Documents de travail

« An economic analysis of a storage policy after a storm occurrence in forestry»

Auteurs

Julien JACOB, Antoine LEBLOIS, Marielle BRUNETTE

Document de Travail n° 2024 – 27

Juin 2024

Bureau d'Économie Théorique et Appliquée BETA

www.beta-economics.fr

@beta_economics

Contact :
jaoulgrammare@beta-cnrs.unistra.fr

An economic analysis of a storage policy after a storm occurrence in forestry

Julien JACOB* Antoine LEBLOIS† Marielle BRUNETTE‡

June 11, 2024

Abstract

Storm is among the main threat for European forestry generating huge economic damage. The decrease of the timber price due to the storm occurrence largely contributes to these economic impacts. Timber storage appears as the standard policy to implement in order to limit these negative impacts. Consequently, in this article, we propose a global economic assessment of a storage policy taking into account the impacts on producers, consumers and the cost of public funds. For that purpose, we develop a tractable theoretical model which assesses welfare losses and gains incurred/earned by all agents of the society (forester (supply), consumers (downstream agents), and the public agent), from the storage. The model is then simulated. Our results show that globally, the storage policy is always desirable except for the consumers in the case of storms associated with a low magnitude.

Keywords: risk, price, forest, storage.

JEL classification numbers: D61 (Allocative Efficiency • Cost–Benefit Analysis); D81 (Criteria for Decision-Making under Risk and Uncertainty); Q23 (Forestry).

*BETA, CNRS - University of Strasbourg. Postal address: Faculté des Sciences Économiques et de Gestion, 61 avenue de la Forêt Noire, 67000 Strasbourg Cedex, France. julienjacob@unistra.fr

†CEE-M, Univ Montpellier, CNRS, INRAE, Montpellier SupAgro, Montpellier, France. antoine.leblois@inrae.fr

‡Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRA, BETA, France; Associate researcher to the Climate Economic Chair, Paris, France. marielle.brunette@inrae.fr

1 Introduction

Forest ecosystems are threatened by natural hazards, and among them, storm is the most damaging event. In Europe, over the period 1950-2000, an annual average of 35 million m^3 of wood was damaged by disturbances, and more than half were due to storms (Schelhaas et al., 2003). Europe was hit by several extreme storms these last decades, such as Lothar and Martin in 1999, Gudrun in 2005, Kyrill in 2007 and Klaus in 2009. In France, Lothar and Martin felled about 8% of the total growing stock in a forest area covering 15 million hectares. Klaus felled 32% of the maritime pine growing stock in Aquitaine (forest area of 1 million ha). In Sweden, Gudrun damaged approximately 2% of the growing stock on a national basis (Gardiner et al., 2011). Occurrence of storm generates huge losses. For example, Lothar and Martin in 1999 are responsible for 30 millions m^3 of damage in Germany for a total financial loss of €1.4 billion, and 140 millions m^3 of damage in France amounting to €4.57 billion (Caurla et al., 2015). More recently, Klaus was associated with a total of 42 millions m^3 of damage in south-western France for a loss estimated between €1.34-1.77 billion (Lecocq et al., 2009). An important consequence of the storm occurrence is the sudden and unplanned increase in the supply of timber in the market that translates into a price decrease.

After Gudrun, the average prices of sawlogs of spruce and pine in Sweden was only 63% and 86%, respectively, of those in the year before the storm (Gardiner et al., 2011). After Klaus, 50% of the windfalls suffered from a depreciation due to a price decrease on the timber market (Nicolas, 2009). Hurricane Hugo in U.S in 1989 was another example, damaging 20% of the southern pine on the South Carolina Coastal Plain. Modelling revealed a 30% negative price spike due to salvage (Prestemon and Holmes, 2000). In order to try to cope with this price decrease after storm occurrence, a classical option for governments is to facilitate wood storage. After Lothar and Martin, Germany provided a public help of €15.3 millions for windfall hauling, transportation, storage and replanting (Holecy and Hanewinkel, 2006), whereas French government implemented a 10-years program providing €920 millions with the objective to remove windfall timber, to clear and replant, and to create storage areas for harvested timber (CGAEER, 2010). After Klaus, the French government dedicated €25 millions to the creation of storage area (Bavard et al., 2013).

Climate change is suspected to have a serious impact on storm occurrence, both on frequency and intensity, so that the return period is projected to reduce significantly and the associated damage are predicted to increase (Della-Marta and Pinto, 2009; Gardiner et al., 2011; Brèteau-Amores et al., 2020). In addition, Schelhaas et al. (2010) show that forest damage from wind are expected to increase in the future mainly as a consequence of increase in the total growing stock and in vulnerability. The public intervention through financial help could then be multiplied in the future, thus coming up against the limited capacity of the government budget. In this context, to provide a global economic assessment of policies based on storage, taking into account their impacts on producers, consumers and the cost of public funds, becomes a question of great importance.

In the literature, the management of production risk in forestry due to storm occurrence has been analysed through prevention and insurance (Brunette and Couture, 2008; Holecy and Hanewinkel, 2006; Brunette et al., 2015b). The literature also focuses on price volatility and most of the time this volatility is an ad hoc component of the analysis of the research question, as in Rakotoarison and Loisel (2017) for example, where storm risk and price risk are considered independently one from another. The question of the management of price volatility is sometimes also evoked through contract (Brodrechtova, 2015; Barkaoui and Dragicevic, 2016). To our knowledge, only one paper assumed that storm occurrence has an impact both on production and price (Brunette et al., 2015a). However, the way to manage price risk after storm occurrence is rarely evoked. Two exceptions are the articles of Costa and Ibanez (2005) and Caurla et al. (2015) dealing both with storage.

Costa and Ibanez (2005) provided a cost-benefit analysis of the storage policy implemented after the windstorms of 1999 in France. They show that on average, the windfalls have been stored for 3.5 years for a global unit costs of €17.2/m^3. The authors indicated that, from the point of view of the forest owners, the storage was not profitable, and for the public authority, the overall balance is not positive too since 85% of created storage area had negative outcomes. This article provides a cost analysis and neglects the benefits for the demand side of the market. In addition, since it is applied to a particular case study, the results lack of generality.

Caurla et al. (2015) assessed the economic impacts of the public help implemented by French government after Klaus in 2009 on the forest sector. They show that the global impact was beneficial, in-site storage and export abroad were favored, as compared to a situation without a plan, which favored direct consumption. In addition, the price decrease after Klaus was reduced when the storage proportion increase. This article is also based on a particular case study.

This short overview lets appeared that storage has been analysed in forestry through case studies with mitigated results in terms of economic impact.[1] In addition, the articles provide a partial approach both in terms of actors (only producers and public funds) and analysis (only the costs). As a consequence, the objective of this article is to provide an economic analysis of the storage policy by developing a welfare analysis, which assesses costs and benefits incurred/earned by all agents of the society (forester (supply), consumers (downstream agents), and the public agent), from the policy of storage. The desirability of the policy is assessed by comparison with the absence of policy (*laissez-faire*). We propose to address this research question through the development of a tractable theoretical model. We also provide empirical evidence through simulations. We show that globally, the policy is always desirable except for the consumers in case of storms associated with a low magnitude.

The rest of the paper is structured as follows. Section 2 presents the microeconomics model with in a first step the standard hypothesis without the storage policy and then, we introduce the policy. Section 3 presents the results of the simulations. Section 4 discusses the implications of the results and concludes.

2 Model

We first presents the basics of the model without storage (benchmark), and then we introduce the policy.

2.1 Setting

We consider a representative risk-neutral forester aiming at maximizing its own expected profit. This forester is in a monopoly position, and faces the whole demand for wood. Only one species of wood exists. The forester can harvest standing wood, which is considered as being wood of high quality. In addition, in case of a storm occurring, a

[1] Note that some theoretical articles in economics offer interesting perspective on the way to model storage although not applied to a forestry context. See for example Deaton and Laroque (1992) and Newberry (1989).

quantity Q of wood falls on the ground. This quantity, denoted by Q, is windfall, and we assume that this windfall is a wood of lower quality than the standing wood which is harvested. As a consequence, in case of a storm, the market of wood becomes dual: the harvested standing wood (high quality), and the windfall (low quality).

We consider 3 periods: in a first period (period 0), the forester decides a first quantity of standing wood to harvest. This quantity is QR_0. We consider that there is a lag in time between the harvesting period, and the time where the wood is sold: the cost of harvesting QR_0 is incurred in period 0, while the benefit from selling QR_0 is earned in the next period, period 1.

However, in period 1, a storm may occur (with a probability p). In that case, there is a quantity Q of windfall. As regards windfall, since the quality of wood deteriorates very quickly, the forester has to sell it at the period of storm: so, in period 1, both the longshoring cost of the windfall is incurred and the benefit from selling it is earned. Moreover, still in period 1, the forester has the possibility to harvest another quantity of standing wood and, again, the cost is incurred in period 1 but the benefit from selling is earned in the next period, period 2. In case of storm, this harvested quantity is denoted QR_1^H, and in the case where no storm occurs (probability $(1-p)$), the quantity harvested in period 1 is QR_1^{NH}.[2]

In period 2, the forester earns the benefit from selling the standing wood that was harvested during period 1 (see the expression of forester's profit later).

This setup can be represented by the decision tree in Figure 1 where F stands for "Forester" and N stands for "Nature". There is no discount factor, and we consider no capacity constraint as regards the ability to harvest.

Let $\overline{k}$ be the unit cost of harvesting standing wood, and $\underline{k}$ be the unit cost of longshoring windfall. Hence, the total cost of harvesting QR_0 in period 0 is $\overline{k}QR_0$, and the total cost of longshoring Q in period 1 in case of storm is $\underline{k}Q$. For a given quantity of wood, the cost of longshoring windfall is higher than the cost of harvesting standing wood: $\underline{k} > \overline{k}$. Indeed, it is more complicated and it takes more time and workforce to evacuate wood after a windstorm than harvesting wood as usual.

When a storm occurs, the market becomes dual: both wood of high quality (harvested standing wood) and wood of low quality (windfall) are present on the market. For a

[2]The superscript H stands for "harm" and denotes the state of Nature where storm occurs. The superscript NH (no harm) refers to the state of Nature where no storm occurs.

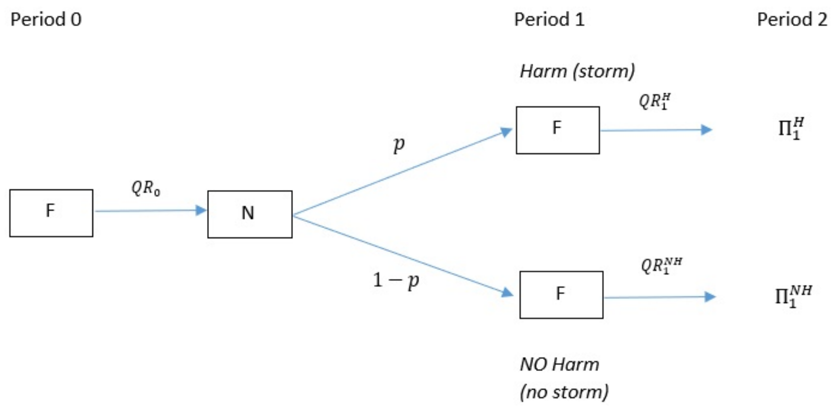


Figure 1: Decision tree

given quantity of wood, we suppose that the consumers' willingness to pay for the wood of high quality is higher than for the wood of low quality. However, both kinds of wood are imperfect substitutes. As a result, the demand functions are the following.

The demand for wood of high quality (indexed by $\overline{Q}$), for a given quantity QR of harvested standing wood, if no storm occurred is:

$$P_{\overline{Q}}(QR) = \alpha_R - \beta_R QR$$

The demand for wood of high quality (indexed by $\overline{Q}$), for a given quantity QR of harvested standing wood, and a given quantity of windfall Q, if storm occurred is:

$$P_{\overline{Q}}(QR, Q) = \alpha_R - \beta_R QR - \delta Q$$

The demand for wood of low quality (indexed by $\underline{Q}$), for a given quantity QR of harvested standing wood, and a given quantity of windfall Q (if storm occurred) is:

$$P_{\underline{Q}}(Q, QR) = \alpha - \beta Q - \delta QR$$

Our assumptions about demand lead to: $\alpha_R > \alpha > 0$, $0 < \beta_R < \beta$. δ is a parameter that takes into account for the imperfect substitution between the two kinds of wood, with $0 < \delta < 1$.[3]

We now turn to present the benchmark case, which is a case of *laissez-faire* (when no policy is introduced in case of storm). Then, we will present what happens when a

[3]These demand functions are inverse demand functions, providing the maximum willingness to pay for a given quantity of wood.

policy of storage is introduced in case of storm occurring. In each case, we first determine the private decisions that are made, and then their impact on the whole society (social welfare analysis).

2.2 Benchmark: *laissez-faire* policy

In case of *laissez-faire*, there is no public intervention in case of storm: the market is free. We first determine private decisions made by the forester, and then their impact in terms of social welfare.

2.2.1 Private decisions

First, we have to determine the decisions made by the forester. We make a backward resolution.

In period 1, in case where there is no storm, the forester's profit Π_1^{NH} is:

$$\begin{aligned}\Pi_1^{NH}\left(QR_1^{NH}\right) &= P_{\overline{Q}}(QR_0)QR_0 - \overline{k}QR_1^{NH} + P_{\overline{Q}}\left(QR_1^{NH}\right)QR_1^{NH} \\ &= (\alpha_R - \beta_R QR_0)QR_0 - \overline{k}QR_1^{NH} + \left(\alpha_R - \beta_R QR_1^{NH}\right)QR_1^{NH}\end{aligned}$$

which is the sum of the revenue from the harvested wood QR_0 (harvested in period 0), minus the cost of harvesting QR_1^{NH} in period 1, and the revenue from selling QR_1^{NH} in period 2 (that we incorporate in period 1 for simplicity - since there is no discount factor).

The optimal quantity of harvested wood in period 1, QR_1^{NH*}, satisfies:

$$\begin{aligned}\frac{\partial\Pi_1^{NH}\left(QR_1^{NH}\right)}{\partial QR_1^{NH}} = 0 \quad &\Rightarrow \quad -\overline{k} + \alpha_R - 2\beta_R QR_1^{NH} = 0 \\ &\Rightarrow \quad QR_1^{NH*} = \frac{\alpha_R - \overline{k}}{2\beta_R}\end{aligned}$$

In period 1, in the case where storm occurs, the forester's profit Π_1^H is:

$$\begin{aligned}&\Pi_1^H\left(QR_1^H\right) = P_{\bar{Q}}(QR_0, Q)QR_0 - \overline{k}QR_1^H + P_{\underline{Q}}(Q, QR_0)Q - \underline{k}Q + P_{\bar{Q}}\left(QR_1^H\right)QR_1^H \\ &= (\alpha_R - \beta_R QR_0 - \delta Q)QR_0 - \overline{k}QR_1^H - \underline{k}Q \\ &+(\alpha - \beta Q - \delta QR_0)Q + \left(\alpha_R - \beta_R QR_1^H\right)QR_1^H\end{aligned}$$

Relatively to the previous case, there is now the cost (-$\underline{k}Q$) of longshoring windfall, the benefit from selling it in period 1 ($P_{\underline{Q}}(Q, QR_0)Q$), and the duality of the market is introduced.

The optimal quantity of harvested wood in period 1, QR_1^{H*}, satisfies:

$$\frac{\partial \Pi_1^H(QR_1^H)}{\partial QR_1^H} = 0 \quad \Rightarrow \quad -\bar{k} + \alpha_R - 2\beta_R QR_1^H = 0$$
$$\Rightarrow \quad QR_1^{H*} = \frac{\alpha_R - \bar{k}}{2\beta_R}$$

We can note that, in this case of *laissez-faire*, these two quantities QR_1^{NH*} and QR_1^{H*} are similar. The occurrence of storm has no impact on the decision about harvesting in period 1, since the benefit from harvesting is earned in period 2 while both cost and benefit from windfall Q are made in period 1.

In period 0, the expected profit is:

$$E[\Pi_0(QR_0)] = -\bar{k}QR_0 + p\Pi_1^H\left(QR_1^{H*}\right) + (1-p)\Pi_1^{NH}\left(QR_1^{NH*}\right)$$

And solving $\frac{\partial E[\Pi_0(QR_0)]}{\partial QR_0} = 0$ leads to:

$$QR_0^* = \frac{\alpha_R - 2p\delta Q - \bar{k}}{2\beta_R}$$

Now we turn to assess the social impact of these decisions, by making a welfare analysis which takes into account benefits and costs from all economic agents.

2.2.2 Social welfare

As usually done in the literature in public economics, social welfare is calculated by summing all the benefits and costs, for all parties. In the present case where no public policy is implemented, social welfare consists in summing the forester's expected profit (determined above), and the consumers' surplus.

As regards the consumers' surplus, we know that consumers get utility from the consumption of wood, and that utility leads to demand functions: $P_{\overline{Q}}(QR)$ when no storm occurs, and $P_{\overline{Q}}(QR, Q)$ and $P_{\underline{Q}}(Q, QR)$ when a storm occurs (see Section 2.1). Recalling that demand functions are the consumers' willingness to pay for each quantity of wood, we can, from the differences between these functions and market prices, deduce the consumers' surplus from wood consumption. Consumers' surplus are index for consumers' net utility from consumption of wood, and they are positive arguments in the social welfare function. For a quantity QR of wood of high quality, the surplus is $\frac{1}{2}\beta_R(QR)^2$. For a quantity Q of wood of low quality, the surplus is $\frac{1}{2}\beta(Q)^2$ (see more details and calculations in Appendix A.1).

All-in-all, the expected social welfare in case of *laissez-faire* is:

$$\begin{aligned} SW\left(QR_0^*, QR_1^{H*}, QR_1^{NH*}\right) &= E[\Pi_0(QR_0^*)] + \frac{1}{2}\beta_R(QR_0^*)^2 + p\left[\frac{1}{2}\beta_R\left(QR_1^{H*}\right)^2\right] \\ &+ (1-p)\left[\frac{1}{2}\beta_R\left(QR_1^{NH*}\right)^2\right] \end{aligned} \quad (1)$$

As a last remark, let us note that in case of a storm of a high magnitude, it cannot be excluded that $P_{\underline{Q}}(Q, QR_0)$ and/or $P_{\bar{Q}}(QR_0, Q)$ fall to zero. In such a case (that we develop in Appendix A.2), the forester's revenue fall to zero and the consumers only demand the quantity of wood for which the price equals zero, even if the market is not cleared. Such a possibility will be taken into account in our numerical simulations (see Section 3).

Now that our benchmark is introduced, we turn to present the public policy of storage.

2.3 Storage policy

2.3.1 Private decisions

As said in Introduction, among the policies that can be implemented in case of storm, providing storage areas is one of the main policies which has been used in the past. With such a policy, in case of storm, the public agent makes storage areas available to the forester. This makes the forester possible to "smooth" the quantity Q of windfall across periods 1 and 2 (instead of having to sell Q in period 1 only).[4] Let Q_S be the quantity of windfall that will be stored in period 1, to be sold in period 2, with $0 \leq Q_S \leq Q$. The complementary quantity of windfall $(Q - Q_S)$ is sold in period 1. The unit cost of storing is $k_S > 0$. So the total cost of storing Q_S is $k_S Q_S$. As it was the case when this policy was implemented in France or in Germany (especially following Lothar and Martin in 1999), this cost is incurred by the public agent. Taking into account the cost of using

[4] In this section, to ease the exposition of the model, we assume that the market price remains strictly positive. For the case of a market price falling to zero in case of storm occurring, see Appendix A.4. Such a possibility will be taken into account in our numerical analysis (see Section 3).

public funds $\lambda > 0$, the total storage cost for the social planner is: $(1+\lambda)k_S Q_S$.

When a public policy is implemented, decisions remain private. And recall that the representative forester aims at maximizing its own expected profit. We still solve backward. First, we solve for periods 2 and 1. Given that decisions for periods 1 and 2 are all made in period 1, we only consider period 1 (and we integer in period 1 the payoffs earned in period 2).

In case where no storm occurs, the forester aims at maximizing:

$$\begin{aligned}
\Pi_1^{NH}(QR_1^{NH}) &= P_{\overline{Q}}(QR_0)QR_0 - \overline{k}QR_1^{NH} + P_{\overline{Q}}\left(QR_1^{NH}\right)QR_1^{NH} \\
&= (\alpha_R - \beta_R QR_0)QR_0 - \overline{k}QR_1^{NH} + \left(\alpha_R - \beta_R QR_1^{NH}\right)QR_1^{NH} \qquad (2)
\end{aligned}$$

i.e., the sum of the benefit from selling QR_0 (decided in period 0), the cost of harvesting QR_1^{NH}, and the benefit from selling QR_1^{NH} (earned in period 2).

The optimal quantity QR_1^{NHs} satisfies:

$$\begin{aligned}
\frac{\partial \Pi_1^{NH}\left(QR_1^{NH}\right)}{\partial QR_1^{NH}} = 0 \quad &\Rightarrow \quad -\overline{k} + \alpha_R - 2\beta_R QR_1^{NH} = 0 \\
&\Rightarrow \quad QR_1^{NHs} = \frac{\alpha_R - \overline{k}}{2\beta_R} \qquad (3)
\end{aligned}$$

In case of storm occurrence, the forester aims at maximizing:

$$\begin{aligned}
\Pi_1^{H}(QR_1^{H}, Q_S) &= P_{\overline{Q}}(QR_0, (Q-Q_S))QR_0 - \overline{k}QR_1^{H} + P_{\overline{Q}}\left(QR_1^{H}, Q_S\right)QR_1^{H} - \underline{k}Q \\
&+ P_{\underline{Q}}((Q-Q_S), QR_0).(Q-Q_S) + P_{\underline{Q}}\left(Q_S, QR_1^{H}\right).Q_S
\end{aligned}$$

That may be rewritten as follows:

$$\begin{aligned}
\Pi_1^{H}\left(QR_1^{H}, Q_S\right) &= (\alpha_R - \beta_R QR_0 - \delta(Q-Q_S))QR_0 - \overline{k}QR_1^{H} \\
&+ \left(\alpha_R - \beta_R QR_1^{H} - \delta Q_S\right)QR_1^{H} - \underline{k}Q \\
&+ (\alpha - \beta(Q-Q_S) - \delta QR_0).(Q-Q_S) \\
&+ \left(\alpha - \beta Q_S - \delta QR_1^{H}\right).Q_S \qquad (4)
\end{aligned}$$

i.e., the sum of the benefit from selling QR_0 (decided in period 0), the cost of harvesting QR_1^{H}, the benefit from selling QR_1^{H} in period 2, the longshoring cost of windfall Q in period 1, and the benefits from selling $(Q-Q_S)$ in period 1 and Q_S in period 2.

Contrary to the case where no storm occurred, here the forester has to make two decisions to maximize its profit: deciding which quantity Q_S of windfall to store, and which quantity QR_1^H of standing wood to harvest. The optimal quantities QR_1^{Hs} and Q_S^s simultaneously satisfy:

$$\begin{aligned}\frac{\partial \Pi_1^H\left(QR_1^H, Q_S\right)}{\partial QR_1^H} &= -\bar{k} + \alpha_R - 2\beta_R QR_1^H - 2\delta Q_S = 0 \\ \frac{\partial \Pi_1^H\left(QR_1^H, Q_S\right)}{\partial Q_S} &= -2\delta QR_1^H + 2\beta Q - 4\beta Q_S + 2\delta QR_0 = 0\end{aligned}$$

Proceeding by substitution, we find:

$$QR_1^{Hs} = \frac{\alpha_R - 2\delta\left[\frac{\frac{\delta\alpha_R}{\beta_R} - \frac{\delta\bar{k}}{\beta_R} - 2\beta Q - 2\delta QR_0}{\frac{2\delta^2}{\beta_R} - 4\beta}\right] - \bar{k}}{2\beta_R} \tag{5}$$

$$Q_S^s = \frac{\frac{\delta\alpha_R}{\beta_R} - \frac{\delta\bar{k}}{\beta_R} - 2\beta Q - 2\delta QR_0}{\frac{2\delta^2}{\beta_R} - 4\beta} \tag{6}$$

We can remark that, contrary to the benchmark case of *laissez-faire*, under storage policy the decisions of harvesting in period 1 are different depending on the occurrence of storm or not (*i.e.*, QR_1^{NHs} is different from QR_1^{Hs}). Indeed, under storage, in period 2 there is now a "competition" between wood that is harvested in period 1, QR_1^{Hs}, and the quantity of windfall that has been stored, Q_S^s.

Finally, in period 0, the forester has to decide about the quantity of standing wood QR_0 to harvest, having in mind what happens in case of storm (probability p), and in the absence of storm (probability $(1-p)$). So the forester has to maximize:

$$E\left[\Pi_0(QR_0)\right] = -\bar{k}QR_0 + p\Pi_1^H\left(QR_1^{Hs}, Q_S^s\right) + (1-p)\Pi_1^{NH}\left(QR_1^{NHs}\right) \tag{7}$$

And so the optimal quantity QR_0^s satisfies:

$$\frac{\partial E\left[\Pi_0(QR_0)\right]}{\partial QR_0} = -\bar{k} + p\frac{\partial \Pi_1^H\left(QR_1^{Hs}, Q_S^s\right)}{\partial QR_0} + (1-p)\frac{\partial \Pi_1^{NH}\left(QR_1^{NHs}\right)}{\partial QR_0} = 0 \tag{8}$$

More details about this equation are provided in Appendix A.3. This equation cannot be solved analytically, numerical simulations will be presented in Section 3.

2.3.2 Social welfare

Now that private decisions in case of a storage policy are determined, we have to evaluate the social welfare that derives from implementing such a policy. In that case, there are now three parties in the economy: the forester, the consumers, and the public agent.

As regards the forester, the social welfare has to take into account the forester's expected profit, $E\left[\Pi_0(QR_0^s)\right]$. Second, as in the benchmark case, we have to take into account the surplus that consumers get from consumption of wood. And finally, we also have to take into account the cost, for the public agent, to implement the policy. As described above, in case of storage following a storm, the public agent pays the whole cost of storage. Taking into account the cost of mobilizing public funds, we obtain an expected social cost of: $p(1+\lambda)k_S Q_S^s$.

All in all, the expected social welfare of implementing a storage policy is:

$$\begin{aligned} SW\left(QR_0^s, QR_1^{Hs}, QR_1^{NHs}, Q_S^s\right) &= E[\Pi_0(QR_0^s)] + \frac{1}{2}\beta_R(QR_0^s)^2 \\ &+ p\left[\frac{1}{2}\beta_R\left(QR_1^{Hs}\right)^2 + \frac{1}{2}\beta(Q_S^s)^2 + \frac{1}{2}\beta(Q-Q_S^s)^2\right] \\ &+ (1-p)\frac{1}{2}\beta_R\left(QR_1^{NHs}\right)^2 - p(1+\lambda)k_S Q_S^s \qquad (9) \end{aligned}$$

This function will made us able to compare the desirability of storage, relative to making no policy (Eq. (1)). Now, on the basis on this theoretical model, we run numerical calculations that aim at comparing storage and *laissez-faire* under different contexts and scernarii.

3 Results

Because the analytical resolution of the model was not reached, we use a more tractable way, namely simulations, to look at implications of a storage policy for the forester, the consumers and society as a whole (social welfare). The value of the different parameters used to calibrate the model is presented in Table 1.

Given these values, in case where no storm occurs, we obtain: $QR_1^{NH*} = 2498.75$, which can be seen as the value of an harvest during one period in a normal situation. As a consequence, in the following simulations a storm of magnitude $Q = 5000$ could be

Table 1: Values of the parameters for the simulations.

Parameter	Description	Values	Assumptions
$\bar{k}$	Unit cost of harvesting standing wood	1	
$\underline{k}$	Unit cost of longshoring windfall	1.5	$\underline{k} > \bar{k}$
k_s	Unit costs of storing	1.3	
λ	Cost of using public funds	1.2	$\lambda > 0$
δ	Degree of substitution between the two kinds of wood	.1	$0 < \delta < 1$
β_R	Price-elasticity of demand - Wood of high quality	.4	
β	Price-elasticity of demand - Wood of low quality	.8	$\beta_R < \beta$
α_R	Ordinate of the demand function - Wood of high quality	2000	
α	Ordinate of the demand function - Wood of low quality	1600	$\alpha_R > \alpha$

seen as a storm for which the windfall is equivalent to 2 periods of harvest in a normal situation. As an example, in France, the forest damage due to storms Lothar and Martin in 1999 correspond roughly to three years of harvesting (IFN, 2003).

Keep in mind that without any public policy, the producer and the consumer are sharing the surplus. But in case of implementing storage, the public agent has to bear the cost of the public policy.

3.1 Benchmark: no public policy (*laissez-faire*)

We present three graphs for this benchmark case: the social welfare (Fig. 2), the consumer surplus (Fig. 3) and the forester's profit (Fig. 4).

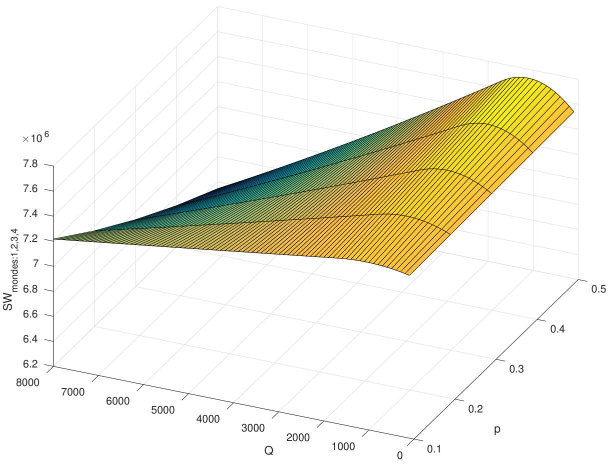


Figure 2: Social welfare without any public policy.

In Figure 2 we can see that, when no policy is implemented, the impact of the magnitude of a storm (*i.e.,* the value of Q) on the social welfare is not linear. For low magnitude ($Q < 1150$ for $p = 0.2$), there is an increase in social welfare with the value of Q. Then, for higher values of Q, the social welfare is decreasing with Q. A look at the evolution of consumers' surplus and forester's profit helps to disentangle the effects.

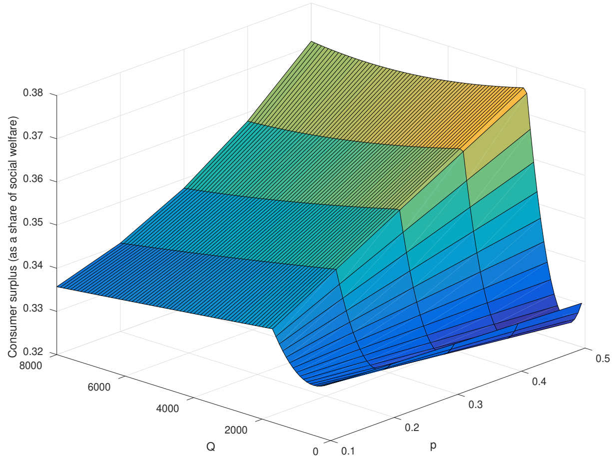


Figure 3: Consumer surplus (share of social welfare) without any public policy.

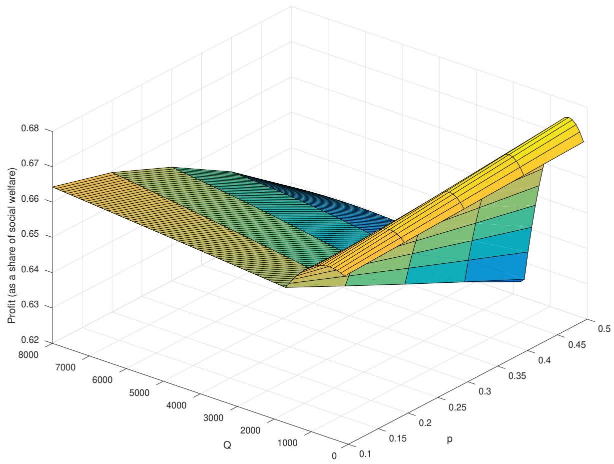


Figure 4: Forester profit (share of social welfare) without any public policy.

Figures 3 and 4 represent, respectively, the share of the consumers' surplus and the share of the forester's profit, in the social welfare, when no policy is applied, depending on the probability and the magnitude of the storm. In this case of *laissez-faire*, these two shares complete to one. From these figures we can see that, for low magnitudes of storm ($Q < 1700$ for $p = 0.2$), an increase in the magnitude of storm increases the share of social welfare which is captured by the consumers: windfall leads both to an increase in the global quantity of wood that is available, and a decrease in prices. In that case the consumers' surplus increases more rapidly than the profit.[5] But for higher magnitudes of

[5]Note that for very small magnitude of storm (*i.e.,* $0 < Q < 500$), the consumers' surplus is decreasing in relative terms (while, in absolute value, it decreases for $0 < Q < 300$ and then increases for $Q > 300$). This is so because for the lowest values of Q, the price of windfall is high while the forester yet decreases the quantities of harvested wood (in a way to maintain high prices). The resulting consumers' surplus

storm ($Q > 1700$), the market of windfall collapses, so that the consumers' demand for that kind of wood is saturated. Any increase in the value of Q will not be consumed by consumers, and leads to a reduction in the quantity of harvested wood by the forester in the aim of keeping a high level of price for that kind of wood: this leads to a reduction in consumers' surplus. As regards the evolution of profit, in value, the profit is always decreasing in the value of Q. However, for high values of Q ($Q > 1700$ for $p = 0.2$), the decrease of profit with Q is lower than the decrease of consumers' surplus, since the forester attempts to reduce the decrease in price by reducing the quantity of harvested wood.[6] So, in relative terms, the share of profit increases, but both profit and consumers' surplus are decreasing, as illustrated by the reduction in the expected social welfare (Fig. 2). Finally, due to the monopoly position of the forester, the allocation of social welfare is more profitable to him.

3.2 A comparison between the storage policy and the benchmark

We present the graphs for the social welfare (Fig. 5), consumer surplus (Fig. 6) and forester's profit (Fig. 7) when implementing a storage policy, as compared to the absence of policy (*laissez-faire*). On these graphs, a global surplus of 1.1 means a surplus 10% over the surplus in the no policy benchmark case.

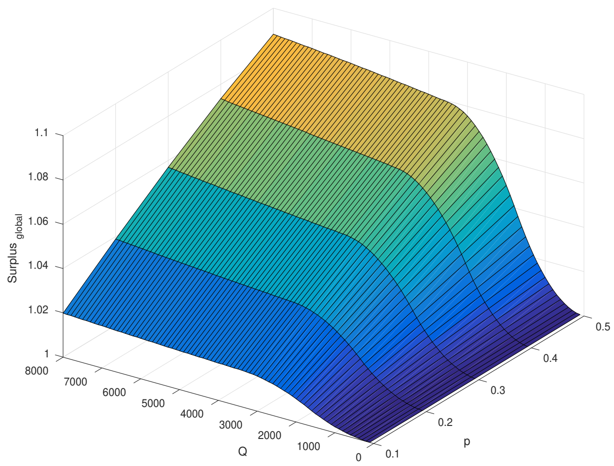


Figure 5: Social welfare of storage policy, as compared to the absence of policy.

This first graph shows that the storage policy increases the total surplus as compared

gets down.

[6]Despite the reduction of the quantity of harvested wood (QR_0), the decrease in its price $P_{\bar{Q}}(QR_0, Q)$, following the impact of a high quantity Q of windfall on the market, and the cost of longshoring Q, lead both to the decrease in profit.

to the absence of policy. However, we can observe on Fig. 6 and 7 that, for each economic agent, the situation may be different. Indeed, the consumer is not always a winner with this policy (see Fig. 6). In details, three situations appear depending on the magnitude of the storm.

For storm with a low magnitude ($Q < 1700$), the forester captures most of the surplus and the consumer is the looser. This is explained by the fact that the forester smooths the quantity of windfall over periods 1 and 2, thanks to the possibility of storage. This leads, for each period, to a reduction in the available quantities of wood for the consumer, and to an increase in price (relatively to the no-policy case), which explains that the consumer is disadvantaged by the policy.

From a windfall of $Q = 1700$, the situation becomes more favorable to the consumer: the quantity of windfall is sufficiently high, over both periods 1 and 2, to provide wood in high quantity at a relatively low price for the consumers. The consumers' surplus increases, the profit decreases (see Fig. 6 and 7).

The catch-up is done from $Q = 3400$. For even higher values of Q, relatively to the no-policy case, the situation of the forester is unchanged (he earns no revenue from windfall, the market of which has collapsed), but the situation of the consumer is better off since the storage increases the global quantity of wood made available (over all periods).

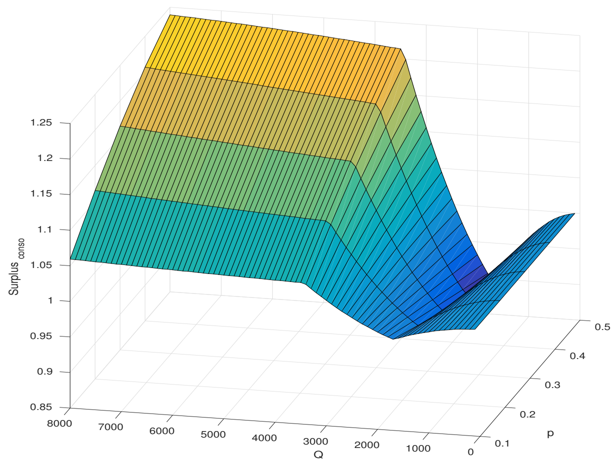


Figure 6: Consumer surplus with storage, as compared to the absence of policy.

Result 1 *A storage policy is always socially desirable, from a global point of view. However, it is detrimental for consumers in case of storm of low magnitude.*

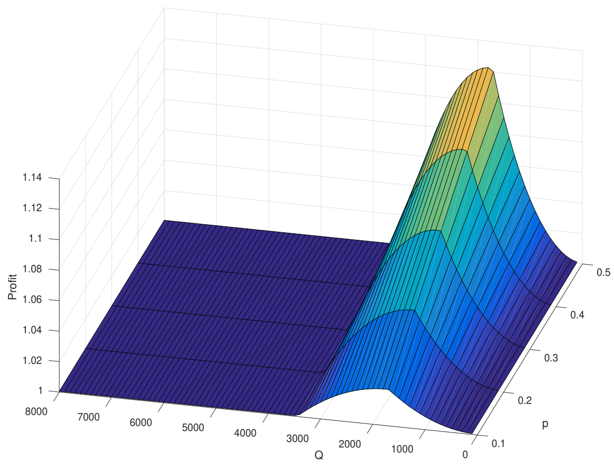


Figure 7: Profit with storage, as compared to the absence of policy.

3.3 Sensitivity analysis

In Appendix B, we develop a sensitivity analysis to check how our results are sensitive to a change in the context, and especially to a change in: (i) the elasticity of substitution between the two kinds of wood (δ) (Appendix B.1), and (ii) the price-elasticity of demands for each kind of wood (β and β_R) (Appendix B.2).

Concerning the sensitivity to the degree of substitution δ, our analysis shows that an increase or a decrease in δ does not question the social desirability of the storage policy: it always leads to a strictly higher social welfare than no policy. However, it has to be noted that the relative desirability of storage is decreasing with δ, especially in cases where storms are characterized by a high probability p and a high magnitude Q. This is so because an increase in the degree of substitution δ means a lower distinction, for the consumer, between the two kinds of woods: they may use one type or the other, in a more similar manner. Hence, the virtues of storage for the forester, in terms of smoothing the supply of windfall over periods, are reduced since the harvested wood can be consumed as well, thus "contaminating" the market of windfall. As a consequence, the forester reduces the quantity of harvested wood in order to try to maintain prices at a high level. This reduction in the global quantity of wood reduces the level of consumers' surplus, and so the social desirability of the policy. Conversely, in case of a low value of δ, the duality of the market of wood (in case of storm) is maximum: the two kinds of wood are dedicated for different kinds of use by the consumers. So the efficiency of storage in smoothing the supply over periods is maximum for the forester. So, the forester has no need to restrict the quantity of harvested wood, and the consumer may benefit from a relatively large supply of wood, ensuring a high level of surplus.

Result 2

The degree of substituability between high-quality wood (harvested) and low-quality wood (windfall) does not question the social desirability of the storage policy. However, in case of a high degree of substituability, the desirability of storage is reduced when a storm of high magnitude is highly expected (high values of p and Q).

As regards the sensitivity to the degrees of price-elasticities of demand (β and β_R), again a variation in theses parameters does not question the social desirability of the storage policy. However, the relative desirability of storage is positively correlated to the values of price-elasticities of demand: the higher (the lower) the price-elasticities of demand, the stronger (the lower) the relative desirability of storage. This is a pure relative effect: in fact, our simulations shows that the absolute benefit from storage remains roughly stable when varying the values of price-elasticites of demand (other parameters holding constant), while a decrease in price-elasticities of demand lead to an increase in profits, consumers' surplus and social welfare, both when storage or no policy is implemented.[7]

Result 3

The values of the price-elasticities of demand do not question the social desirability of the storage policy. However, the relative desirability of storage is positively correlated with the strenght of the price-elasticities of demand for wood.

Finally, we can note that our Result 1 is robust to variations in the degree of substitution (δ) and to variation in the values of price-elasticites of demand (β, β_R): in all our simulations, we find storage to be detrimental to consumers in case of storm of low magnitude[8]. Also, variations (in a reasonable extent) in the unit cost of storage (k_s) and in the cost of using public funds (λ) do not question the social desirability of the policy.

[7]In details, since a decrease in price-elasticities of demand allows the forester to increase its offering quantities without "too rapidly" decreasing prices, the forester is able to increase harvesting quantities (at a given price), and this increases its profits. Since a decrease in price-elasticities of demand means the consumers to have a strong demand, they enjoy surplus from the additionnal quantities offered onto the market.

[8]As in Figure 6, in all our simulations the consumers surplus in case of storage (relatively to those of no policy) is below 1 for $Q < 3400$, i.e. a storm the magnitude of which equals roughly 1.5 period of harvest in a normal situation. Graphs are available upon request.

4 Discussion and conclusion

Storage policy is the main tool used to manage price risk after a storm. It had been used in several countries to try to avoid market collapse, with varying degrees of success. In this article, we provide a tractable theoretical model that takes into account the welfare losses and gains of all agents in society (forester, consumers, public agent). This model complements the few existing works on the subject, as it gains in generality by freeing itself from the study of very specific cases (such as the 1999 storms in France or the Klaus storm in south-west France in 2009), and it allows to fully represent the problem by considering all the agents involved. Simulations of this model allow us to conclude that a storage policy is always socially desirable, from a global point of view, even if it is detrimental to consumers in the event of a low-magnitude storm. Furthermore, we show that this result is robust to variations in the degree of substitutability between high-quality wood (harvested) and low-quality wood (windfall), as well as to the values of the price-elasticities of demand. As regards the literature, Costa and Ibanez (2005) providing a cost analysis, has shown that the storage was neither interesting for the forest owner nor for the public authority. It seems that our article, by considering the benefits, in addition to the costs, and the consumers, in addition to the forest owner and the public authority, goes one step further and to show that storage may be a relevant option.

The proposed theoretical model assumes a risk-neutral forester, whereas in the literature, the risk aversion of forest owners has been proven and quantified (Musshoff and Maart-Noelck, 2014; Sauter et al., 2016; Brunette et al., 2017, 2020). However, whether or not the forest owner's risk aversion has an impact on the risk management decision is not a matter of unanimity. Indeed, Sauter et al. (2016) showed that forest owner's risk aversion has no impact on the willingness to pay for forest insurance, while Brunette et al. (2020) showed that risk aversion has a significant and negative impact on private forest owner's incentives to adopt adaptation strategies to cope with climate change. How risk aversion impacts our result is clearly the next step of this article. From this perspective, the question of which theoretical approach to adopt will be central. Indeed, the question of whether forest owner's behaviors are more in line with expected utility theory or other alternative models such as prospect theory is still topical.[9]

[9] An article by Reynaud and Couture (2012) proved that, among their sample of French farmers,

Furthermore, we assume the the forester is in a monopoly situation, whereas other market configurations (duopoly, oligopoly) may be relevant, depending on the considered country. Indeed, in some countries (France, Sweden, Finland, Austria, etc.), the forest is mainly private and then associated to numerous private forest owners with none of which has the power to influence the market price. Atomicity assumption characterized such a market. Conversely, in other countries (Switzerland, Canada, Russia, Poland, Bulgaria, etc.) the forest is mainly public. At the extreme, in Central Asia, all the forest area is publicly owned (Pulla et al., 2013; UNECE, 2020). Monopoly assumption is better suited for these countries.

To date, the market risk arising from storms has mainly been managed by the public authorities through storage policies. However, other public policy tools are also conceivable, such as the implementation of a floor price. Such a policy was discussed in France after Lothar and Martin in 1999, but never implemented. We can imagine that the floor price will be decided by the public authorities, and that the difference between the market price and the floor price would be subsidized by the public authorities. Further research in this direction may be interesting. In addition, there are other individual tools, such as supply contracts, which enable forest owners to sell their timber at a price fixed bilaterally in the contract. This means that they do not suffer from a fall in prices, but conversely, they cannot benefit from a rise in prices. This tool is better suited to dealing with price volatility than with price shock such as after storm.

In conclusion, in this article we consider the storage policy for disturbed wood after a storm. However, the model is more generic and could be applied to other resources for which storage is a relevant option to avoid falling prices and ensure a constant supply of the market: cereals, water, etc.

almost half behave in line with expected utility and the other half in line with prospect theory.

Authors' contributions

M. Brunette identified the research question. She wrote the introduction and the discussion. J. Jacob conceived the theoretical model. A. Leblois realized the simulations and the graphs. All the three authors wrote the article and validated the content.

Funding

The Institut national de la recherche agronomique et de l'environnement (INRAE); the Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture (IRSTEA) through the PSDR4-AFFORBALL project. The UMR BETA is supported by a grant overseen by the French National Research Agency (ANR) as part of the "Investissements d'Avenir" program (ANR-11-LABX-0002-01, Lab of Excellence ARBRE).

References

Barkaoui, A. and A. Z. Dragicevic (2016): "Nash bargaining and renegotiation with social preferences: Case of the roundwood log supply contracts in the French timber market," *Forest Policy and Economics*, 69, 90–100.

Bavard, D., O. De Lagarde, and M. Magrum (2013): "Évaluation du volet mobilisation des bois chablis — Plan de solidarité nationale consécutif à la tempête Klaus du 24 Janvier 2009," *CGAAER, Paris.*

Brodrechtova, Y. (2015): "Economic valuation of long-term timber contracts: Empirical evidence from Germany," *Forest Policy and Economics*, 55, 1–9.

Brunette, M. and S. Couture (2008): "Public compensation for windstorm damage reduces incentives for risk management investments," *Forest Policy and Economics*, 10, 491–499.

Brunette, M., S. Couture, and J. Laye (2015a): "Optimising forest management under storm risk with a Markov decision process model," *Journal of Environmental Economics and Policy*, 4, 141–163.

Brunette, M., J. Foncel, and E. N. Kéré (2017): "Attitude towards risk and production decision: an empirical analysis on French private forest owners," *Environmental Modeling & Assessment*, 22, 563–576.

Brunette, M., M. Hanewinkel, and R. Yousefpour (2020): "Risk aversion hinders forestry professionals to adapt to climate change," *Climatic Change*, 162, 2157–2180.

Brunette, M., J. Holecy, M. Sedliak, J. Tucek, and M. Hanewinkel (2015b): "An actuarial model of forest insurance against multiple natural hazards in fir (Abies Alba Mill.) stands in Slovakia," *Forest Policy and Economics*, 55, 46–57.

Brèteau-Amores, S., R. Yousefpour, M. Hanewinkel, and M. Fortin (2020): "Composition diversification vs. structure diversification: How to conciliate timber production and carbon sequestration objectives under drought and windstorm risks in forest ecosystems," *WP BETA 2020-31.*

Caurla, S., S. Garcia, and A. Niedzwiedz (2015): "Store or export? An economic evaluation of financial compensation to forest sector after windstorm. The case of Hurricane Klaus," *Forest Policy and Economics*, 61, 30–38.

CGAEER (2010): "Bilan du plan national pour la forêt (2000-2009) à la suite des tempêtes de décembre 2009," Rapport du CGAEER $n°$10089, Conseil général de l'alimentation, de l'agriculture et des espaces ruraux.

Costa, S. and L. Ibanez (2005): "Can wood storage be profitable? French experience after the windstorms in 1999," *Journal of Forest Economics*, 11, 161–176.

Deaton, A. and G. Laroque (1992): "On the Behaviour of Commodity Prices," *The Review of Economic Studies*, 59, 1–23.

Della-Marta, P. and J. Pinto (2009): "Statistical uncertainty of changes in winter storms over the North Atlantic and Europe in an ensemble of transient climate simulations," *Geophysical Research Letters*, 36, L14703.

Gardiner, B., K. Blennow, J. Carnus, P. Fleischner, F. Ingemarson, G. Landmann, M. Lindner, M. Marzano, B. Nicoll, C. Orazio, J. Peyron, M. Reviron, M. Schelhaas, A. Schuck, M. Spielmann, and T. Usbeck (2011): "Destructive storms in European forests: Past and forthcoming impacts," Final report, European Commission - DG Environment.

Holecy, J. and M. Hanewinkel (2006): "A forest management risk insurance model and its application to coniferous stands in southwest Germany," *Forest Policy and Economics*, 8, 161–174.

IFN (2003): "Les tempêtes de décembre 1999: Bilan national et ensignements," *https://inventaire-forestier.ign.fr/IMG/pdf/*$L_I F_n o02_t$*empetes.pdf*, 2.

Lecocq, M., S. Costa, J. Peyron, et al. (2009): "Estimate of the financial impact of hurricane Klaus for forest owners," *Forêt-Entreprise*, 189, 48–52.

Musshoff, O. and S. C. Maart-Noelck (2014): "An experimental analysis of the behavior of forestry decision-makers—The example of timing in sales decisions," *Forest Policy and Economics*, 41, 31–39.

Newberry, D. M. (1989): "The Theory of Food Price Stabilisation," *The Economic Journal*, 99, 1065–1082.

NICOLAS, J. (2009): "Les conséquences de la tempête du 24 janvier 2009 dans le sud-ouest," Rapport d'information $n°$1836, Assemblée Nationale.

PRESTEMON, J. P. AND T. P. HOLMES (2000): "Timber price dynamics following a natural catastrophe," *American Journal of Agricultural Economics*, 82, 145–160.

PULLA, P., A. SCHUCK, P. J. VERKERK, B. LASSERRE, M. MARCHETTI, AND T. GREEN (2013): "Mapping the distribution of forest ownership in Europe," *European Forest Institute, Joensuu.*

RAKOTOARISON, H. AND P. LOISEL (2017): "The Faustmann model under storm risk and price uncertainty: A case study of European beech in Northwestern France," *Forest Policy and Economics*, 81, 30–37.

REYNAUD, A. AND S. COUTURE (2012): "Stability of risk preference measures: results from a field experiment on French farmers," *Theory and decision*, 73, 203–221.

SAUTER, P. A., T. B. MÖLLMANN, F. ANASTASSIADIS, O. MUSSHOFF, AND B. MÖHRING (2016): "To insure or not to insure? Analysis of foresters' willingness-to-pay for fire and storm insurance," *Forest Policy and Economics*, 73, 78–89.

SCHELHAAS, M.-J., G. HENGEVELD, M. MORIONDO, G.-J. REINDS, Z. W. KUNDZEWICZ, H. TER MAAT, AND M. BINDI (2010): "Assessing risk and adaptation options to fires and windstorms in European forestry," *Mitigation and Adaptation Strategies for Global Change*, 15, 681–70.

SCHELHAAS, M.-J., G.-J. NABUURS, AND A. SCHUCK (2003): "Natural disturbances in the European forests in the 19th and 20th centuries," *Global Change Biology*, 9, 1620–1633.

UNECE (2020): "Who owns our forests? Forest ownership in the ECE region," .

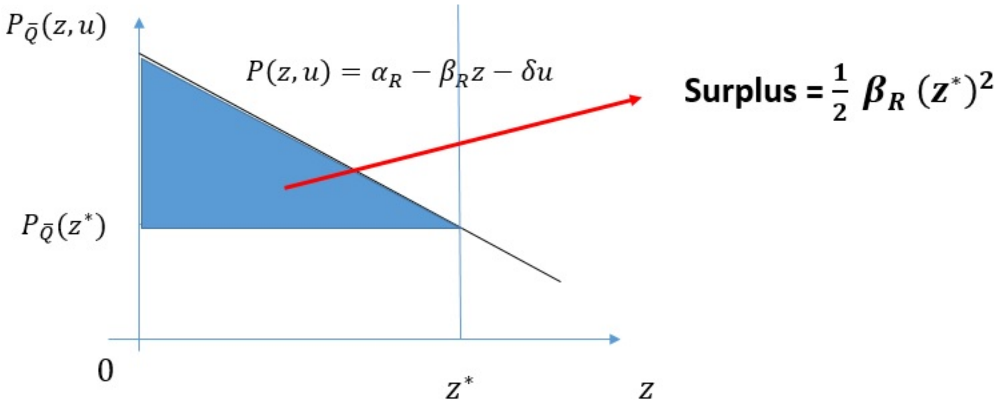
A Appendix related to the theoretical part of the article

A.1 Details and calculations about the consumers' surplus

As said in the body of the paper, the utility from consuming wood leads to demand functions, $P_{\overline{Q}}(QR)$ in case of no storm, and $P_{\overline{Q}}(QR, Q)$ and $P_{\underline{Q}}(Q, QR)$ in case of storm.

These demand functions provide, for each given quantity n of wood under consideration, how much, in monetary terms, the consumers are willing to pay to buy this n^{th} quantity. It is the maximum willingness to pay for the marginal quantity. The selling price is set for the quantity which equals both the marginal willingness to pay and the marginal (expected) profit of the forester. This price is the same for all the n quantities which are sold, even if the consumers have not the same willingness to pay for all quantities. Especially, for quantities "before" the n^{th}, the willingness to pay are higher.[10] It follows that for the quantities before the n^{th}, the consumers get a surplus of satisfaction, which is represented by the difference in their demand function (*i.e.*, their willingness to pay) and the selling price, as represented in Figure 8.

Figure 8: Consumers' surplus: example for wood of high quality



NB: on this figure, quantities are z, and quantities for the substitute good are u.

For a quantity QR of wood of high quality, the surplus is $\frac{1}{2}\beta_R(QR)^2$. For a quantity Q of wood of low quality, the surplus is $\frac{1}{2}\beta(Q)^2$.

♦

[10] Indeed, the principle of saturation implies the decreasing marginal utility from consumption: the utility derived from consumption is decreasing with the quantities. It follows that the maximum willingness to pay is also decreasing in quantities.

A.2 Policy of *laissez-faire*: when prices fall to zero

As said in the body of the paper, in case of a storm of a high magnitude, it cannot be excluded that both $P_{\underline{Q}}(Q, QR_0)$ and/or $P_{\bar{Q}}(QR_0, Q)$ fall to zero. What happens in such a case?

Answering this question requires, first, to recall how $P_{\bar{Q}}(QR_0, Q)$ and $P_{\underline{Q}}(Q, QR_0)$ behaves when QR_0 and/or Q vary. Recall that we have: $P_{\bar{Q}}(QR_0, Q) = \alpha_R - \beta_R QR_0 - \delta Q$ and $P_{\underline{Q}}(Q, QR_0) = \alpha - \beta Q - \delta QR_0$, with $\alpha_R > \alpha > 0$ and $0 < \beta_R < \beta$. As a result, the value of $P_{\underline{Q}}(Q, QR_0)$ reaches zero "more quickly" (i.e., for lower values of (QR_0, Q)) than the value of $P_{\bar{Q}}(QR_0, Q)$. As a consequence, for a given value of QR_0, an increase in Q can, first, lead to a situation in which $P_{\underline{Q}}(Q, QR_0)$ falls to zero but $P_{\bar{Q}}(QR_0, Q)$ remains strictly positive; and a further increase in Q can lead to both $P_{\underline{Q}}(Q, QR_0)$ and $P_{\bar{Q}}(QR_0, Q)$ falling to zero. We will call the former situation (i.e, Q such that $P_{\underline{Q}}(Q, QR_0) = 0$ and $P_{\bar{Q}}(QR_0, Q) > 0$, QR_0 given) being *Universe 2* and the latter situation (i.e, Q such that $P_{\underline{Q}}(Q, QR_0) = 0$ and $P_{\bar{Q}}(QR_0, Q) = 0$, QR_0 given) being *Universe 3*.

When a price falls to zero, two consequences have to be distinguished. First, for the forester, the corresponding earnings falls to zero (e.g., if the price of the windfall Q falls to zero, the forester enjoys no earning from that kind of wood). Second, for the consumers, they only demand the quantity of wood for which the price falls to zero. For instance, considering the quantity Q of windfall, it is possible that the price $P_{\underline{Q}}(Q, QR_0)$ reaches the value of zero before the market is cleared. As a consequence, the consumers only demand the quantity for which the function $P_{\underline{Q}}(Q, QR_0)$ equals zero, and there remains a quantity which is not bought (this is waste). So we can define:

$$Q|_{P_{\underline{Q}}=0} = \frac{\alpha - \delta QR_0^*}{\beta} \tag{10}$$

as the demanded quantity of wood of low quality for which $P_{\underline{Q}}(Q, QR_0^*) = 0$, given QR_0^*.

$$QR_0|_{P_{\underline{Q}}=0} = \frac{\alpha - \beta Q}{\delta} \tag{11}$$

as the quantity of harvested wood for which $P_{\underline{Q}}(Q, QR_0) = 0$, for a given Q.

$$Q|_{P_{\bar{Q}}=0} = \frac{\alpha_R - \beta_R QR_0^*}{\delta} \tag{12}$$

as the demanded quantity of wood of low quality for which $P_{\bar{Q}}(QR_0^*, Q) = 0$, given QR_0^*.

$$QR_0|_{P_{\bar{Q}}=0} = \frac{\alpha_R - \delta Q}{\beta_R} \tag{13}$$

as the quantity of harvested wood for which $P_{\bar{Q}}(QR_0, Q) = 0$, for a given Q

From this possibility for prices to reach the value of zero in case of storm, we obtain a forester's profit equal to:

$$\Pi_1^H(QR_1^H) = P_{\bar{Q}}(QR_0, Q)QR_0 - \bar{k}QR_1^H - \underline{k}Q + P_{\bar{Q}}(QR_1^H)QR_1^H \tag{14}$$

in the case of Universe 2, where the value of $P_{\underline{Q}}(Q, QR_0)$ is fallen to zero, and

$$\Pi_1^H(QR_1^H) = -\bar{k}QR_1^H - \underline{k}Q + P_{\bar{Q}}(QR_1^H)QR_1^H \tag{15}$$

in the case of Universe 3, where the value of both $P_{\underline{Q}}(Q, QR_0)$ and $P_{\bar{Q}}(QR_0, Q)$ are fallen to zero.

As regards the values of consumers' surplus (CS, see details about calculation of consumers' surplus in Appendix A.1), we obtain:

$$CS = \frac{1}{2}\beta_R(QR_0^*)^2 + p\left[\frac{1}{2}\beta_R\left(QR_1^{H*}\right)^2 + \frac{1}{2}\beta_R(Q|_{P_{\underline{Q}}=0})^2\right]$$
$$+(1-p)\frac{1}{2}\beta_R\left(QR_1^{NH*}\right)^2 \tag{16}$$

since, in Universe 2, the price $P_{\underline{Q}}(Q, QR_0)$ reaches zero for a quantity $Q|_{P_{\underline{Q}}=0}$ of windfall (in case of storm). Consumers only demand (and enjoys surplus on) a quantity $Q|_{P_{\underline{Q}}=0}$ of windfall, and the remaining quantity $Q - Q|_{P_{\underline{Q}}=0}$ is not bought (waste).
When Universe 3 holds, we obtain:

$$CS = p\left[\frac{1}{2}\beta_R(QR_0|_{P_{\bar{Q}}=0})^2 + \frac{1}{2}\beta_R\left(QR_1^{H*}\right)^2 + \frac{1}{2}\beta_R(Q|_{P_{\underline{Q}}=0})^2\right]$$
$$+(1-p)\left[\frac{1}{2}\beta_R(QR_0^*)^2 + \frac{1}{2}\beta_R\left(QR_1^{NH*}\right)^2\right] \tag{17}$$

since, in Universe 3, in addition to $P_{\underline{Q}}(Q, QR_0)$, the price $P_{\bar{Q}}(QR_0, Q)$ also falls to zero in case of storm. As a consequence, the consumers only demand a quantity $QR_0|_{P_{\bar{Q}}=0} < QR_0^*$ of wood of high quality, and the remaining quantity $QR_0^* - QR_0|_{P_{\bar{Q}}=0}$ is waste.

Social welfare is the sum of the forester's expected profit $E[\Pi_0(QR_0)]$ and of the consumers' surplus CS, knowing that in this case of *laissez-faire*, Universe 2 is reached when $Q > Q|_{P_{\underline{Q}}=0}$ (leading to $P_{\underline{Q}}(Q, QR_0) = 0$), and Universe 3 holds when both $Q > Q|_{P_{\bar{Q}}=0}$ and/or $QR_0 > QR_0|_{P_{\bar{Q}}=0}$ (leading both to $P_{\underline{Q}}(Q, QR_0) = 0$ and $P_{\bar{Q}}(QR_0, Q) = 0$).

A.3 Solving QR_0^s in case of a storage policy

In case of storage policy, the optimal quantity of wood harvested in period 0, QR_0^*, satisfies condition (8), that is:

$$\frac{\partial E[\Pi_0(QR_0)]}{\partial QR_0} = -\overline{k} + p\frac{\partial \Pi_1^H\left(QR_1^{Hs}, Q_S^s\right)}{\partial QR_0} + (1-p)\frac{\partial \Pi_1^{NH}\left(QR_1^{NHs}\right)}{\partial QR_0} = 0$$

with:

$$\frac{\partial \Pi_1^{NH}\left(QR_1^{NHs}\right)}{\partial QR_0} = \alpha_R - 2\beta_R QR_0$$

and:

$$\begin{aligned}
\frac{\partial \Pi_1^H\left(QR_1^{Hs}, Q_S^s\right)}{\partial QR_0} &= \frac{P_{\overline{Q}}(QR_0,(Q-Q_S))}{\partial QR_0}QR_0 + 1.P_{\overline{Q}}(QR_0,(Q-Q_S)) - \overline{k}\frac{dQR_1^{Hs}}{dQR_0} \\
&+ \frac{P_{\overline{Q}}\left(QR_1^H, Q_S\right)}{\partial QR_0}QR_1^{Hs} + \frac{dQR_1^{Hs}}{dQR_0}P_{\overline{Q}}(QR_1^H, Q_S) \\
&+ \frac{P_{\underline{Q}}((Q-Q_S),QR_0)}{\partial QR_0}(Q-Q_S^s) + \frac{d(Q-Q_S^s)}{dQR_0}P_{\underline{Q}}((Q-Q_S),QR_0) \\
&+ \frac{P_{\underline{Q}}\left(Q_S, QR_1^H\right)}{\partial QR_0}Q_S^s + \frac{dQ_S^s}{dQR_0}P_{\underline{Q}}(Q_S, QR_1^H)
\end{aligned}$$

with:

$$\begin{aligned}
\frac{dQR_1^{Hs}}{dQR_0} &= \frac{2\delta^2}{\beta_R\frac{2\delta^2}{\beta_R} - 4\beta} \\
\frac{dQ_S^s}{dQR_0} &= \frac{-2\delta}{\frac{2\delta^2}{\beta_R} - 4\beta} \\
\frac{d(Q-Q_S^s)}{dQR_0} &= -\frac{dQ_S^s}{dQR_0} \\
\frac{P_{\overline{Q}}(QR_0,(Q-Q_S))}{\partial QR_0} &= -\beta_R - \frac{-2\delta^2}{\frac{2\delta^2}{\beta_R} - 4\beta} \\
\frac{P_{\overline{Q}}(QR_1^H, Q_S)}{\partial QR_0} &= -\frac{2\delta^2}{\frac{2\delta^2}{\beta_R} - 4\beta} + \frac{2\delta^2}{\frac{2\delta^2}{\beta_R} - 4\beta} = 0 \\
\frac{P_{\underline{Q}}((Q-Q_S),QR_0)}{\partial QR_0} &= \frac{-2\delta\beta}{\frac{2\delta^2}{\beta_R} - 4\beta} - \delta \\
\frac{P_{\underline{Q}}(Q_S, QR_1^H)}{\partial QR_0} &= \frac{2\delta\beta}{\frac{2\delta^2}{\beta_R} - 4\beta} - \frac{2\delta^3}{\beta_R\left[\frac{2\delta^2}{\beta_R} - 4\beta\right]}
\end{aligned}$$

♦

A.4 Storage: case of market price falling to zero

The rationale of storage is similar to those that was introduced in the body of the paper: in case of storm (in period 1), the forester has the possibility to collect, from the windfall Q, a quantity Q_S, in order to sell it in the future (period 2).

However, in case of a strong storm (i.e., a high value of Q), it could be possible that some market prices fall to zero (despite the possibility to "smooth" the quantity of windfall over periods). Such a possibility is excluded in the body of the paper, but this part of Appendix aims at showing what happens in such a case.

When the price of windfall that is sold in period 1 ($Q-Q_S$, i.e., the remaining quantity of windfall after having collected Q_S for storage) falls to zero, then the consumers will demand:

$$(Q - Q_S)|_{P_{\underline{Q}}=0} = \frac{\alpha - \delta QR_0}{\beta}$$

which satisfies: $P_{\underline{Q}}(Q - Q_S, QR_0) = 0$, given QR_0, Q and Q_S.

Moreover, given the substitutability between the windfall $(Q - Q_S)$ and the harvested wood (QR_0) in period 1, the price of harvested wood can also fall to zero. In that case, the quantity of harvested wood which is demanded by consumers is:

$$QR_0|_{P_{\bar{Q}}=0} = \frac{\alpha_R - \delta(Q - Q_S)}{\beta_R}$$

given a quantity $(Q - Q_S)$ of windfall available in period 1.

As a consequence, in period 1, if the market of windfall collapses then only $(Q - Q_S)|_{P_{\underline{Q}}=0}$ is consumed and $(Q-Q_S)-(Q-Q_S)|_{P_{\underline{Q}}=0}$ is waste. If the market of harvested wood collapses in period 1, then only $QR_0|_{P_{\bar{Q}}=0}$ is consumed and $QR_0 - QR_0|_{P_{\bar{Q}}=0}$ is waste. The forester's profit in period 1 is:

$$\begin{aligned}\Pi_1^H\left(QR_1^H, Q_S\right) &= \max\left\{0; P_{\overline{Q}}(QR_0, (Q-Q_S))\right\}\min\left\{QR_0|_{P_{\bar{Q}}=0}; QR_0\right\} \\ &- \overline{k}QR_1^H + P_{\overline{Q}}(QR_1^H, Q_S)QR_1^H - \underline{k}Q \\ &+ \max\left\{0; P_{\underline{Q}}((Q-Q_S), QR_0)\right\}\min\left\{(Q-Q_S)|_{P_{\underline{Q}}=0}; (Q-Q_S)\right\} \\ &+ P_{\underline{Q}}(Q_S, QR_1^H).Q_S\end{aligned}$$

And the consumers' surplus in case of storm is:

$$\begin{aligned}CS^H &= \frac{1}{2}\beta_R\left(QR_1^H\right)^2 + \frac{1}{2}\beta(Q_S)^2 + \frac{1}{2}\beta\left(\min\left\{((Q-Q_S)|_{P_{\underline{Q}}=0}); (Q-Q_S^*)\right\}\right)^2 \\ &+ \frac{1}{2}\beta_R\left(\min\left\{QR_0|_{P_{\bar{Q}}=0}; QR_0\right\}\right)^2\end{aligned}$$

The cost of policy remains similar, and the social welfare is still the sum of expected profit, expected consumer surplus, minus the expected cost of public policy.

B Sensitivity analysis

In this section, we present the results of sensitivity analysis realized on several parameters : δ, β and β_R.

B.1 Substitutability: sensitivity analysis on δ

In the benchmark, $\delta = 0.1$. We look at the impact of changing δ with $\delta = 0.05$; $\delta = 0.3$ on the social welfare for each case.

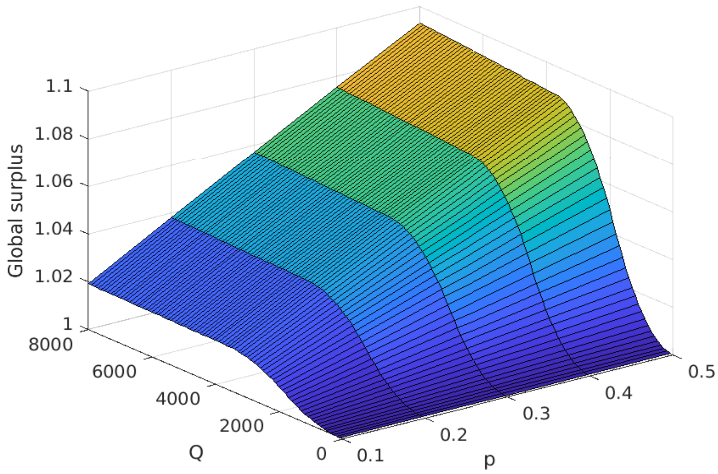


Figure 9: Social welfare relative to no public policy, with $\delta = 0.05$.

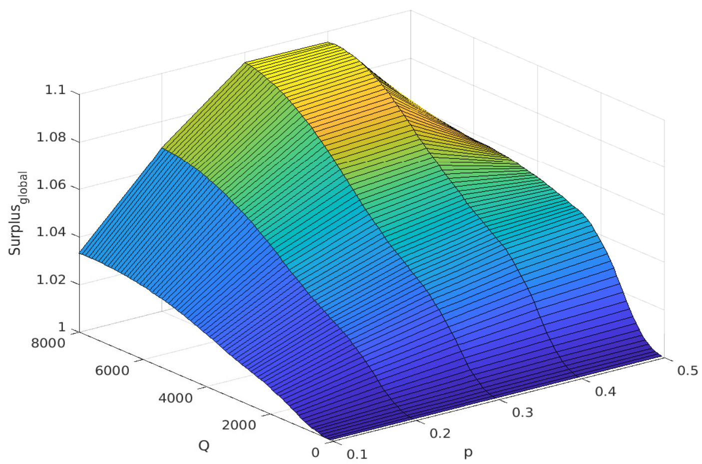


Figure 10: Social welfare relative to no public policy, with $\delta = 0.30$.

B.2 Price-elasticity of the demand for wood

In the benchmark, $\beta = 0.8$ and $\beta_R = 0.4$. We look at the impact of changing β and β_R with $\beta = 1$ and $\beta_R = 0.5$; $\beta = 0.7$ and $\beta_R = 0.3$; $\beta = 0.6$ and $\beta_R = 0.2$ on the social welfare for each case.

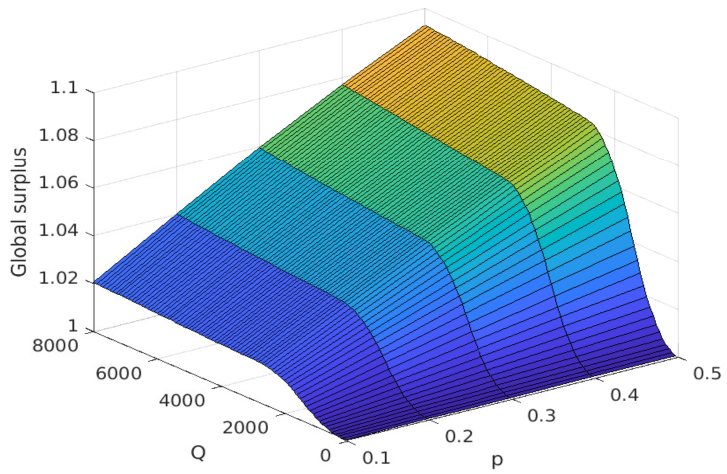


Figure 11: Social welfare relative to no public policy, with $\beta = 1$ and $\beta_R = 0.5$.

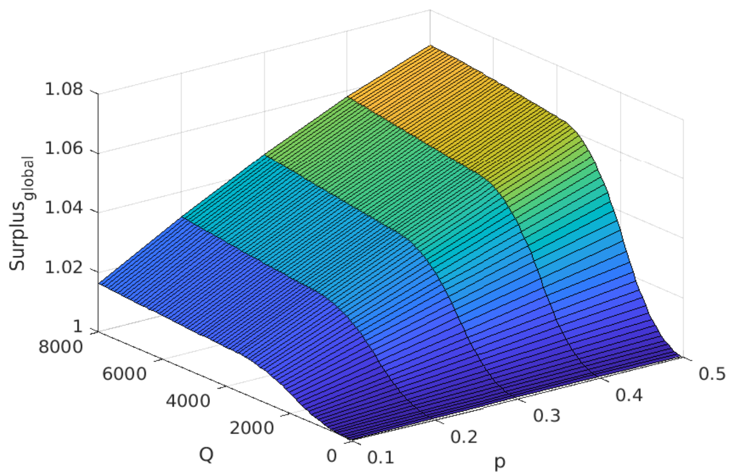


Figure 12: Social welfare relative to no public policy, with $\beta = 0.7$ and $\beta_R = 0.3$.

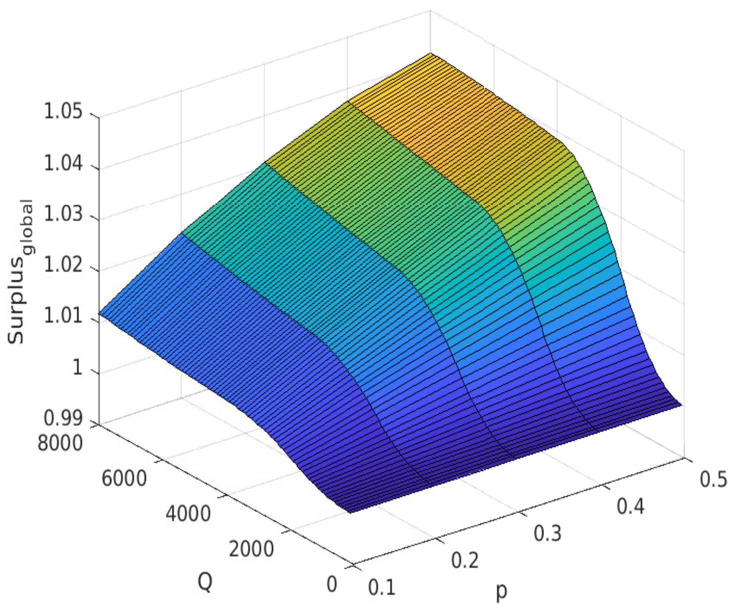


Figure 13: Social welfare relative to no public policy, with $\beta = 0.6$ and $\beta_R = 0.2$.