such that $0 < b_{D_{recy,i}} < 1$.

Foreign and local demand are expressed under as functions of the composite demand for recycled pulp and their prices in the market:

$$M_{recy,i,t} = b_{D_{recy,i}}^{\varphi_{recy,i}} D_{recy,i,t} \left(\frac{\tilde{P}_{recy,i,t}}{P^*_{recy,t}} \right)^{\varphi_{recy,i}} \tag{2}$$

$$LD_{recy,i,t} = \left(1 - b_{D_{recy,i}}\right)^{\varphi_{recy}} D_{recy,i,t} \left(\frac{\tilde{P}_{recy,i,t}}{P_{recy,i,t}} \right)^{\varphi_{recy,i}} \tag{3}$$

Where:

- $\tilde{P}_{recy,i,t}$ is the price of composite recycled pulp, in region i at year t;
- $P_{recy,i,t}$ is the price of recycled pulp in France, in region i at year t;

- $P^{*}_{recy,t}$ is the price of recycled pulp abroad, at year t;

The composite demand of recycled pulp depends on its price and also the evolution of the price ratio with its substitute (or complement) product, wood-pulp. The introduction of this cross-elasticity will be key to determine the effect of the recycling industry on the rest of the forest products sector.

$$D_{recy,i,t} = D_{recy,i,t-1} \left(\frac{\tilde{P}_{recy,i,t}}{\tilde{P}_{recy,i,t-1}} \right)^{\sigma_{recy}} \left(\frac{\frac{\tilde{P}_{recy,i,t}}{\tilde{P}_{pulp,i,t}}}{\frac{\tilde{P}_{recy,i,t-1}}{\tilde{P}_{pulp,i,t-1}}} \right)^{\eta_{recy,pulp}} \tag{4}$$

Where

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

2.2.2. Supply of waste paper and cardboard

There is a regional supply of recovered waste paper and cardboard, with a substitution between local and international supply, with the following expression:

$$S_{waste,i,t} = \left[\left(1 - b_{S_{waste,i}}\right) LS_{waste,i,t}^{\frac{\varphi_{waste,i}-1}{\varphi_{waste,i}}} + b_{S_{waste,i}} X_{waste,i,t}^{\frac{\varphi_{waste,i}-1}{\varphi_{waste,i}}} \right]^{\frac{\varphi_{waste,i}}{\varphi_{waste,i}-1}} \tag{5}$$

Where:

- $S_{waste,i,t}$ is the supply of composite waste paper and cardboard, in region i at year t;
- $LS_{waste,i,t}$ is the supply of waste paper and cardboard in region i at year t;
- $X_{waste,i,t}$ is the supply of waste paper and cardboard to foreign markets, (meaning the amount of exports of waste paper and cardboard), from region i at year t;
- $\varphi_{waste,i}$ is the elasticity of transformation between waste paper and cardboard sold abroad and waste paper and cardboard sold in France;
- $b_{S_{waste,i}}$ is a constant parameter such that $0 < b_{S_{waste,i}} < 1$.

Foreign and local supply are expressed under as functions of the composite supply of waste paper and cardboard and their prices in the market:

$$X_{waste,i,t} = b_{S_{waste,i}}^{\varphi_{waste,i}} S_{waste,i,t} \left(\frac{\tilde{P}_{waste,i,t}}{P^*_{waste,t}} \right)^{\varphi_{waste,i}} \tag{6}$$

$$LS_{waste,i,t} = \left(1 - b_{S_{waste,i}}\right)^{\varphi_{waste,i}} S_{waste,i,t} \left(\frac{\tilde{P}_{waste,i,t}}{P_{waste,i,t}} \right)^{\varphi_{waste,i}} \tag{7}$$

Where:

- $\tilde{P}_{waste,i,t}$ is the price of composite waste paper and cardboard, in region i at year t;
- $P_{waste,i,t}$ is the price of waste paper and cardboard in France, in region i at year t;
- $P^*_{waste,t}$ is the price of waste paper and cardboard abroad, at year t;

The composite supply of waste paper and cardboard depends on its price and also the stock of waste paper and cardboard that could be recovered for recycling purposes:

$$S_{waste,i,t} = S_{waste,i,t-1} \left(\frac{\tilde{P}_{waste,i,t}}{\tilde{P}_{waste,i,t-1}} \right)^{\epsilon_{waste}} \left(\frac{W_{i,t}}{W_{i,t-1}} \right)^{\beta_{waste}} \tag{8}$$

Where:

- $W_{i,t}$ 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 $t-1$.[3] Under this assumption, the stock is given by:

$$W_{i,t} = \gamma_{i,t}(LD_{pulp,i,t-1} + M_{pulp,i,t-1} + LD_{recy,i,t-1} + M_{recy,i,t-1}) \tag{9}$$

Where:

[3] Following a common assumption in literature concerning recycling of resources, we do not account for the duration of use of the pulp produced. This means that each year, paper is produced, consumed and then recycled or disposed of the following year. From ADEME[1], we know that french consumption of paper and cardboard in 2014 consists of packaging for 52% and the recovered share consists in 62% of packaging.

- $\gamma_{i,t}$ 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;
- $LD_{pulp,i,t-1}$ is the local demand in pulp in region i at year $t-1$;
- $M_{pulp,i,t-1}$ is the foreign demand in pulp in region i at year $t-1$;
- $LD_{recy,i,t-1}$ is the local demand in recycled pulp in region i at year $t-1$;
- $M_{recy,i,t-1}$ is the foreign demand in recycled pulp in region i at year $t-1$;

Waste paper and cardboard are transformed by a recycling industry. The input-output function gives the amount of waste necessary to produce a secondary input. Practically, waste paper and cardboard can be transformed into recycled pulp, thus giving the following function:

$$D_{waste,i,t} = a_{recy,waste} S_{recy,i,t} \tag{10}$$

Where:

- $D_{waste,i,t}$ is the total demand for waste paper and cardboard in region i at year t;
- $a_{recy,waste}$ is the input-ouput coefficient, the volume of waste needed to produce one unit of recycled pulp;
- $S_{recy,i,t}$ is the production of recycled pulp in region i at year t;

The recycling industry has a constant cost of production m_{recy} for each unit of recycled pulp produced.

3. Impacts of recycling on the forest sector

We run the model through a numerical solver, in order to assess the effect of the recycling loop we added.[4] From the structure of FFSM++, there are two links between recycled products and other wood products. First, the waste resource comes from transformed products

[4] In order to calibrate the model, we use the calibration done for previous articles using FFSM++, detailed in Caurla et a.l.[7][5]. We add the specific calibration of the recycling sector using data from Lenglet et a.l.[14] for material flows, Buongiorno et a.l.[4] for economic parameters such as elasticities, and Federec [11] for carbon data specific to recycling activities.

wood-pulp and recycled pulp, allowing an impact of other products on the recycling loop. Second, both transformed products have an influence on each other, through the cross-elasticity defined in equation (4).[5] According to this equation, recycled and wood-pulp are substitutes when $\eta < 0$ and complements when $\eta > 0$. Based on the related literature described earlier, we find small values for price-elasticities and cross-elasticities. Regarding substitution or complementarity, there is still a discussion in the literature,[17] with results that can depend on the specific third transformation product, not detailed in FFSM. In order to test the impact of the recycling industry, we test a cost reduction of c_{recy} with an initial year calibrated with the current french sector, with different substitution hypothesis. From these sensitivity tests, we display the different impacts on the forest sector.

3.1. Impacts on the pulp industry

The direct impact of cost reduction is obviously on the recycling industry, with an increased production, no matter the substitution hypothesis. Figure 3 shows the impact of a cost m reduction for low substitutes: a 9% increase of total demand with a 80% of cost reduction.[6]

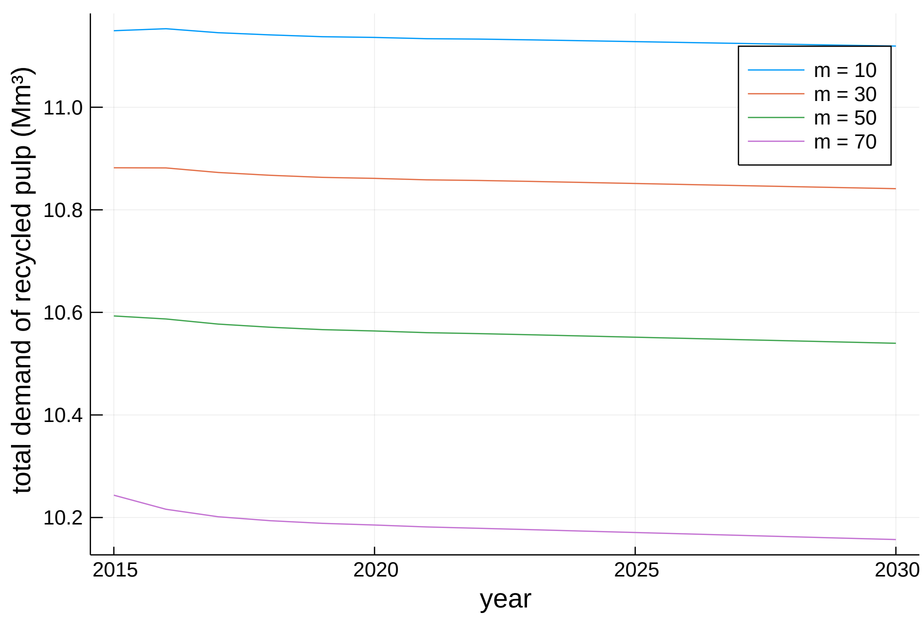

Figure 3: Demand for recycled pulp, low substitution ($\eta = -0,2$)

[5]Symmetrically, we define the cross elasticity in the demand equation for wood-pulp $\eta_{pulp,recy} = \eta_{recy,pulp} = \eta$.

[6]Note that this parameter of cost m corresponds to c_{recy} defined above.

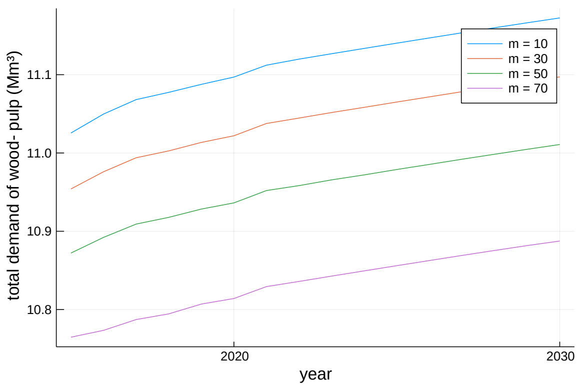

Figure 4: Demand for wood-pulp ($\eta = 0, 2$)

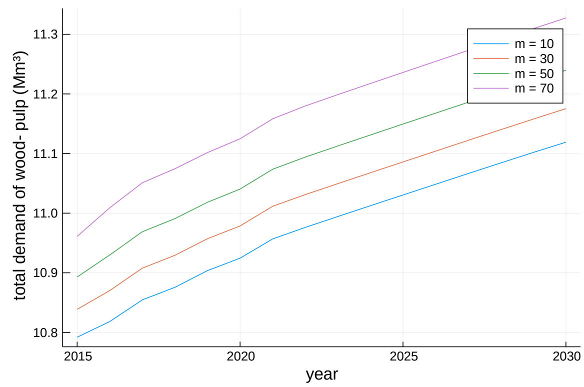

Figure 5: Demand for wood-pulp ($\eta = -0, 2$)

Alternatively, the impact on the wood-pulp demand is driven by the cross-elasticity, with lesser results that for the recycling industry. Figures 4 and 3 show that recycling has a positive impact on the the regular wood-pulp industry when complements (a 3% demand increase) and a negative impact when substitutes (a 2% decrease in demand). We can also note that the effect is smaller on this industrial branch than on the recycling branch. Complementarity can be interpreted as 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. 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.

These changes in demand for the pulp industry induce changes in emissions, directly linked to the transformation of the products. For both substitution and complementary cases ($\eta = \pm 0, 2$), a rise in emissions is driven by the higher demand for recycled pulp when costs are lower. We calibrated emissions with data from Ademe and Federec [11], a study that shows a higher climate impact for the recycling process.[7] Table 1 shows this effect on emissions of the pulp industry, for year 2070. Note that these results are steady from mid-term (2030) up to long term horizons (2080).

[7] We use 195 $kgCO_2/m^3$ for wood-pulp and 364 $kgCO_2/m^3$ for recycled pulp, emissions coefficient relative to the transformation process of the pulp and taking into account that production is distributed between pulp for cardboard and for paper products.

c_{recy}	50	30	10
Relative change, $\eta = -0,2$	+3%	+6%	+8%
Absolute change in $MtCO_2$, $\eta = -0,2$	0,135	0,235	0,327
Relative change, $\eta = 0,2$	+3%	+5%	+7%
Absolute change in $MtCO_2$, $\eta = 0,2$	0,127	0,199	0,264

Table 1: Changes in 2070 yearly emissions linked to transformation in the pulp industry (compared with scenario where $c_{recy} = 70$)

3.2. Impacts on other forest products

Considering quantities of other wood-products, recycling has a very small impact. This is consistent with Buongiorno's results showing little effect of recycling on the global forest sector.[4] Figure 6 shows a 0,2% rise in demand for fuel-wood with a 80% cost reduction of recycling. This result is also a competition effect, as fuelwood comes from the same transformation as wood-pulp, the industrial wood subsector (see Figure 2). For this reason, we hardly see any effect on other wood-products such as plywood. Inversely, complementary products induces a small reduction of the demand for fuel-wood. For this reason, we hardly see any effect on other wood-products such as plywood. This result suggests the possibility of conflicting political implications of combining fuelwood and recycling policies : with complementary products, both policies would have contradictory effects. In this case, substitution between recycled and wood-pulp is also a barrier (like high costs) for the development of recycling.

Considering low cross-elasticities, we also get small absolute changes in emissions, especially compared to the rise in emissions due to increased recycling in the pulp industry (mostly through increased or decreased energy substitution with the change in fuel-wood demand). For this reason, the absolute change in net emissions in the sector is in the same order of magnitude as the change in emissions for the pulp industry.

3.3. Impacts on the resource

Finally, the carbon impact of recycling should be studied considering changes in carbon stocks, thus examining the impact on the forest resource. Given the very small effect of recycling on the rest of the industry when costs are reduced, we expect small relative effects. However, absolute effects on sequestration should be compared to absolute effect on emissions in order to get a net impact on the carbon balance. This total balance is shown in Figure 2.

We can easily see the impact of the substitution/complementarity hypothesis in the pulp industry here. For complementary products ($\eta = 0,2$) we get a lower sequestration in the

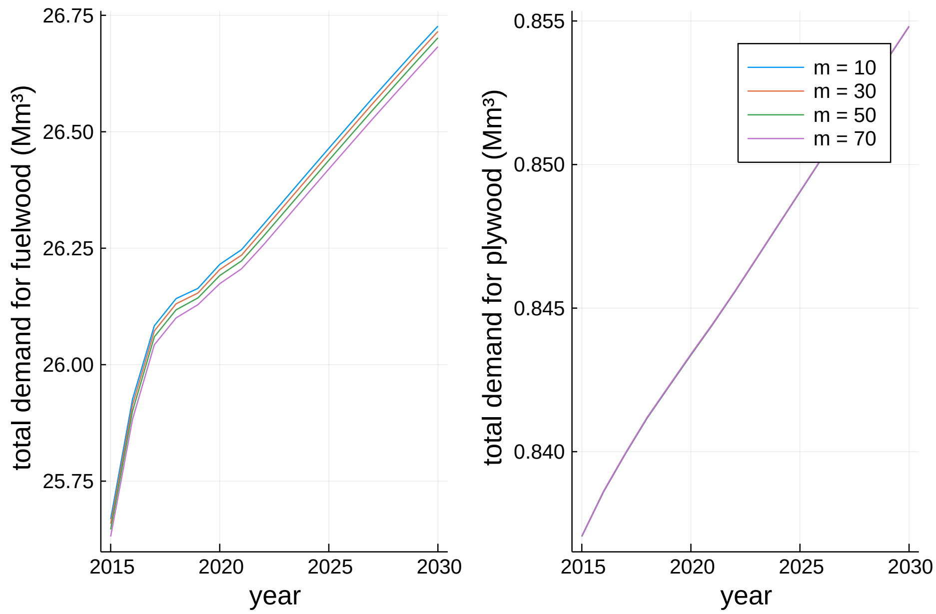

Figure 6: Demand for other forest products, with substitution ($\eta = -0,2$)

c_{recy}	50	30	10
Absolute change in MtCO2, $\eta = -0,2$	0,040	0,061	0,083
Absolute change in MtCO2, $\eta = 0,2$	-0,328	-0,516	-0,690
Absolute change in MtCO2, $\eta = -1$	0,542	0,913	1,181

Table 2: Changes in 2070 yearly sequestration for the whole sector (compared with scenario where $c_{recy} = 70$)

global forest sector (all emissions sources aggregated). On the contrary, substitution induces a small but higher sequestration. We added a scenario with a very optimistic substitution hypothesis ($\eta = -1$), showing up to $1,181$ MtCO2 in additional sequestration for high cost reductions (corresponding to a relative 1% rise in total sequestration in the sector).

4. Conclusion

Recycling is a key element of the circular economy. When focusing on the forest sector, increasing recycling is expected to have a potential impact not only on waste and forest resources, but also on carbon emissions. The aim of this paper is to assess, within diverse sets of parameters regarding complementarity and substitutability of virgin and recycled pulp, how paper recycling impacts the forest sector.

First, recycling is expected to have an impact on the wood-pulp industry. We test this impact by reducing the cost of transformation of the recycling branch. We find the expected qualitative result as demand for recycled pulp is higher. Regarding wood-pulp, substitution plays an important role, as it determines wether recycling has a negative (substitutes) or positive (complements) impact on the demand. These economical outcomes lead to higher emissions in this specific sectors, for any hypothesis on the cross-elasticity.

Second, this effect on the paper industry may have indirect outcomes on industries that compete with it for timber resources, like industrial wood products. However our model shows small effects on industries of transformed products from industrial wood (fuelwood and pannels), with a higher production when recycled and wood-pulp are substitutes. This effect is besides negligible for other wood products (plywood, sawnwood,...).

Finally, environmental impacts of recycling combine impacts on forest resources, waste and carbon. Focusing on carbon, we assess that given the very small relative effect of recycling on other industries of wood products, there is little to negligible relative evolution of the sequestration potential of the forest. 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.

This paper is a preliminary analysis on the economic and carbon impacts of paper and cardboard recycling. Further investigation is required, 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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