TSE WP working paper series

12-350

Research Group: Food Farm and Firms

November 2012

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How do GM / non GM coexistence regulations affect markets and welfare?

Marion Desquilbet* and Sylvaine Poret†‡

Abstract

This paper presents a theoretical economic model assessing the effects of the level of mandatory genetically modified (GM) / non-GM coexistence regulations on market and welfare outcomes. We assume vertical differentiation of GM and non-GM goods on the consumer side. Producers are heterogeneous in their production cost for GM crops. Producers of non-GM crops face a probability of having their harvest downgraded if gene flow from GM fields raises its content in GMOs (genetically modified organisms) above the labeling threshold. The government may impose on GMO producers mandatory *ex ante* isolation distances from non-GM fields in order to decrease the probability of non-GM harvest downgrading. It may also introduce an *ex post* compensation to non-GMO farmers for profit losses due to harvest downgrading, imposing GMO farmers' participation to a compensation fund via a tax on GM seeds. Assuming endogenous crop choices and prices, we study the effects of *ex ante* regulation and *ex post* liability of GMO producers on market equilibrium, on the achievement of coexistence, and on both global and interest group welfare.

Keywords: genetically modified organisms, coexistence, identity preservation, regulation, liability, vertical differentiation, law and economics.

JEL classification: D62; H23; K32; L15.

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1 Introduction

The introduction of genetically modified organisms (GMOs) in the agri-food system entails antagonistic effects and therefore raises intricate issues. On one hand, currently available GM crops allow returns for some companies upstream in the agricultural supply chain and productivity gains for many producers, a part of which can be transferred to consumers through price reductions on final products. On the other hand, some political and farm groups, environmentalists and consumers/citizens oppose them. Reasons for this opposition include perceived potential environmental and health risks, opposition to the private appropriation of genetic resources, and ethical concerns. The ways in which public authorities have been regulating GMOs, compromising between the interests of these opposing groups, have been influenced by the political shape of the controversy. Interest group involvement and public opinions have been very different across countries and, as a consequence, current GMO regulations vary greatly. Notably, in the United States, GMO/non-GMO labeling is voluntary and coexistence between GMOs and non-GMOs is not regulated. At the opposite end of the spectrum, the European Union (EU) has adopted mandatory labeling of GMOs and has defined a framework to regulate the coexistence of GM and non-GM crops in fields. In this paper we propose a theoretical market and welfare analysis of this coexistence policy, a topic that has only been partially addressed by economists so far. Our model accounts for both *ex ante* coexistence regulations, such as isolation distances between fields, and *ex post* liability measures, by which GMO producers compensate non-GMO producers for economic damages due to GMO commingling in their harvest. We identify and discuss the contrasting effects of these two types of coexistence regulations in light of the literature on the economic analysis of law.

The considerable and lasting societal opposition to GMOs in the EU has led to numerous revisions of the regulatory framework in an attempt to restore public confidence (see Devos et *al.*, 2006, for a thorough analysis). In particular, GM labeling has been made mandatory on the premise that consumers have a right to information and that labeling enables them to make informed choices (EC, 1997; EC, 2003a). More precisely, any food or feed product containing GMOs has to be labeled as such, unless it contains less than 0.9% of GM material and this presence is adventitious or technically unavoidable (EC, 2003a). This labeling threshold reflects a balance of power between notifiers (requesting high thresholds) and non-governmental organizations and consumers (demanding low ones) (Devos et *al.*, 2006). Its implementation is complicated by sampling uncertainties and measurement errors, so that in practice operators typically use much lower contractual thresholds (0.01% to 0.1%) (Bertheau, 2012).

This labeling legislation indeed guarantees a right to information. The right to make an informed choice, however, only follows when both GM and non-GM products are available in the market. This issue is addressed in the first version of the EC recommendations on coexistence, published in 2003 (EC, 2003b). This version of the recommendations points out that the ability of the food industry to deliver a high degree of consumer choice depends on the ability of the agricultural sector to maintain different production systems. It defines coexistence as the ability of farmers to make a practical choice between conventional, organic and GM-crop production, in compliance with the legal obligations for labeling and/or purity standards. To prevent potential economic losses and other impacts of the admixture of GM and non-GM crops, this recommendation allows Member States to impose mandatory regulations on farmers growing GM crops in order to limit gene flows from their fields to neighboring non-GM fields. The second version of the EC recommendations on coexistence, issued in 2010, retreats from this vision of coexistence as ensuring freedom of choice. Indeed, it no longer provides a formal definition of coexistence, defining coexistence measures simply as measures to avoid the unintended presence of GMOs in conventional and organic crops (EC, 2010).

Existing national coexistence regulations rely mainly on isolation distances, which define a minimum spacing between GM plantings and those non-GM plantings dedicated to identity preserved (IP) non-GM markets. These isolation distances may be planted with a non-GM variety of the same crop, planted with another crop, or left uncultivated. In some countries, either instead of isolation distances or as a complement to them, GMO farmers may adopt mandatory buffer zones by planting strips at the outer border of the GM field with a non-GM variety of the same crop, or by staggering sowing. In addition, within the framework of national civil law, Member States may also adopt specific provisions for liability in cases of GMO admixture. These provisions may include the definition of procedures to compensate the economic damage suffered by non-GMO producers who end up facing a GMO admixture in their harvest above the tolerance threshold. Currently defined liability rules for farmers cultivating GMOs vary between states. In some countries GMO farmers must subscribe to an insurance scheme or provide a financial guarantee to feed a compensation fund, and are still liable even if they follow mandatory regulations set up to limit the extent of admixture. Other countries have not introduced specific liability rules and rely on general civil liability (Beckmann et al., 2006; EC, 2009; Koch, 2010).

The practical experience of these regulations is yet limited. At the present time, *Bt* maize is the only GM crop grown in the EU in significant amounts, and 90% of that production takes place in Spain where no coexistence regulations are enforced. Austria, France, Greece, Hungary, Germany and Luxembourg currently apply bans on GMO cultivation, *via* safeguard clauses on GMO events (Lusser *et al.*, 2012; USDA FAS, 2011; EC, 2012). Portugal is the only country where coexistence regulations have already been put into practice. Authorities there have observed good compliance with *ex ante* coexistence regulations and the implementation of *ex post* regulation has not been necessary, as no excessive GMO admixture in non-GM crops has yet been observed. These observations must, however, be taken with some caution given that the current adoption rate of *Bt* corn in Portugal is only 4% (Quedas and de Carvalho, 2012).

From an economic perspective, the rejection by some consumers of GMO technology, which is advantageous for some producers, splits the pre-existing market in two: one market for the non-GM product, another for the GM product. These two markets may be perceived as more or less differentiated for consumers, depending on the stringency of the labeling threshold. On the production side, the cultivation of GM crops creates a negative externality on non-GMO producers, who strive to prevent GMO commingling in their harvest at levels above the labeling threshold.

The law and economic literature addresses how to choose between *ex ante* safety regulation and *ex post* liability, or how to combine both types of regulations, in order to correct an externality. Because the advantages of each instrument are context specific, there is no definitive judgment on the superiority of either one (Burrows, 1999).[1] Less attention has been bestowed on the joint use of *ex ante* and *ex post* policies, although their complementarity is widespread in practice for the control of environmental and products-related external costs. In this literature, the objective is to find the combination of liability rules and safety standards to be imposed on firms in order to minimize the expected social cost of accidents (Shavell, 1984b; Kolstad, Ulen and Johnson, 1990; Burrows, 1999; Schmitz, 2000). In the context of GM / non-GM coexistence regulation, the externality is a form of non-point source pollution, because it is technically impossible to trace the admixture created by gene flow to a definite source. As a result, it is possible that the perpetrators could avoid facing a suit for harm done. In this case, tort liability alone is not adapted, thus *ex ante* safety regulation is warranted (Shavell, 1984a). In addition, there may be a case for *ex post* compensation by GM farmers for economic losses faced by non-GM farmers, because technical *ex ante* coexistence measures do not entirely eliminate the risk of gene flow. Then, *ex ante* safety regulation and tort liability may complement each other: their joint use may optimally correct

[1]See Shavell (1984a) for a discussion on the theoretical determinants of the relative desirability of safety regulation and liability and Desquilbet and Poret (2012) for a discussion in the context of the coexistence between GM and non-GM crops.

inefficiencies that appear when only one approach is used to correct an externality. This view is supported by the analysis of Beckmann et al. (2010) on GM / non-GM coexistence, who conclude that a combination of *ex ante* regulations and *ex post* liability rules is superior to precautionary *ex ante* regulations alone. The externality created by GM gene flow is particularly complex, however, in that it affects a market. Its regulation therefore affects the availability of choices faced by producers and consumers, as well as prices and quantities on the markets of both the harming and the harmed products. The general results of the literature are obtained for non-market externalities. While Beckmann et al. (2010) consider the non-market GMO externality, these authors do not make market effects endogenous. It is *a priori* not evident to what extent these results apply to coexistence in the GM and non-GM markets. Our objective in this paper is to assess the welfare effects of *ex ante* and *ex post* coexistence regulations, taking into account how they affect the interrelated markets of the GM and non-GM goods.

While a substantial agronomic literature addresses the effects of alternative *ex ante* regulations on GMO admixing (see e.g. Sanvido et al., 2008; Ceddia et al., 2009; Devos et al., 2008a), there are yet few economic studies analyzing the impacts of coexistence regulations. Market and welfare models of GMO introduction in the presence of consumer aversion for GMOs usually assume that no coexistence regulation is in place (Lapan and Moschini, 2004; Fulton and Giannakas, 2004; Lapan and Moschini, 2007; Desquilbet and Bullock, 2009). Munro (2008) discusses policy options to restore efficiency with a stylized market model of GM and non-GM crops in which GMO producers exert a spatial negative externality on non-GMO producers. He shows that market-based instruments such as a tax on GM seeds or a subsidy on non-GM production may be insufficient to ensure production efficiency. However, he does not analyze *ex ante* or *ex post* coexistence regulations, and his discussion is not related to the current EU regulatory framework for coexistence.

The analysis of Demont et al. (2008 and 2009) is more in line with the current EU regulation. The authors simulate the effects of two alternative spatial *ex ante* coexistence regulations, an isolation distance and a pollen barrier. The isolation distance is a perimeter surrounding a non-GM field in which no GM crop may be grown. The pollen barrier is a field border between a GM and a non-GM field, of a smaller width than the isolation distance, which must be planted with a non-GM variety but harvested and marketed with the GM crop. The pollen barrier may border either the GM field or the non-GM field, if the GMO farmer compensates the non-GMO farmer for the cost of this barrier. In this setting, the authors argue that small, negotiable pollen barriers are preferable to large isolation distances, especially if market premiums for non-GM IP crops are non-existent or low. Desquilbet and Bullock (2010) question the generality of these results on two grounds. First, the authors include only producer profits in their analysis, ignoring consumer utility. Second, they adopt some restrictive assumptions, such as the absence of any non-GM crop harvest downgrading with either of the two instruments, and the exogeneity of GM and non-GM prices and adoption rates.

In this paper, our aim is to contribute to this economic literature by analyzing the impact of *ex ante* and *ex post* coexistence regulations on prices and market shares of GM and non-GM products, on coexistence achievement, and on global and interest group welfare. We adopt the typical modeling assumptions that, compared to non-GMOs, GMOs are seen as an inferior good by consumers but allow productivity gains for producers. We develop a non-spatial stylized model where *ex ante* coexistence regulations are isolation distances on which GMO producers must grow a non-GM crop. For simplicity, we assume that GMO farmers comply perfectly with these technical measures (even though they bear additional costs because of this regulation). We also assume that non-GMO producers do not take any measures to prevent GMO commingling. These producers face a probability of harvest downgrading that decreases with both the *ex ante* regulation level (higher isolation distances diminish admixture risks) and the regulatory tolerance threshold for GMO content in non-GM products. We assume that when *ex post* regulation is in place, GMO farmers may contribute to a compensation fund via a tax on GM seeds, and that the government also contributes to this compensation fund (via taxpayer money) in order to exactly compensate profit losses of non-GMO farmers facing harvest downgrading. We use this model to analyze the effects of *ex ante* and *ex post* coexistence regulations on market and welfare outcomes. A major characteristic of our model is to allow prices, GMO adoption rates and the extent of non-GM harvest downgrading to be endogenous.

This article proceeds as follows. Section 2 presents the general assumptions that are used in the model. Section 3 presents the different results according to the regulations in place. Section 4 concludes.

2 Model

We let $r \in [0, 1]$ denote the regulatory threshold for authorized adventitious presence of GMOs in Identity Preserved (IP) non-GM products: if $r = 0$, no GMO presence is tolerated in the non-GM grain; while a threshold of $r = 1$, that is, an authorized presence of 100% GMOs in the non-GM product, is never binding. We assume that producers are profit-maximizers and may produce three different types of a particular crop. The first one is produced using a GM seed and is indexed by

g. The second type of grain (indexed by n) is produced from a non-GM seed but is not sold as IP: either it is produced by non-GMO producers but downgraded because its GMO content is above the regulatory threshold, or it is produced by GMO producers on some part of their crop area to comply with an *ex ante* coexistence regulation, and is blended with the GMO harvest. Consumers consider n and g to be the same product, referred to here as conventional (indexed by c). The third type, indexed by i, is the IP grain: it is grown from a non-GM seed by non-GM producers, and has a GMO content below the regulatory threshold. For simplicity reasons, we concentrate on the agricultural stage, which is the target of EU coexistence regulations, assuming that no additional commingling occurs at the handling and processing stages.[2]

2.1 Consumers

As in Fulton and Giannakas (2004) and Lapan and Moschini (2007), we model the conventional good as the low-quality good, and the IP good as the high-quality good, in a vertical differentiation framework *a la* Mussa and Rosen (1978). Note that by doing so, we ignore two important aspects of consumer behavior with respect to GMOs and non-GMOs. First, several dimensions of consumers' negative attitudes towards GMOs relate to public-good attributes (for example, environmental effects, ethical issues such as the interaction between man and nature, or inequity resulting from biotechnology sector concentration), and therefore the welfare effects of GMOs for consumers cannot be assessed through markets and prices alone (Desquilbet and Poret, 2012). Second, the marketing of GM and non-GM products depends heavily on strategic interactions between retailers, and not only on consumer concern (Lusk, 2011). These simplifications are common to most existing market models of GMOs and non-GMOs.

We assume a continuum of consumers characterized by a willingness to pay for quality θ distributed uniformly between 0 and 1. Each consumer consumes either one unit of the conventional good (c), or one unit of the IP good (i), or none. The quality of the IP good with zero GMO content is normalized to 1. Consuming the conventional product results in a discount in quality $a < 1$ (that is, the perceived quality of the GM good is $1 - a$). The parameter a can be viewed as the consumers' degree of aversion to GM products. When the labeling threshold is r, we assume that the perceived quality of the IP good is $1 - ar$ (the lower the authorized presence of GMOs in the non-GM IP good, the higher its perceived quality). Then, the utility of the consumer with a

[2]For example, the cross-pollination from GM maize to conventional maize is considered to be the main source of adventitious GM presence in non-GM maize harvests (Czarnak-Klos and Rodriguez-Cerezo, 2010).

willingness to pay for quality θ is given by:

$$\begin{cases} \theta(1-ar)-p_i & \text{if he buys one unit of the IP good,} \\ \theta(1-a)-p_c & \text{if he buys one unit of the conventional good, and} \\ 0 & \text{if he buys neither of these goods,} \end{cases} \tag{1}$$

where p_i is the per-unit grain price of the IP good (the IP price) and p_c the per-unit grain price of the conventional good (the conventional price).[3]

The following threshold values allow us to characterize consumers' choices (we omit their price arguments):

$$\begin{cases} \theta^c & = \frac{p_c}{1-a}, \\ \theta^i & = \frac{p_i}{1-ar}, \\ \widetilde{\theta} & = \frac{p_i-p_c}{a(1-r)}. \end{cases} \tag{2}$$

All consumers characterized by $\theta > \theta^j$ ($j = c, i$) obtain a positive utility from consuming good j; while all consumers characterized by $\theta > \widetilde{\theta}$ obtain a higher utility from consuming the IP good rather than the conventional good. Immediate calculations show that the threshold values of θ must verify either $\theta^c = \theta^i = \widetilde{\theta}$ (in which case every consumer is indifferent between consuming the IP good or the conventional good), or $\theta^c < \theta^i < \widetilde{\theta}$, or $\widetilde{\theta} < \theta^i < \theta^c$. When $r < 1$, omitting the argument a, our utility functions imply the following demand functions:

For any $r \in [0,1)$,

$$\text{When } \theta^c < \theta^i, \begin{cases} D^c(p_c, p_i, r) = \min(\widetilde{\theta}, 1) - \theta^c, \\ D^i(p_c, p_i, r) = 1 - \min(\widetilde{\theta}, 1). \end{cases} \tag{3}$$

$$\text{When } \theta^i \leq \theta^c, \begin{cases} D^c(p_c, p_i, r) = 0, \\ D^i(p_c, p_i, r) = 1 - \min(\theta^i, 1). \end{cases} \tag{4}$$

2.2 Producers

2.2.1 Basic assumptions

We assume the existence of a continuum of competitive producers characterized by a parameter α, distributed uniformly on $[0, 1]$. This parameter represents per-unit production costs for the GM

[3] Our formulation is close to that adopted by Lapan and Moschini (2007). It is simpler, however, because we assume that consumers care about the regulatory threshold r, as opposed to the actual GM content of the non-GM IP product. In the Lapan and Moschini (2007) model, the perceived quality of the non-GM good depends on the actual presence of GMOs in the non-GM good in equilibrium, which is at most equal to the regulatory threshold.

crop, which differ depending on land quality. We assume that all producers face an additional cost c_n when they produce the non-GM crop (for which total per-unit production costs are therefore $\alpha + c_n$). Yield is identical for the two grain types n and g and is normalized to one. The GM seed is more expensive that the non-GM seed, with an additional cost w. The profit obtained if neither the conventional nor the IP crop is grown is normalized to zero.

Without gene flows from GM to non-GM crops and without coexistence regulation, per-unit profit functions are $p_c - \alpha - w$ for GMO producers and $p_i - \alpha - c_n$ for non-GMO producers. We now define these profit functions in the presence of gene flow from GM to non-GM crops, and when the government implements labeling and coexistence regulations.

2.2.2 Coexistence regulations

The *ex ante* coexistence regulation mandates each GMO producer to undertake a level of effort $e \in [0, 1)$. This level of effort is the proportion of his land that he plants with the non-GM variety, and sells as conventional together with the GM production. This formulation captures in a stylized fashion *ex ante* regulations such as isolation distances, which prevent GMO producers from growing GMOs too close to non-GM fields.[4] We assume perfect compliance of GMO producers with the mandatory effort, at no cost.

Non-GMO producers sell their harvest as IP, at price p_i, if its GMO content is less than the regulatory threshold r. Otherwise, their production is downgraded; that is, sold as conventional at price p_c. Noting the aggregate production of the GM good as Q_g, we model the probability of downgrading as:

$$h(e, r, Q_g) = (1 - e)(1 - r)Ind(Q_g), \tag{5}$$

where $Ind(Q_g)$ is an indicator function equal to zero if $Q_g = 0$, and equal to 1 otherwise.[5] The functional form of $h(.)$, chosen for its simplicity, verifies several intuitive properties. First, the probability of downgrading is decreasing in its first two arguments: the higher the *ex ante*

[4] The actual constraint brought about by *ex ante* regulations in real landscapes is more complicated for two reasons. First, a GMO producer does not have to implement the *ex ante* regulation if he knows at planting time that his neighbors will not choose to grow identity-preserved non-GM crops. Second, the size and isolation of fields differ between producers, making the proportion of land affected by the *ex ante* regulation heterogenous between producers. For simplicity reasons, these refinements are kept out of our model.

[5] It could be more realistic to assume that the probability of downgrading depends on the relative proportion of GMOs in total production ($\frac{Q_g}{Q_g+Q_i}$). However, the model would not be solvable with this assumption. Additionally, the probability of downgrading the non-GM production of one farmer mainly depends on whether or not his neighbor cultivates GMOs, not on the total GM production.

regulation e, the lower the GM gene flow towards non-GM fields; similarly, the higher the labeling threshold r, the higher the proportion of grain that meets this threshold. Second, none of the non-GM production is downgraded either when the standard is never binding ($h(e, 1, Q_g) = 0$) or when the effort of GMO producers is maximum and therefore equivalent to an absence of GM plantings ($h(1, r, Q_g) = 0$).

The government may also implement an *ex post* regulation by exactly compensating the profit losses faced by non-GMO producers if their production gets downgraded. We define this *ex post* regulation by an indicator function:

$$L = \begin{cases} 0 \text{ if no } \textit{ex post} \text{ regulation is in place,} \\ 1 \text{ if an } \textit{ex post} \text{ regulation is in place.} \end{cases}$$

We assume that when an *ex post* regulation is in place ($L = 1$), the regulator uses two instruments to compensate profit losses of non-GMO producers due to downgrading: a per-unit tax t on GM seed paid by GMO producers, with $t \geq 0$, and a government participation with taxpayer money.

2.2.3 Per-unit profit, aggregate supply, economic damage, tax revenue

We let $\pi^g(.)$ denote the profit obtained by GMO producers, who plant GM seeds on a proportion $(1 - e)$ of their area and non-GM seeds on the remaining proportion e. We let $\pi^i(.)$ denote the expected profit of non-GMO producers. Given that the government implements the instruments r (regulatory threshold for GMO content in the non-GM grain), e (*ex ante* regulatory effort imposed on GMO producers), L (*ex post* liability of GMO producers) and t (GM seed tax), omitting the argument c_n, the per-unit profit functions take the form:

$$\begin{aligned} \pi^g(p_c, e, L, t; \alpha) &= p_c - ec_n - (1 - e)(w + Lt) - \alpha = \alpha^g - \alpha, \\ \pi^i(p_c, p_i, Q_g, r, e, L; \alpha) &= p_i - c_n - (1 - L)(p_i - p_c)h(e, r, Q_g) - \alpha = \alpha^i - \alpha \end{aligned}$$

Threshold values α^g and α^i are defined so that all producers characterized by $\alpha < \alpha^j$ obtain a positive profit from producing good j. From the profit functions defined above, it is immediate that when $\alpha^i > \alpha^g$, the IP good (i) is more profitable than the GM good (g) for all producers; the reverse holds when $\alpha^i < \alpha^g$. All producers obtain the same profit from i and g when $\alpha^i = \alpha^g$. Let $\mathtt{P}_g$ and $\mathtt{P}_i$ denote the domains where the profit-maximizing choice of producers is to produce, respectively, the GM good (combined with the non-GM good on a proportion e of the crop area), and the IP good. Using the above properties, our profit functions imply the following production domains:

$$\text{when } \alpha^i > \alpha^g, \quad \begin{cases} \mathtt{P}_g = \emptyset \\ \mathtt{P}_i = \{\alpha \in [0,1] : \alpha \leq \alpha^i\} \end{cases}$$
$$\text{when } \alpha^i = \alpha^g, \quad \mathtt{P}_g \cup \mathtt{P}_i = \{\alpha \in [0,1] : \alpha \leq \alpha^g\}$$
$$\text{when } \alpha^i < \alpha^g, \quad \begin{cases} \mathtt{P}_g = \{\alpha \in [0,1] : \alpha \leq \alpha^g\} \\ \mathtt{P}_i = \emptyset \end{cases}$$

Let S^g, S^n and S^i denote quantities supplied of goods g, n and i. On the domain $\mathtt{P}_g$, a proportion $1-e$ of production is GM while a proportion e is non-GM. On the domain $\mathtt{P}_i$, a proportion $1-h(.)$ is sold as IP while a proportion $h(.)$ gets downgraded because of GM content exceeding the permitted level. Our production domains therefore imply the following supply correspondence:

For any $e \in [0,1)$,

$$S(p_c, p_i, Q_g, r, e, L, t) = \Bigg\{ (S^g, S^n, S^i) : S^g = (1-e) \int_{\alpha \in \mathtt{P}_g} d\alpha,$$
$$S^n = e \int_{\alpha \in \mathtt{P}_g} d\alpha + h(e, r, Q_g) \int_{\alpha \in \mathtt{P}_i} d\alpha, \; S^i = (1 - h(e, r, Q_g)) \int_{\alpha \in \mathtt{P}_i} d\alpha \Bigg\}.$$

When GM and IP products coexist in the market, a proportion $1-h$ of IP producers' production is sold as IP, while a proportion h is downgraded. Given that the IP consumption is $1-\widetilde{\theta}$, the total production of IP producers is therefore $\frac{1-\widetilde{\theta}}{1-h}$, and their downgraded production is $\frac{h}{1-h}(1-\widetilde{\theta})$. The unit profit loss on this downgraded production is equal to the price difference $p_i - p_c$. Therefore, the total economic damage caused by downgrading is:

$$D = \frac{(1-e)(1-r)}{e+r-er}(1-\widetilde{\theta})(p_i - p_c). \tag{6}$$

Maintaining the assumption of coexistence of both goods in the market, the quantity of conventional product consumed is $\widetilde{\theta}-\theta^c$. Since $\frac{h}{1-h}(1-\widetilde{\theta})$ of this quantity is downgraded production of IP producers, the production of GMO producers must account for the remaining $\widetilde{\theta}-\theta^c-\frac{h}{1-h}(1-\widetilde{\theta})$. A proportion $(1-e)$ of this production is sown with GM seeds. As a result, the revenue from the GM seed tax is:

$$T = \left(\widetilde{\theta} - \theta^c - \frac{(1-e)(1-r)}{e+r-er}(1-\widetilde{\theta})\right)(1-e)t. \tag{7}$$

2.3 Definition of equilibrium and benchmark cases

Given the model parameters a, c_n, w and the policy instruments r, e, L, t, we have that p_c, p_i, Q_g $\in R^3_+$ is an *equilibrium* if: (a) $S^g = Q_g$, (b) $(S^g, S^n, S^i) \in S(p_c, p_i, Q_g, e, r, L, t)$ (each producer maximizes profits), (c) $S^g + S^n = D^c(p_c, p_i, s)$, and $S^i = D^i(p_c, p_i, s)$ (each consumer maximizes utility and markets clear).

In a benchmark case without GMOs (non-GMO consumers perceive no discount of quality), the non-GM good provides a per-unit profit $p - \alpha - c_n$, and a per-unit utility $\theta - p$. The equilibrium price is $p^0 = \frac{1+c_n}{2}$, the equilibrium quantity is $Q^0 = \frac{1-c_n}{2}$ and welfare is $W^0 = \frac{(1-c_n)^2}{4}$.

Consider now a different benchmark where GMOs are introduced without any regulation: no labeling (or equivalently $r = 1$) and no coexistence regulation ($e = L = 0$). The GM and non-GM goods provide per-unit profits $\pi^g = p_c - w - \alpha$ and $\pi^i = p_i - c_n - \alpha$ respectively, while consumers demand only the cheapest product, with $D(p) = 1 - \frac{p}{1-a}$. In this situation, as long as $w < c_n$, only the GM good is produced and consumed, and the equilibrium price is then $p_c^0 = \frac{1-a}{2-a}(1 + w)$. The equilibrium quantity is $Q_c^0 = \frac{1-a-w}{2-a}$ and welfare is $W_c^0 = \frac{(1-a-w)^2}{2(2-a)}$.

We consider hereafter that the price of the GM seed is lower than the non-GM crop additional cost of production, and therefore that the GMO technology provides efficiency gains to producers.

Assumption 1. $w < c_n$.

3 The effects of coexistence regulations

We now study several forms of regulation: a regulatory maximum threshold for the adventitious presence of GMOs in the non-GMO production, *ex ante* regulation in addition to the threshold, and *ex ante* regulation with *ex post* liability.

3.1 Equilibrium characterization

Whether both, neither, or only one of the IP and the conventional goods are produced and consumed in equilibrium depends on the values of the supply and demand parameters (c_n and a), on the price of the GM seed (w), and on the policy instruments characterizing labeling, *ex ante* and *ex post* regulation (r, e, L and t). Table 1 below summarizes the conditions under which each type of equilibrium may emerge. The equilibrium prices in each type of equilibrium are also presented, considering either *ex ante* regulation only (column 2), or both *ex ante* and *ex post* regulations (column 3) (the proof is given in Appendix A.1).[6]

[6]Production and consumption choices are defined as follows. In a coexistence equilibrium, producers characterized by $\alpha \leq \alpha^g$ produce either the GM good with the mandatory isolation distances, or the non-GM IP good which is subject to some downgrading. Consumers characterized by $\theta^c \leq \theta \leq \widetilde{\theta}$ consume the conventional good, while

[Insert Table 1]

Figures 1 and 2 illustrate both possible configurations of equilibrium domains when only *ex ante* regulation is in place. In both figures, domains with only conventional production and with coexistence are separated by their common frontier $(C1)$, which compares the additional cost of IP production to the net utility from IP rather than conventional consumption. The equilibrium with only the conventional crop appears when consumers' aversion to GM products (a) is low and the additional cost of the non-GM crop (c_n) is high. As a rises and c_n falls, the equilibrium changes, first to coexistence, then to IP cultivation only. In addition, there exist multiple equilibria for some values of the parameters: some equilibria with coexistence and some with only conventional cultivation coexist with an equilibrium with only IP. These multiple equilibria arise because the profit obtained from IP cultivation depends on whether or not some GMOs are cultivated as well: if they are, IP producers are not compensated for the expected damage created by the negative externality of GM production, which results in the downgrading of some of their production.[7] The difference between Figure 1 and Figure 2 in the configuration of equilibrium domains stems from the position of the curve $C4$ and therefore from the scope for multiple equilibria.

[Insert Figure 1]

[Insert Figure 2]

With *ex ante* and *ex post* regulations (Figure 3), IP producers are fully compensated for any crop downgrading they face, and GMO producers face the same regulations whether or not IP crops are actually cultivated. In this case, there is no multiple equilibrium because unit profit functions do not depend on which equilibrium occurs.[8] The equilibrium areas are laid out as in Figure 1: an increase in a and/or a decrease in c_n shifts the equilibrium from conventional cultivation to coexistence, and then to IP-only cultivation. *Ex post* regulation (which compensates

consumers characterized by $\theta > \widetilde{\theta}$ consume the IP good. In an equilibrium with only the conventional crop, producers characterized by $\alpha \leq \alpha^g$ all produce the GM good (sowing the non-GM seed on a proportion e of their crop area), while consumers characterized by $\theta \geq \theta^c$ consume the conventional good. Finally, in an equilibrium with only IP, producers characterized by $\alpha \leq \alpha^i$ all produce the IP good, which is consumed by consumers characterized by $\theta \geq \theta^i$.

[7] More precisely, the unit profit π_i is written $p_i - c_n - (p_i - p_c)(1-e)(1-r) - \alpha$ if GMOs are cultivated, and $p_i - c_n - \alpha$ if they are not, which allows for multiple equilibria.

[8] More precisely, the unit profit π_i is written $p_i - c_n - \alpha$ whether GMOs are cultivated or not and the unit profit π_g is written $p_c - ec_n - (1-e)(w+t) - \alpha$ whether or not IP crops are cultivated (in our model GMO producers have to implement the isolation distance e and to pay the tax t regardless of whether IP crops are actually cultivated).

IP producers for the profit losses caused by crop downgrading) is favorable for IP production; the area with conventional-only production is therefore smaller, and the area of IP-only cultivation is larger under joint *ex ante* and *ex post* regulations (Figure 3) compared with *ex ante* regulation alone (Figures 1 and 2).

[Insert Figure 3]

3.2 Coexistence regulations and the emergence of coexistence

We now analyze how changes in regulations affect the emergence of coexistence. Freedom of choice between GMOs and non-GMOs for producers and consumers is a stated objective of the European recommendation on coexistence (Commission of the European Communities, 2010). The set of parameter values for which this freedom of choice is effective, in the sense that both goods do coexist on markets, is an indicator of the achievement of this political goal.

Proposition 1. ***Effects of coexistence regulations on the emergence of coexistence***

For given levels of the supply and demand parameters (c_n and a), of the price of the GM seed (w) and of the threshold of GMO content for labeling (r), changes in coexistence regulations affect the types of goods produced and consumed in equilibrium as follows.

For a given level of ex ante regulation, when ex post regulation is introduced, a former coexistence equilibrium either remains a coexistence equilibrium or changes into an equilibrium with only IP, while a former equilibrium with only conventional crops may turn into a coexistence equilibrium.

Either with or without ex post regulation in place, an increase in the level of ex ante regulation may cause an equilibrium with only the conventional good to disappear in favor of a coexistence equilibrium, or a coexistence equilibrium to disappear in favor an equilibrium with only IP.

Proof. A. $C2 < C4 \leq C4'$, $C4 < C6$. When $t > 0$, $C4 < C4'$.

B. Expressions $C1$, $C6$, $C2$ and $C4'$ are increasing in e. □

The mechanisms at work when *ex post* regulation is introduced or when the level of *ex ante* regulation is increased are alike: both regulation changes make the IP crop more profitable and the GM crop less profitable, possibly making the IP good appear on the market, or the GM good disappear from the market.

As a consequence, the absence of IP goods on the market when no coexistence regulations are in place does not necessarily indicate that consumers are not interested in them. It may be that gene flow in fields, and the implied downgrading of IP production, makes such production too expensive in the absence of regulation. This production choice may yet become profitable when coexistence measures imposed on GMO producers reduce the probability of gene flow towards non-GM fields. This endogeneity of production choices therefore makes the analysis more complicated than what is suggested for example by Devos et al. (2008b) when they state that *"In markets where consumers are unwilling to pay significant price premiums for GM-free maize, there is no coexistence issue stricto sensu."*. Because producers' incentives to supply GM or non-GM crops are endogenous and subject to change when regulation is introduced, the absence of market signals for IP crops in the absence of coexistence regulation is not an indicator that such coexistence policy is not desirable.

To complete the description of the emergence of coexistence, we define a measure of the size of the coexistence area in Figures 1 to 3. We write this coexistence area in relation to the two axes of these figures, c_n and a. Denoting A the coexistence area with *ex ante* regulation alone, and A' the coexistence area with *ex ante* and *ex post* regulations, we have:

$$A = \int_0^{a^{max}} [C1 - C2]\, da \quad \text{with} \quad a^{max} = \frac{(1-e)(1-w)}{1-e[1-(1-r)(e+r-er)]},$$

$$A' = \int_0^{\frac{(1-e)(1-(w+t))}{1-er}} [C6 - C4']\, da.$$

We now examine how different combinations of regulatory instruments affect the size of the coexistence area. First, we note that with *ex post* regulation in place, the GM seed tax reduces the area of coexistence, because it introduces an additional cost for GM producers without changing the per-unit profit for IP producers (Proposition 2 below).

Proposition 2. ***Size of the coexistence area and level of the GM seed tax***

For any given parameter values, when ex post regulation is in place, the area of coexistence (A') is largest when the ex post regulation is funded entirely by taxpayer money.

Proof. See Appendix A.2. □

Next, we analyze the size of the coexistence area when the regulator can choose both the level of *ex ante* regulation (e) and the presence or absence of *ex post* regulation, funded entirely by taxpayers (L). We take the authorized threshold level of GMOs in IP products (r) as given. Such a regulatory choice may be representative of the current situation in the European Union, where the implementation of coexistence measures is posterior to regulation on the threshold for GMO content, which is now politically difficult to adjust. The results are shown graphically in Figure 4. The derivation of this Figure is detailed in Appendix A.2.

The white area represents the equilibria for which the coexistence area is larger with *ex post* regulation than without, while the dark area represents the opposite case. Lax *ex ante* technical measures to reduce GMO gene flows (that is, a small e) are favorable to GMO producers. Under such conditions, coexistence appears for a wider range of parameters (c_n, a), as long as this lax *ex ante* effort of GMO producers is counterbalanced by *ex post* compensation, favorable to IP producers (white area). On the contrary, a stringent *ex ante* regulation (e high) is favorable to IP producers. Then, coexistence emerges for a wider range of parameters in the absence of *ex post* regulation (dark area). Furthermore, a lax regulation on the level of adventitious presence of GMOs in IP goods (r high) reduces IP demand. Coexistence is then favored when *ex post* regulation, which is favorable to IP producers, is in place.

[Insert Figure 4]

We consider now the level of *ex ante* regulation that maximizes the size of the coexistence area for a given r: let $e(r)$ and $e'(r)$ denote this level with, respectively, *ex ante* regulation alone, and the mixed policy regulation. The introduction of *ex post* regulation makes the coexistence area maximal for a lower level of *ex ante* regulation ($e(r) > e'(r)$).This is because both types of regulation have a negative impact on GMO producers.

Areas of coexistence correspond to all possible equilibria in which both GM and IP goods are produced and consumed. In some of these equilibria, however, one of the two goods may only be marketed in an infinitesimal amount. To provide further insight on the scope of coexistence, we now study the quantity of each type of good consumed and the quantity of IP production downgraded in a coexistence equilibrium, depending on the regulation in place. Table 2 summarizes the total quantities marketed in equilibrium (Q and Q'), as well as IP consumption (Q_i and Q'_i), conventional consumption (Q_c and Q'_c), and IP downgrading (Q_d and Q'_d), with *ex ante* regulation alone (column 2) and with both *ex ante* and *ex post* regulations (column 3). The table also details the effects of the level of *ex ante* regulation and of the labeling threshold on these different quantities.

[Insert Table 2]

From the table it can be seen that IP consumption is higher with both coexistence regulations in place than with *ex ante* regulation alone ($Q'_i > Q_i$), while conventional consumption is lower

($Q'_c < Q_c$). The quantity of IP downgraded is higher under the two regulations ($Q'_d > Q_d$), because *ex post* regulation encourages IP production.

A higher level of technical standards (e) leads to higher production costs for GM producers. With *ex ante* regulation alone, it also lowers downgrading costs for IP producers. In equilibrium, as e increases, under either one or both coexistence regulations, conventional consumption decreases by a greater amount than IP consumption increases. The more complex effect of an increase in e on IP downgrading is detailed in the following equation. The equivalent holds in the mixed policy condition, with variables Q'_d and Q'_i in place of Q_d and Q_i.

$$\frac{\partial Q_d}{\partial e} = \frac{1-r}{e+r-er}\left[\underbrace{(1-e)\frac{\partial Q_i}{\partial e}}_{\text{supply effect}} - \underbrace{\frac{Q_i}{e+r-er}}_{\text{direct effect}}\right]. \tag{8}$$

The negative direct effect is the reduction in downgrading which results from an increase in the required technical measures for GM production. Since $Q_i < Q'_i$, this direct effect is lower when *ex ante* regulation is implemented alone. The positive supply effect reflects the indirect effect of *ex ante* technical measures on IP production. We find that the positive supply effect necessarily dominates the negative direct effect with *ex ante* regulation alone. Under such conditions, stricter technical measures in fields cause IP downgrading to increase, because the IP production grows. When both regulations are in place, stricter technical measures in fields induce a decrease in downgrading as long as the IP production is relatively high compared to the GM production, and an increase otherwise.

A higher labeling threshold reduces the IP quality perceived by consumers and therefore the demand for the IP good. With both *ex ante* and *ex post* regulations in place, an increase in this labeling threshold results in a decrease in both IP consumption and IP downgrading, and an increase in conventional consumption, with no price change. With *ex ante* regulation alone, an increase in the labeling threshold directly diminishes the expected costs of IP downgrading, which leads to a decrease in the IP price. When the probability of downgrading (h) is so high that $Q_d \geq Q_i$, that is, when $e \leq \frac{1-2r}{2(1-r)}$, an increase in the labeling threshold leads to an increase in IP consumption and a decrease in conventional consumption. The results are reversed for a low threshold (and therefore a low probability of downgrading). Under *ex ante* regulation alone the analysis of IP downgrading, described in the following equation, is more complex.

$$\frac{\partial Q_d}{\partial r} = \frac{1-e}{e+r-er}\left[\underbrace{(1-r)\frac{\partial Q_i}{\partial r}}_{\text{effect on } Q_i} - \underbrace{\frac{Q_i}{e+r-er}}_{\text{direct effect}}\right]. \tag{9}$$

When the probability of downgrading (h) is so high that $Q_d \geq Q_i$, the positive effect of the increase in IP consumption may counterbalance the negative direct effect related to the decrease of IP downgrading. In this case, as the labeling threshold increases, IP downgrading increases even more, which may jeopardize coexistence. With low additional costs of IP production, on the contrary, the direct effect dominates and an increase in the labeling threshold reduces IP downgrading. When the probability of downgrading is low, both effects work in the same direction on IP downgrading, and a higher labeling threshold induces a decrease in IP downgrading.

3.3 Market and welfare effects

With *ex ante* regulation alone, total welfare in a coexistence equilibrium,is given by:

$$W = \int_0^{\alpha^g} (\alpha^g - \alpha) d\alpha + \int_{\theta^c}^{\widetilde{\theta}} (\theta(1-a) - p_c) d\theta + \int_{\widetilde{\theta}}^1 (\theta(1-ar) - p_i) d\theta.$$

Proposition 3 below details the effects of labeling ($r < 1$) on total welfare, absent any coexistence regulation. By increasing the utility of consumers who turn to the IP good, when mandatory labeling allows the emergence of coexistence it induces an increase in welfare.

Proposition 3. *Absent any coexistence regulation ($e = L = t = 0$), the introduction of labeling, when it allows the emergence of coexistence, leaves unchanged the conventional price, total production and consumption, producers' profits and the utility of consumers who keep consuming the conventional good. The utility of consumers who turn to the (more expensive) IP good increases and total welfare increases.*

Proof. See Appendix A.4. □

Market and welfare effects of *ex ante* regulation are summarized in Proposition 4 below.

Proposition 4. *In a coexistence equilibrium without ex post regulation, an increase in the level of ex ante regulation causes the conventional price to increase and the IP price to decrease. Conventional consumption decreases and IP consumption increases, resulting in a decrease in total (conventional + IP) consumption. Consumers of the conventional good and producers are hurt, while consumers of the IP good are better off. The introduction of a low level of ex ante regulation is welfare-increasing if and only if the following condition holds:*

$$-1 + \frac{1}{r^2} + \frac{1+w}{2-a} - \frac{c_n - w}{a(1-r)r^3} > 0 \quad (10)$$

This condition is more likely to hold if the aversion towards GMOs (a) and the GM seed cost (w) are large and the additional cost of non-GM production (c_n) is small.

Proof. See Appendix A.5. □

At initial market prices, the first effect of an increase in the *ex ante* regulation is to force GMO farmers to dedicate some of their crop area to isolation distances sown with non-GM seeds, decreasing their profitability while leaving their total production of conventional good unchanged (since GM and non-GM goods have identical yields in our setting). The aggregate production of IP producers is also unchanged, but the proportion of it which gets downgraded decreases. Therefore, the profitability of the GM crop decreases while the profitability of the IP crop increases, and conventional production decreases while IP production increases (total production remains unchanged). As a second effect, these changes tend to raise the price of the conventional good and lower the price of the IP good, thereby increasing the profitability of the conventional crop and decreasing the profitability of the IP crop (note that the two crops must be equally profitable for a coexistence equilibrium to be sustained after the introduction of the regulation).

The possible welfare-increasing effect of the *ex ante* regulation arises because this regulation forces GMO producers to internalize some of the costly gene flow externality that they exert towards consumer-preferred IP good producers. There is no general property on the level of the regulatory threshold, r, under which this condition is more likely to hold. Nevertheless, numerical evaluation indicates that the condition (10) is more likely to hold for intermediate values of the regulatory threshold r. This is the result of the two opposite effects related to the regulatory threshold. A loose regulatory standard (r high) discourages the demand for IP goods, since the number of IP consumers $(1-\widetilde{\theta})$ and the utility of each IP consumer $(\theta(1-ar)-p_i)$ are low. At the same time, a strict regulatory threshold (r low) discourages the production of IP goods, since it entails much downgrading (α^i low) and a high price difference between IP and GMOs.

We now turn to the case where both *ex ante* and *ex post* regulations are in place. Under such conditions, aggregate welfare is the sum of producers' profits and the utility of both types of consumers, minus the damage funded by taxpayer money. The total compensation to IP producers for the downgrading they incur is D (Equation (6)), of which T (Equation (7)) is paid by the GM seed tax revenue and the rest by taxpayers.In a coexistence equilibrium aggregate welfare is given by:

$$W' = \int_0^{\alpha^g}(\alpha^g-\alpha)d\alpha + \int_{\theta^c}^{\widetilde{\theta}}(\theta(1-a)-p_c)d\theta + \int_{\widetilde{\theta}}^{1}(\theta(1-ar)-p_i)d\theta$$
$$-\frac{h}{1-h}(1-\widetilde{\theta})(p_i-p_c) + (\widetilde{\theta}-\theta^c-\frac{h}{1-h}(1-\widetilde{\theta}))(1-e)t.$$

Proposition 5 below summarizes market and welfare effects in this case.

Proposition 5. *In a coexistence equilibrium with ex post regulation, for a given level of ex ante regulation, the introduction of a GM seed tax as as substitute to taxpayer funding for downgrading compensation induces an increase in the conventional price and a decrease in the IP price. Producers' profits and conventional consumers' utility decrease, while IP consumers' utility increases. The total production level decreases, with the conventional quantity lower and the IP quantity higher. IP downgrading increases. Total welfare decreases (therefore, the optimal level of the tax on GM seeds is* $t = 0$*).*

Assume now that ex post regulation is funded entirely by taxpayers ($t = 0$*). Absent ex ante regulation, the introduction of labeling increases the total welfare. With labeling in place, the introduction of a low level of ex ante regulation is welfare-increasing if the following condition holds:*

$$-2(c_n - w)(1+r-r^2) + a[2 + c_n(1+r-r^2) - w(1+r(1-r)^2) - r(2+r-r^2)] - a^2(1-r)^2(1+r) > 0 \tag{11}$$

This condition is more likely to hold if the aversion towards GMOs (a) *and the GM seed cost* (w) *are large and the additional cost of non-GM production* (c_n) *and the regulatory threshold* (r) *are small.*

Proof. See Appendix A.6. □

For any given level of *ex ante* regulation, with *ex post* regulation in place, social welfare is maximized when the damage related to the externality is paid entirely through taxpayers' money, not by GMO producers through a GM seed tax. This is due to the fact that the GM seed tax introduces a market distortion.

Compared with an unregulated equilibrium, the introduction of labeling and of *ex post* liability funded entirely by taxpayers increase the total welfare when the enforced regulations allow the coexistence to emerge. These regulations change neither the producers' profit nor the surplus of consumers who continue to buy the GM good. However, they allow some consumers to choose the IP good, which increases their utility.

Even when an *ex post* regulation funded by taxpayers' money protects IP producers from damages related to the externality, an *ex ante* regulation may increase total welfare. This is the case when the aversion towards GMOs and the GM seed cost are large and the additional cost of non-GM production and the regulatory threshold are low. Indeed, under these conditions the expected damage D at the coexistence equilibrium is decreasing with the level of the *ex ante* regulation, which allows such a regulation to increase total welfare.

Contrary to the *ex ante* regulation case, the condition (11) is more likely to hold when the regulatory threshold is low. A strict regulatory standard (r low) increases the demand for IP goods and does not discourage their production, since IP producers do not bear the cost of downgrading, and the price difference between IP and GM goods is low.

We now study the effects of the introduction of ex post regulation, funded entirely by taxpayers, from a baseline equilibrium with ex ante regulation alone. The next three propositions address successively the three possible equilibrium configurations that arise. In the first, from a coexistence equilibrium with ex ante regulation alone, the introduction of ex post regulation maintains a coexistence equilibrium; in the second, starting again from a coexistence equilibrium, the introduction of ex post regulation shifts the equilibrium to one with only the IP good; and in the third, from an equilibrium with only conventional production, the introduction of ex post regulation shifts the equilibrium to a coexistence one.

Proposition 6. *For given values of the other parameters, the introduction of ex post regulation funded entirely by taxpayers, when it maintains a coexistence equilibrium (that is, when $C4 < c_n < C1$), leaves the conventional price unchanged. The IP price decreases. Total production and consumption are unchanged, with some former conventional producers and consumers turning to IP production and consumption. Producers' profits and the utility of consumers who continue to consume the conventional good are unchanged. The utility of continued and new consumers of the IP good increases, but this increase is more than offset by the cost to taxpayers. Total welfare therefore decreases.*

Proof. See Appendix A.7. □

This proposition establishes that the implementation of taxpayer-funded *ex post* regulation increases the utility of former or new consumers of the IP product only at the cost of a higher expense for taxpayers, and is therefore never a welfare-increasing policy option.

This result is not surprising given that the *ex post* regulation gives no incentive to GMO producers to decrease the amount of damage they inflict on IP producers. This effect is a direct consequence of our assumption that GMO producers never undertake any effort to decrease gene flow in the absence of a restrictive *ex ante* policy. It is in accordance with the non-point source nature of GM gene flow, which makes it possible for any individual producer to escape the threat of being held individually liable for his actions, therefore giving him no incentive to internalize the externality that he exerts on producers wishing to identity-preserve their non-GM crop.

Results are similar when the introduction of *ex post* regulation shifts the equilibrium configuration from conventional production alone (in which case the welfare level is simply $\int_0^{\alpha^g}(\alpha^g - \alpha)d\alpha + \int_{\theta^c}^1(\theta(1-a) - p_c)d\theta$) to coexistence, as indicated in Proposition 7.

Proposition 7. *For given values of the other parameters, the introduction of ex post regulation funded entirely by taxpayers, when it makes the equilibrium shift from conventional production alone to coexistence (that is, when $Max(C1, C4) < c_n < C6$), leaves the conventional price unchanged. Total production and consumption are unchanged, with some former conventional producers and consumers turning to IP production and consumption. Producers' profits and the utility of consumers who keep consuming the conventional good are unchanged. The utility of consumers who turn to the (more expensive) IP good increases, but this increase is more than compensated by the cost to taxpayers. Total welfare therefore decreases.*

Proof. See Appendix A.8. □

With a relatively high supply parameter (c_n), the introduction of *ex post* regulation allows coexistence to emerge from a situation where only the conventional crop was produced and consumed. From this initial situation, consumers willing to consume IP goods may request the enforcement of *ex post* liability regulation. Such a policy would not affect producers and other consumers, but would be paid by taxpayers.

Finally, the introduction of *ex post* regulation may also destroy coexistence, in favor of an equilibrium with only IP (and with a welfare level given simply by $\int_0^{\alpha^i}(\alpha^i - \alpha)d\alpha + \int_{\theta^i}^1(\theta(1 - ar) - p_i)d\theta$)). The effects of such a transition are detailed in the following proposition.

Proposition 8. *For given values of the other parameters, the introduction of ex post regulation, funded entirely by taxpayers, which shifts the equilibrium from coexistence to IP production alone (that is, when $C2 < c_n < Min(C1, C4)$) results in a new price for IP goods which is above the former conventional price and below the former IP price. Total production and consumption increase. The profit increases for every producer and the utility increases for every consumer. As a result, total welfare increases.*

Proof. See Appendix A.9. □

With a relatively low supply parameter (c_n), the introduction of *ex post* regulation makes coexistence disappear in favor of the IP good. This policy increases total welfare by eliminating the damages caused by GMO cultivation, which decreases the IP price and increases producers' profit.

The results in Propositions 6 to 8 show that coexistence is costly in terms of social welfare, because coexistence creates the potential of damage due to the negative externality one crop has on the other. Moreover, *ex post* regulation cannot reduce expected damages related to crop downgrading, because the externality is a non-point source pollution. This regulation does not provide GMO producers with any incentive to decrease the externality that they exert towards non-GMO producers in our context.

4 Conclusion

In this paper we examine the effects of *ex ante* and *ex post* regulation of GM / non-GM coexistence in fields. To this aim, we define a framework that allows prices, and therefore production and consumption choices, to be endogenous. We use a classical vertical differentiation framework on the consumer side. On the production side, our model captures the main effects of coexistence regulation. GM gene flow is a non-point source pollution and therefore GMO producers do not have the appropriate individual incentives to correct the externality that they exert on non-GMO producers. *Ex ante* technical measures such as isolation distances reduce GM gene flow, and therefore the possible downgrading of some part of the non-GM production. Technical measures are costly for GMO producers, because they force them to give up more profitable GMO production on some part of their crop area. *Ex ante* regulation reduces but does not eliminate the risk of excessive gene flow. *Ex post* compensation of IP producers for any loss of profit due to downgrading may be implemented using public funds and/or the revenue generated by a GM seed tax.

The GM/non-GM coexistence issue is an interesting case within the law and economic literature which studies the efficiency of *ex ante* and *ex post* regulations to reduce externalities. We consider these policy options in light of their effects on both coexistence and welfare. First considering coexistence, we show that the regulation which maximizes the set of demand and supply parameters allowing coexistence is more likely a mixed policy or an *ex post* regulation, depending on the level of the labeling threshold. When coexistence is maintained, the introduction of an *ex post* compensation scheme permits the reduction of the *ex ante* technical measures imposed on GMO producers. At the same time, such regulation favors the production and consumption of the IP good compared to the GM good. Turning to the analysis of welfare, there is no incentive effect of *ex post* regulation on conventional good producers, because the gene flow externality is a non-point source pollution. As a result, we find that *ex post* regulation deteriorates welfare when it maintains or induces coexistence, since such conditions give rise to damages due to gene flow.

This result suggests that coexistence is a costly objective. On the contrary, we find that *ex ante* technical measures may be welfare increasing, as long as consumers care sufficiently for non-GM goods and GMO cost reductions are modest. *Ex ante* regulation reduces the potential damage, that is, the risk of IP crop downgrading. Whether or not the benefits of this damage reduction increase global welfare depends on consumers' preferences and producers' costs. Taking both coexistence and welfare as policy objectives, we conclude that a mixed policy regulation with *ex ante* technical measures and *ex post* compensation may encourage the coexistence of GMOs and non-GMOs on the market while minimizing the loss of social welfare.

For tractability reasons, our model assumes that all producers are identical. In reality, producers are differentiated and antagonism in producers' interests for regulation is strong. Our main results hold, however, if we assume that producers have heterogenous cost savings from GMOs, with per-unit costs $s\alpha + w$ for the GM crop and α for the IP non-GM crop. Notably, because of the non-point nature of the externality exerted by GM producers towards IP producers, the introduction of *ex post* regulation still decreases welfare when assuming that producers experience heterogeneous cost savings from GMO cultivation. In this case, however, IP producers benefit from *ex post* regulation.

As a final point, labeling and coexistence regulations only partially address the market failure arising from the positive non-use and public-good attributes that some consumers associate with non-GM goods (due to concerns that they may have regarding life patenting, environmental effects...). Even in the case where some consumers perceive a high quality difference between these two goods, as long as public-good attributes are driving their preferences, they will not necessarily be reflected in a high willingness to pay, unless these consumers behave altruistically. Other policies are therefore necessary to mitigate these market failures (see Desquilbet and Poret, 2012). Trust in public authorities may be reinforced by stronger risk assessment criteria, although this must be balanced with increased authorization costs, which are already very high. More fundamentally, trust may be reinforced by a more transparent regulatory process, open to public scrutiny. Opposition to GMOs which stem from their development by multinational corporations could, in principle, be partly addressed by competition authorities. Entitling consumers to choose to buy non-GM goods rather than GM goods by a labeling and coexistence policy is important for those consumers who prefer non-GM products; at the same time, it is likely that those consumer-citizens who are strongly opposed to GMOs will not be satisfied with these policies alone, as they do not target market failures resulting from positive non-use public-good attributes these consumers associate with non-GM goods.

Acknowledgements. Funding was provided by the French Agence Nationale de la Recherche (ANR).

Conflicts of interest. The authors declare that they have no conflict of interest.

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Table 1: Prices and equilibrium conditions with labeling and *ex ante* and/or *ex post* regulations

	ex ante regulation alone	*ex ante* and *ex post* regulations
Coexistence	$p_c^* = \frac{1-a}{2-a}(1 + ec_n + (1-e)w)$	$p_c^* = \frac{1-a}{2-a}(1 + ec_n + (1-e)(w+t))$
(Necessary conditions:	$p_i^* = p_c^* + \frac{(1-e)(c_n-w)}{1-(1-e)(1-r)}$	$p_i^* = \frac{(1-a)(1+c_n)+(1-e)(c_n-w-t)}{2-a}$
Either e or $r \neq 0$; $e < 1$)	$c_n \leq \frac{a(1-r)(e+r-er)}{1-e} + w = C1$	$c_n \leq \frac{a(1-r)}{1-e} + w + t = C6$
	$c_n > \frac{a(1-r)(e+r-er)(1+(1-e)w)+(2-a)(1-e)w}{(2-a)(1-e)-a(1-r)e(e+r-er)} = C2$	$c_n > \frac{a(1-r)+(2-ar)(1-e)(w+t)}{(2-a)(1-e)-a(1-r)e} = C4'$
Conventional production alone	$p_c^* = \frac{1-a}{2-a}(1 + ec_n + (1-e)w)$	$p_c^* = \frac{1-a}{2-a}(1 + ec_n + (1-e)(w+t))$
(Necessary condition:	$c_n > C1$	$c_n > C6$
$e < 1$)	$c_n < \frac{1-a-(1-e)w}{e} = C3$	$c_n < \frac{1-a-(1-e)(w+t)}{e} = C3'$
IP alone	$p_i^* = \frac{1-ar}{2-ar}(1+c_n)$	$p_i^* = \frac{1-ar}{2-ar}(1+c_n)$
(Necessary condition:	$c_n \leq \frac{a(1-r)+(2-ar)(1-e)w}{(2-a)(1-e)-a(1-r)e} = C4$	$c_n \leq C4'$
Either e or $r \neq 0$)	$c_n < 1 - ar = C5$	$c_n < C5$
Neither good produced	$c_n > C3$	$c_n > C3'$
	$c_n > C5$	$c_n > C5$

Note: $C3'$ and $C4'$ may be obtained by replacing w by $w+t$ respectively in $C3$ and $C4$.

Table 2: Quantities of each type of products in a coexistence equilibrium with labeling and *ex ante* and/or *ex post* regulations

	ex ante regulation alone	*ex ante* and *ex post* regulations
Total quantity	$Q = \frac{1-a-ec_n-(1-e)w}{2-a}$ • $\frac{\partial Q}{\partial e} < 0$	$Q' = \frac{1-a-ec_n-(1-e)(w+t)}{2-a}$ • $\frac{\partial Q'}{\partial e} < 0$
Quantity of IP good consumed	$Q_i = 1 - \frac{(1-e)(c_n-w)}{a(1-r)(e+r-er)}$ • $\frac{\partial Q_i}{\partial e} > 0$ • $\frac{\partial Q_i}{\partial r} \begin{cases} \geq 0 & \text{when } e \leq \frac{1-2r}{2(1-r)} \\ < 0 & \text{otherwise} \end{cases}$	$Q_i' = 1 - \frac{(1-e)(c_n-(w+t))}{a(1-r)}$ • $\frac{\partial Q_i'}{\partial e} > 0$ • $\frac{\partial Q_i'}{\partial r} < 0$
Quantity of conventional good consumed	$Q_c = \frac{c_nF-w(1-e)[2-a(1-e-r+2er+(1-e)r^2)]-a(1-r)(e+r-er)}{a(2-a)(1-r)(e+r-er)}$ • $\frac{\partial Q_c}{\partial e} < 0$ • $\frac{\partial Q_c}{\partial r} \begin{cases} \leq 0 & \text{when } e \leq \frac{1-2r}{2(1-r)} \\ > 0 & \text{otherwise} \end{cases}$	$Q_c' = \frac{2(1-e)(c_n-(w+t))-a(1-r+(1-er)c_n-(1-e)r(w+t))}{a(2-a)(1-r)}$ • $\frac{\partial Q_c'}{\partial e} < 0$ • $\frac{\partial Q_c'}{\partial r} > 0$
Quantity of IP production downgraded	$Q_d = \frac{h}{1-h}Q_i = \frac{(1-e)[a(1-r)(e+r-er)-(1-e)(c_n-w)]}{a(e+r-er)^2}$ • $\frac{\partial Q_d}{\partial e} > 0$ • when $e \leq \frac{1-2r}{2(1-r)}$, $\frac{\partial Q_d}{\partial r} \begin{cases} < 0 & \text{if } C2 < c_n < C7 \\ \geq 0 & \text{if } C7 \leq c_n \leq C1 \end{cases}$ otherwise $\frac{\partial Q_d}{\partial r} < 0$	$Q_d' = \frac{h}{1-h}Q_i' = \frac{(1-e)[a(1-r)-(1-e)(c_n-(w+t))]}{a(e+r-er)}$ • $\frac{\partial Q_d'}{\partial e} \begin{cases} < 0 & \text{if } C4' < c_n < C8 \\ \geq 0 & \text{if } C8 \leq c_n \leq C6 \end{cases}$ • $\frac{\partial Q_d'}{\partial r} < 0$

Note: $F = 2(1-e) - a(1-e(1-e-r+2er+(1-e)r^2))$, $C7 = \frac{a(e+r-er)}{2(1-e)^2} + w$, and $C8 = \frac{a(1-r)}{(1-e)(1+e+r-er)} + (w+t)$.

A Appendixes

A.1 Characterization of equilibrium

The parameters α^g and α^i are given by $\alpha^g = p_c - ec_n - (1-e)w$ and $\alpha^i = p_i - c_n - (p_i - p_c)(1-e)(1-r)Ind(Q_g)$ in the absence of *ex post* regulation ($L = 0$), and by $\alpha^g = p_c - ec_n - (1-e)(w+t)$ and $\alpha^i = p_i - c_n$ with *ex post* regulation ($L = 1$). In order to determine possible equilibria in each of these two cases ($L = 0$ or 1), we must consider three possible supply cases, depending on whether α^g is smaller, equal to or higher than α^i, and two possible demand cases, depending on whether θ^c is smaller or higher than θ^i.

A coexistence equilibrium arises when $\alpha^i = \alpha^g$, $\theta^c < \theta^i$, $e < 1$ ($S^g > 0$) and either r or $e \neq 0$ ($S^i > 0$). Equations ((a)-(c)), which define an equilibrium, imply that $\alpha^g = 1 - \theta^c$. Solving the system composed of the two equalities above, with the corresponding values for α^i and α^g respectively when $L = 0$ and when $L = 1$, yields the equilibrium prices given in Table 1 for the coexistence case. Equilibrium conditions are $\widetilde{\theta} \leq 1$ and $\theta^c < \theta^i$, which respectively yield $c_n \leq C1$ and $c_n > C2$ when $L = 0$, $c_n \leq C6$ and $c_n > C4'$ when $L = 1$.

An equilibrium with only the conventional crop arises when $\alpha^i < \alpha^g$, $\theta^c < \theta^i$ and $e < 1$. The definition of equilibrium in ((a)-(c)) then implies that $\alpha^g = \widetilde{\theta} - \theta^c$ and $\widetilde{\theta} = 1$. From these equations we obtain the equilibrium conventional prices given in Table 1 for the case with only the conventional crop, respectively when $L = 0$ and when $L = 1$. Solving the equilibrium conditions $\alpha^i < \alpha^g$ and $\theta^c < \theta^i$, we obtain $c_n > C1$ and $c_n < C3$ when $L = 0$, $c_n > C6$ and $c_n < C3'$ when $L = 1$.

An equilibrium with only IP arises when $\alpha^i \geq \alpha^g$, $\theta^c \geq \theta^i$ and either r or $e \neq 0$. The definition of equilibrium in ((a)-(c)) then implies that $\alpha^i = 1 - \theta^i$ and $Q_g = 0$. The equilibrium price of the IP good is the same whether $L = 0$ or 1 and is given in Table 1 for the case with only IP. Whatever the value of L, the equilibrium condition $\theta^i < 1$ is equivalent to $c_n < C5$. When $L = 0$, the conditions $\alpha^i \geq \alpha^g$ and $\theta^c \geq \theta^i$ are respectively equivalent to $p_c \leq \frac{1-ar}{2-ar}(1+c_n) - (1-e)(c_n - w)$ and $p_c \geq \frac{1-a}{2-ar}(1+c_n)$, therefore implying $c_n \leq C4$. When $L = 1$, these same conditions are respectively equivalent to $p_c \leq 1 + ec_n + (1-e)(t+w) - \frac{1+c_n}{2-ar}$ and $p_c \geq \frac{1-a}{2-ar}(1+c_n)$, therefore implying $c_n \leq C4'$.

Finally, when $\alpha^i < \alpha^g$ and $\theta^c \geq \theta^i$, equilibrium conditions ((a)-(c)) imply that $\alpha^g = 0$ and $\theta^i = 1$, therefore there is no production at all. When $\alpha^i > \alpha^g$ and $\theta^c < \theta^i$, equilibrium conditions ((a)-(c)) imply that $\widetilde{\theta} = \theta^c$, which is equivalent to $\theta^i = \theta^c$, and which is in contradiction with the condition $\theta^c < \theta^i$, therefore there is no equilibrium in this case.

A.2 Proof of Proposition 2

With *ex post* regulation, the area of coexistence is $A' = \int_0^{\frac{(1-e)(1-(w+t))}{1-er}} [C6 - C4']\, da$. The upper bound of the integral, $\frac{(1-e)(1-(w+t))}{1-er}$, is decreasing in t. In addition, we have that $\frac{\partial [C6-C4']}{\partial t} = -\frac{a(1-r)}{2(1-e)-a(1-er)}$, which is negative as long as $a < \frac{(1-e)(1-(w+t))}{1-er}$: the term inside the integral is also decreasing in t. Therefore, A' is decreasing in t and is at a maximum when $t = 0$.

A.3 Comparison between A and A'

We calculate that the area of coexistence is given by $A = BX$ in the absence of *ex post* regulation, and $A' = B'X'$ with *ex post* regulation, with

$$\begin{cases} B & = \frac{(1-e)(1-r)(e+r-er)}{2[1-e(1-(1-r)(e+r-er))]^2}, \\ B' & = \frac{(1-e)(1-r)}{2(1-er)^2}, \\ X' & = 3 - t^2 - 2t(1 + w + ln(4)) - \ln(16) - w(2 + w + \ln(16)) + 4(w + t + 1)\ln(w + t + 1), \\ X & = X' \mid_{t=0} > 0 \;\text{ for all }\; w \in [0, 1]. \end{cases}$$

When $t = 0$, $X = X'$ and therefore the comparison of the coexistence areas with and without *ex post* regulation is simply the comparison of B and B'. The comparison of these functions leads to the white and dark areas in Figure 4.

A simple analysis of the function B shows that $B_{|e=0} = \frac{r(1-r)}{2} > 0$, $B_{|e=1} = 0$, $\frac{\partial B}{\partial e}_{|e=0} = \frac{(1-r)(1-2(1-r)r^2)}{2} > 0$ and $\frac{\partial B}{\partial e}_{|e=1} = \frac{-1}{2(1-r)} < 0$. Therefore, the function B has a maximum in e on $(0, 1)$ for some $0 < e < 1$. We obtain that this maximum is unique and is shown by $e(r)$ in Figure 4.

We have that $\frac{\partial B'}{\partial e} \mid_{t=0} = \frac{-(1-r)(1-(2-e)r)}{2(1-er)^3}$. Therefore the function B' has a maximum $e'(r) = \begin{cases} 0 & \text{if } r \leq \frac{1}{2} \\ 2 - \frac{1}{r} & \text{if } r > \frac{1}{2} \end{cases}$.

Figure 4 shows that $e(r) \geq e'(r)$ for $0 \leq r < 1$.

A.4 Proof of Proposition 3

From Table 1, given that $L = e = 0$, p_c is identical in the GM equilibrium without any regulation and in the coexistence equilibrium with labeling only. The total quantity produced and consumed is unchanged. The difference in welfare levels with and without labeling is $W_{|e=0} - W^0c = \frac{(ar(1-r)+w-c_n)^2}{2ar^2(1-r)} > 0$. Since the conventional price and total quantity are unchanged, welfare effects on producers and consumers are straightforward.

A.5 Proof of Proposition 4

In the coexistence equilibrium without *ex post* regulation, the welfare is:

$$W = \frac{1}{2}\left[\frac{(1+ec_n+(1-e)w)^2}{2-a} + \frac{(1-e)^2(c_n-w)^2}{(1-r)a(e+r-er)^2} - ar - \frac{2\,c_n\,(1-e(1-r)(1-e))-2w(1-r)(1-e)^2}{e+r-er}\right].$$

We obtain: $\frac{\partial W}{\partial e}\mid_{e=0}= \underbrace{(c_n-w)}_{>0}\underbrace{\left[-1+\frac{1}{r^2}+\frac{1+w}{2-a}-\frac{c_n-w}{a(1-r)r^3}\right]}_{=Y}.$

Then, $\frac{\partial Y}{\partial w} > 0$, $\frac{\partial Y}{\partial c_n} < 0$, and $\frac{\partial Y}{\partial a} > 0$. Although a general result is impossible to establish for r, we obtain that $\lim\limits_{r\to 0} Y = -\infty$ and $\lim\limits_{r\to 1} Y = -\infty$. Numerical evaluation indicates that $Y > 0$ for intermediate values of r.

A.6 Study of the welfare W'

In the coexistence equilibrium with *ex post* regulation, the welfare is:

$$\begin{aligned} W' = \; & \frac{1}{2}\left[-ra + \frac{2w(1-e)^2(1-r)-2c_n(1-e(1-r)(1-e))}{e+r-er} + \frac{(1+ec_n+(1-e)w)^2-((1-e)t)^2}{2-a}\right. \\ & \left. + \frac{(1-e)^2(c_n-t-w)(c_n(2-e-r+er)+rt-w(2-r)+e(1-r)(t+w))}{(1-r)a(e+r-er)}\right]. \end{aligned}$$

We have: $\frac{\partial W'}{\partial t} = \frac{-(1-e)^2}{(2-a)a(1-r)(e+r-er)}\left[(2-a)(1-e)(1-r)(c_n-w)+(2-ar)(e+r-er)t\right] < 0$. Therefore, the optimal level of the per-unit tax on GM seeds (t) is zero.

From Table 1, given that $L = 1$ and $t = e = 0$, p_c is unchanged compared with the conventional price when there is no regulation at all. The total quantity is also unchanged.

The difference in welfare levels with and without labeling is:

$W'_{|e=0} - W^0c = \frac{[a(1-r)+w-c_n][ar(1-r)+(2-r)w-(2-r)c_n]}{2ar(1-r)} > 0$ since $c_n < \frac{ar(1-r)}{2-r} + w < a(1-r) + w = C1_{|e=0}$.

When $t = 0$, we have: $\frac{\partial W'(t=0)}{\partial e}\mid_{e=0}= \underbrace{\frac{(c_n-w)}{(2-a)a(1-r)r^2}}_{>0} Z$, with $Z = -2(c_n-w)(1+r-r^2) + a[2+c_n(1+r-r^2)-w(1+r(1-r)^2)-r(2+r-r^2)] - a^2(1-r)^2(1+r)$. Then, $\frac{\partial Z}{\partial w} > 0$, $\frac{\partial Z}{\partial c_n} < 0$, and $\frac{\partial Z}{\partial a} > 0$. In addition, we have that $Z = 0$ has a unique real solution in r, $\lim\limits_{r\to 0}\left(\frac{\partial W'(t=0)}{\partial e}\mid_{e=0}\right) = +\infty$, and $\lim\limits_{r\to 1}\left(\frac{\partial W'(t=0)}{\partial e}\mid_{e=0}\right) = -\infty$.

A.7 Proof of proposition 6

From Table 1, given that $t = 0$, p_c^* is identical in the coexistence equilibrium with *ex ante* regulation alone and in the coexistence equilibrium with *ex ante* and *ex post* regulations. The difference between IP prices in these two equilibria is $p_i'^* - p_i = -\frac{(1-e)^2(1-r)(c_n-w)}{e+r-er} < 0$. It follows that $\widetilde{\theta}' < \widetilde{\theta}$, therefore $Q_i^{d\prime} > Q_i^d$.

Welfare effects on producers and consumers are straightforward. The difference in welfare levels with and without *ex post* regulation is: $W' - W = -\frac{(1-e)^4(1-r)(c_n-w)^2}{2a(e+r-er)^2} < 0$. Therefore the cost to taxpayers has to be larger than the utility gain for consumers.

A.8 Proof of proposition 7

From Table 1, p_c^* is identical in the equilibrium with *ex ante* regulation alone and conventional production alone and in the equilibrium with *ex ante* and *ex post* regulations with coexistence, as long as $t = 0$. From the definition of α_g, total production is identical in both cases as long as $t = 0$.

From Figures 2 and 3, and given that $C4' = C4$ when $t = 0$, the coexistence area with *ex post* regulation is defined by $Max(C1, C4) < c_n < C6$ which implies $a < a^{max\prime} = \frac{(1-e)(1-w)}{1-er}$. The difference in welfare levels with and without *ex post* regulation is:

$$W' \mid_{t=0} - W_{\text{c only}} \\ = \frac{a^2(e(1-r)+r)(1-r)^2 - 2a(1-e)(1-r)(c_n-w) + (1-e)^2(2-e(1-r)-r)(c_n-w)^2}{2a(e(1-r)+r)(1-r)}.$$

The denominator is positive while the numerator is a second-order equation in c_n with roots $c_{n1} = \frac{a(1-r)(e+r-er)}{(1-e)(2-e-r+er)} + w \in (0, C6 \mid_{t=0})$ and $C6 \mid_{t=0}$, which is negative (res. positive) inside (resp. outside) these roots. We have that $C1 - c_{n1} = \frac{a(e+r-er)(1-r)^2}{2-(e+r-er)} > 0$, which implies that $c_{n1} < Max(C1, C4)$. Therefore $W' \mid_{t=0} < W_{\text{c only}}$ for any $c_n \in (Max(C1, C4), C6 \mid_{t=0})$.

A.9 Proof of proposition 8

We have that $p_i' \mid_{\text{i only}} = p_i \mid_{\text{coexistence}}$ (that is, from Table 1, $\frac{1-ar}{2-ar}(1 + c_n) = \frac{1-a}{2-a}(1 + ec_n + (1 - e)w) + \frac{(1-e)(c_n-w)}{1-(1-e)(1-r)}$), for a unique value of c_n that we denote as c_{n1} (which is complicated and is not reproduced here). In the same way, we have that $p_i' \mid_{\text{i only}} = p_c \mid_{\text{coexistence}}$ for a unique value of c_n that we denote as c_{n2}. Also, we have that $\alpha_i' \mid_{\text{i only}} = \alpha_g \mid_{\text{coexistence}}$ if and only if $c_n = C4$. We obtain that as long as $w > 0$, $r \in (0, 1)$, $e \in (0, 1)$ and $a \in (0, a^{max})$, necessarily we have that $c_{n1} < C2$ and $c_{n2} < C2$. Therefore, the signs of $p_i' \mid_{\text{i only}} - p_i \mid_{\text{coexistence}}$, $p_i' \mid_{\text{i only}} - p_c \mid_{\text{coexistence}}$ and $\alpha_i' \mid_{\text{i only}} - \alpha_g \mid_{\text{coexistence}}$ do not change on the interval $c_n \in (C2, Min(C1, C4))$. Moreover, for $c_n = C2$, we find that the first price difference is negative, while the second and third ones are positive. Therefore, whatever $c_n \in (C2, Min(C1, C4))$, it has to be that $p_c \mid_{\text{coexistence}} < p_i' \mid_{\text{i only}} < p_i \mid_{\text{coexistence}}$ and $\alpha_i' \mid_{\text{i only}} > \alpha_g \mid_{\text{coexistence}}$.

All former consumers of the IP good necessarily win from the decrease in the IP price. Given that total consumption increases, all former conventional consumers turn to the IP good. Their individual utility changes from $\theta(1-a) - p_c \mid_{\text{coexistence}}$ to $\theta(1-ar) - p_i' \mid_{\text{i only}}$. Therefore, their individual utility increases if and only if $\theta > \frac{p_i'|_{\text{i only}} - p_c|_{\text{coexistence}}}{a(1-r)}$. Using *Reduce* in Mathematica, we find that this inequality is checked for $\theta = \theta_c$, that is for the former conventional consumer characterized by the smallest θ. Therefore it has to be true for all former conventional consumers; that is, all former conventional consumers gain. Finally, all consumers who move from consuming nothing to consuming the IP good gain. Therefore, all consumers gain. Since total production increases, total producer profit increases too. Therefore total welfare increases.

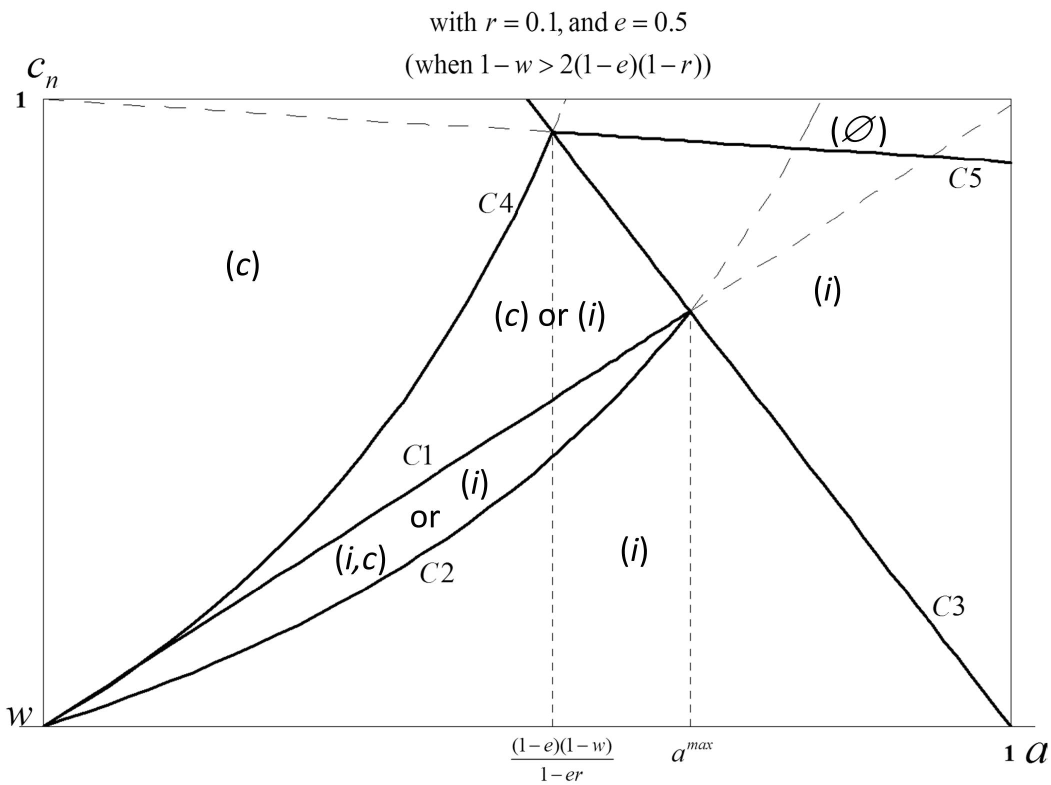

Figure 1: Equilibrium diagram with *ex ante* regulation

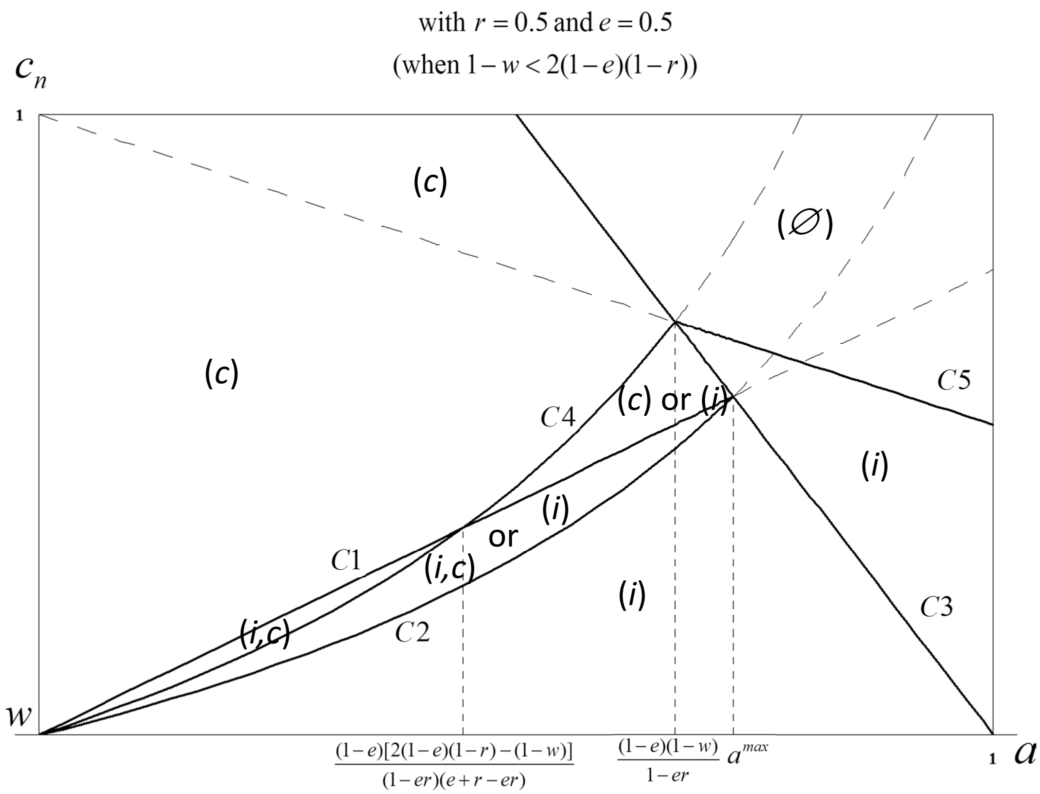

Figure 2: Equilibrium diagram with *ex ante* regulation

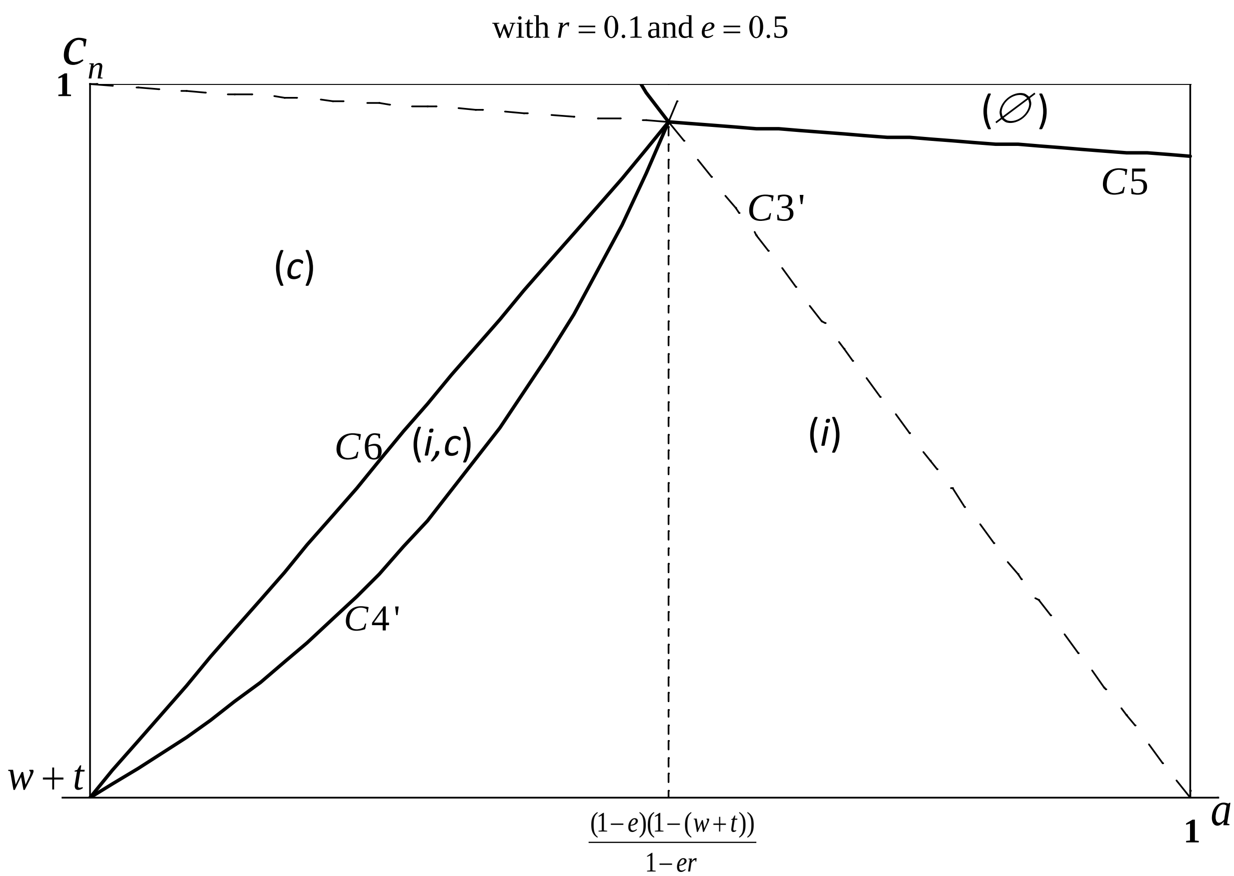

Figure 3: Equilibrium diagram with *ex ante* and *ex post* regulations

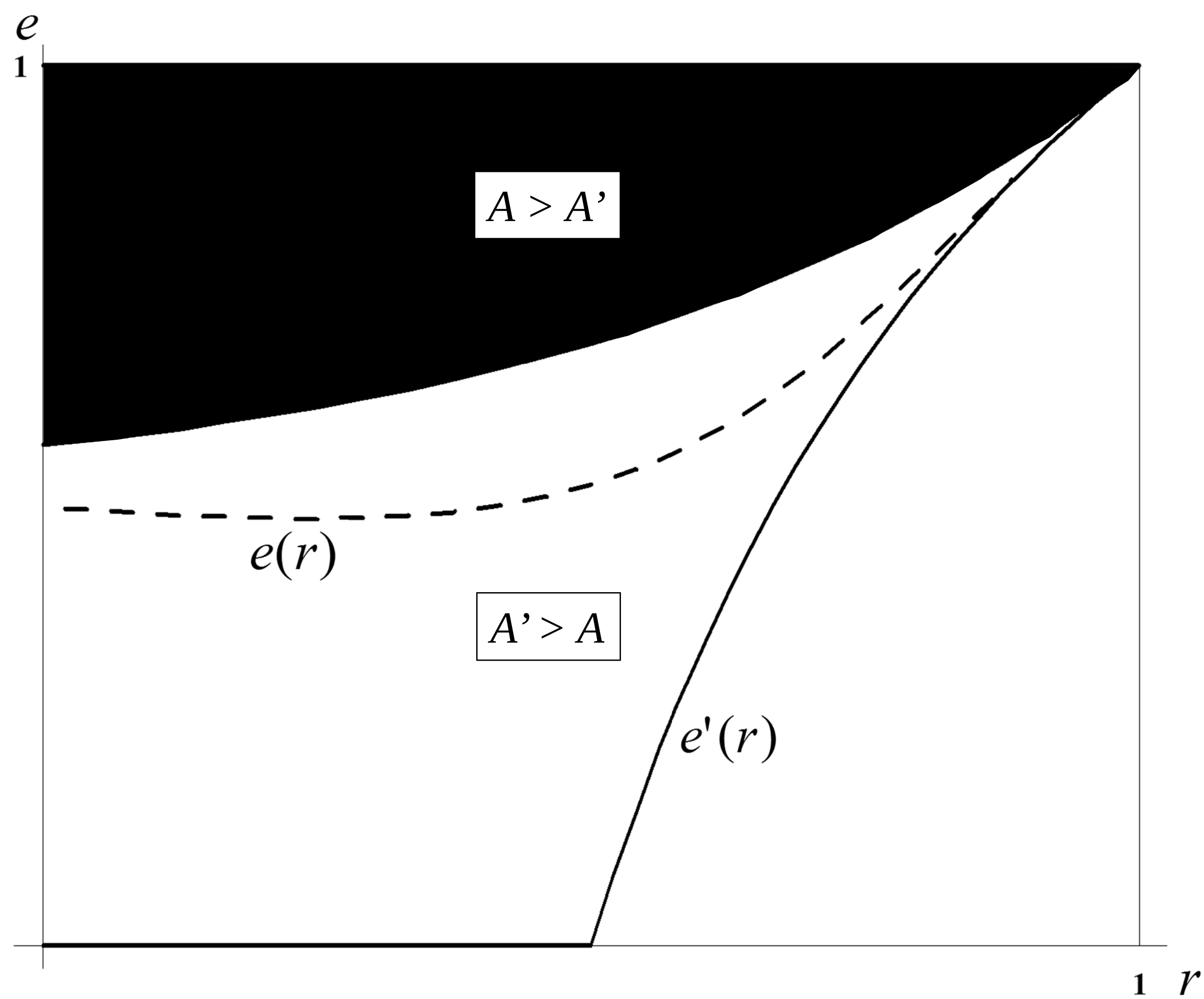

Figure 4: Diagram of areas comparison