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) and non-GM coexistence regulations on market and welfare outcomes. We assume vertical differentiation of GM and non-GM goods on the consumer side. 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, with a compensation fund financed by GMO producers and/or the state. Assuming endogenous crop choices and prices, we study the effects of *ex ante* regulation and *ex post* liability on for outcomes: market equilibrium, the achievement of coexistence, and 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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*Corresponding author. Toulouse School of Economics (GREMAQ, INRA). Manufacture des Tabacs, 21 allée de Brienne, 31015 Toulouse cedex 6 - France. Marion.Desquilbet@toulouse.inra.fr. Phone: (00) 33 5 61 12 85 78. Fax: (00) 33 5 61 22 55 63.

†INRA, UR1303 ALISS, 94205 Ivry-sur-Seine, France. Department of Economics, Ecole Polytechnique, 91128 Palaiseau, France. Sylvaine.Poret@ivry.inra.fr.

‡Senior authorship not implied.

1 Introduction

The introduction of genetically modified organisms (GMOs) into the agri-food system has sparked controversy. 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, consumers and 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 different across countries and, as a consequence, current GMO regulations vary greatly. Notably, the main countries where GMOs are produced, like the United States, Argentina, Brazil, Canada or India, have developed neither mandatory labeling of GMOs nor a specific legislation addressing coexistence issues. 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). The implementation of this regulation 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 provides consumers with information, although this information is incomplete and restricted to the specific labeling requirements defined in this legislation. 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 GMO presence in non-GM crops. 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, in order to limit gene flows from GM fields to neighboring non-GM fields. 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: 90% of *Bt* maize production takes place in Spain where no specific legislation addressing coexistence issues is yet in place, while the remainder of production takes place in Portugal, Czech Republic, Poland, Slovakia and Romania. 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). In Portugal, where coexistence regulations have already been put into practice, authorities 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. The Portuguese case should be extrapolated with caution, however, as the current adoption rate of Bt maize in Portugal is only 4 % (with a higher adoption in some regions, up to 20 %) (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. In a situation where consumers have a higher valuation for non-GM products, only gene flows from GM crops to non-GM crops can generate economic losses. This makes the risk unilateral: the cultivation of GM crops creates a negative externality on non-GMO producers, because their harvest may be downgraded if GMO commingling occurs at levels above the labeling threshold. Non-GMO commingling in GM crops, on the other hand, has no economic impact.

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.[1] Less attention has been paid to 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; Hiriart et al., 2004). These models share three common features. First, each party causing harm may be held individually liable *ex post*. The threat of suit causes each potential injurer to internalize the expected social damages and therefore to undertake a positive level of care *ex ante*. Second, these models consider non-market externalities. Third, these models assume unilateral

[1] See Shavell (1984a) for a discussion of 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.

accident: no decisions are made by potential victims and only potential injurers can take precaution to reduce the probability of causing an accident.

The context of GM / non-GM coexistence regulation is different for three reasons. First, the externality is a form of non-point source pollution. Since it is technically impossible to trace the admixture created by gene flow to a definite source, it is not possible to hold each party individually liable for the harm it has caused. Second, the externality created by GM gene flow 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. Third, gene flow is a case of bilateral accident: both the non-GM and GM producers may influence the probability or the magnitude of admixture through their choice of care levels. Therefore, the results of the law and economic literature cannot be directly transposed to the case of GM / non GM coexistence.

In this coexistence case, because it is possible that the perpetrators could avoid facing a suit for harm done, we can expect that tort liability alone is not adapted and that *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 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. However, 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 optimal combination of *ex ante* and *ex post* regulations to impose on GMO producers in order to reduce their harm, taking into account market effects. Throughout the paper, we also maintain the assumption that it is impossible to hold each GMO producer individually liable for the harm he or she causes (circumstances in which the law can relax causation requirements are discussed in the conclusion). Furthermore, our model would not be tractable if we allowed that both GMO and non-GMO farmers may undertake actions to reduce gene flow. We make the simplifying assumption that the accident is unilateral and that non-GMO producers do not undertake activities of their own, for example isolation distances in their fields, to reduce gene flow. Our model is in accordance with the EU regulations on coexistence, where property rights are mainly assigned to non-GMO producers at the farm stage, in the sense that GMO farmers are responsible for ensuring the GM-free status of non-GMO farmers or compensate them otherwise, as discussed in Beckmann et al., 2011. These authors, as well as Ceddia et al. (2011), study the alternative cases where only GMO farmers or only non-GMO farmers take measures to reduce gene flow, but do not study the case where both types of farmers take such measures simultaneously; in addition, both papers assume that market prices are exogenous.

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 IP producers bear all the costs of segregation and identity preservation activities necessary to keep the GMO content of their product below the regulatory threshold. In these models, no *ex ante* or *ex post* coexistence regulations are in place to mitigate the negative externality exerted by GMO producers (Lapan and Moschini, 2004; Fulton and Giannakas, 2004; Moschini et al., 2005; Lapan and Moschini, 2007). Desquilbet and Bullock (2009) assume that the existence of the IP sector also imposes externality costs on GMO producers, because they lose flexibility in producing, moving and storing grain. But these authors do not model coexistence regulations either. Munro (2008) discusses policy options to restore efficiency, using a stylized market model of GM and non-GM crops in which GMO producers exert a negative spatial 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 regulations. Demont et al. (2008) argue that mandatory isolation distances may be overly stringent. If a farmer willing to adopt GMOs has a neighbor wishing to grow the non-GM crop, this farmer may prefer cultivate the non-GM crop rather than to implement an isolation distance in its own field. This farmer's decision may, in turn, deter another neighbor from adopting GMOs, in a similar fashion. The authors refer to this phenomenon as a "domino effect". Demont et al. (2009) 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 low or non-existent. 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. Demont et al. (2010) argue that their 2009 article aims at analyzing the flexibility of spatial *ex ante* coexistence regulations and that market effects can be kept exogenous in this analysis. Gray et al. (2011) devise a model to endogenously determine the efficient width of pollen barriers depending on actual gene flows and whether the pollen barrier is implemented in the GM or the non-GM field. As shown by Groeneveld et al. (2012), coordination of land use allocations is another means to attain flexibility in coexistence rules and to reduce the impact of minimum distance requirements. The analysis in these last two papers is also conducted with exogenous market prices. Another way to reduce the burden of coexistence regulations is for neighboring farmers to coordinate their crop locations so as to minimize the risk of gene flow. This approach studied by Furtan et al. (2007) in the case where non-GM producers are responsible for ensuring the non-GM status of their crop.

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. These assumptions only hold for currently commercialized GMOs that are mainly insect-resistant or herbicide-tolerant crops; a different model set-up would be required to analyze GMOs in the commercial pipeline, such as those with altered nutritional composition. To keep our model analytically tractable, we do not model the organic sector. Analyzing the effects of GMO introduction in a market that is already differentiated between conventional and organic products would be more consistent with the EU regulatory framework on coexistence. Moschini et al. (2005) introduce this more realistic feature in their model but then resort to simulations in their analysis.

We develop a non-spatial, stylized model where *ex ante* coexistence regulations impose buffer zones 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). In our model, GMO farmers are willing to plant a non-GM buffer zone at the border of their GM field, and therefore no domino effect occurs. Moreover, we do not allow coordination between farmers. We also assume that non-GMO farmers do not take any measures to prevent GMO commingling caused by gene flow. These producers face a probability of harvest downgrading that decreases with both the *ex ante* regulation level (larger buffer zones diminish admixture risks) and the regulatory tolerance threshold for GMO content in non-GM products. We assume that when *ex post* regulations are 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 primary 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 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 regular (indexed by r). 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. We concentrate on the agricultural stage, which is the target of EU coexistence regulations, and assume that no additional commingling occurs at the handling and processing stages.[2]

[2]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).

2.1 Consumers

As in Fulton and Giannakas (2004) and Lapan and Moschini (2007), we model the regular 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 in 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 their 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). The simplifications we adopt in this article 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 regular good (r), or one unit of the IP good (i), or nothing. The quality of the IP good is normalized to 1. Consuming the regular product results in a discount in quality $a \in (0, 1)$ (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. Then, the utility of the consumer with a willingness to pay for quality θ is given by:

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

where p_i is the per-unit grain price of the IP good and p_r is the per-unit grain price of the regular good.

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

$$\begin{cases} \theta^r & = \frac{p_r}{1-a}, \\ \theta^i & = p_i, \\ \widetilde{\theta} & = \frac{p_i - p_r}{a}. \end{cases} \tag{2}$$

Consumers of the regular good are characterized by $\theta > \theta^r$ and $\theta < \widetilde{\theta}$ (they obtain a positive utility from consuming the regular good, and a higher utility from consuming the regular good rather than the IP good). Consumers of the IP good are characterized by $\theta > \theta^i$ and $\theta > \widetilde{\theta}$ (they obtain a positive utility from consuming the IP good, and a higher utility from consuming the IP good rather than the regular good). Immediate calculations show that the threshold values of θ must verify $\theta^r < \theta^i < \widetilde{\theta}$, or $\theta^r = \theta^i = \widetilde{\theta}$, or $\widetilde{\theta} < \theta^i < \theta^r$. Omitting the argument a, our utility functions imply the following demand functions:[3]

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

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

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 crop, which differ depending on land quality. We assume that all producers face an additional cost $v \in (0, 1]$ when they produce the non-GM crop (for which total per-unit production costs are therefore $\alpha + v$). Yield is identical for the two grain types n and g and is normalized to one.[4] The profit obtained if neither the regular nor the IP crop is grown is normalized to zero.

In the absence of gene flows and coexistence regulation, per-unit profit functions are $p_r - \alpha$ for GMO producers and $p_i - \alpha - v$ 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.

[3]Given that θ is distributed uniformly between 0 and 1, as long as the threshold values $\widetilde{\theta}$, θ^r and θ^i are between 0 and 1, demand functions for the regular and the IP good are respectively $\widetilde{\theta} - \theta^r$ and $1 - \widetilde{\theta}$ when $\theta^r < \theta^i < \widetilde{\theta}$, 0 and $1 - \theta^i$ when $\widetilde{\theta} \leq \theta^i \leq \theta^r$. From their definitions, θ^r and θ^i are higher than 0. $\widetilde{\theta}$ appears in these demand functions only when $\theta^r < \theta^i < \widetilde{\theta}$, in which case it also has to be higher than 0. However, the three thresholds values may be higher than 1. Equations (3) and (4) take such possible cases into account. (For example, when $\widetilde{\theta} \leq \theta^i \leq \theta^r$, consumers of the IP good are characterized by $\theta^i < \theta$ and $0 \leq \theta \leq 1$. If $\theta^i > 1$, there is no demand for the IP good, which is what we obtain in equation (4) given that $\min(\theta^i, 1) = 1$ in this case).

[4]With higher yields for GM crops, the welfare-enhancing effect of GMO adoption would be stronger and coexistence regulations imposing a burden on GMO producers would be less likely to improve welfare.

2.2.2 Coexistence regulations

Non-GMO producers sell their harvest as IP, at price p_i, if its GMO content is below the regulatory threshold. Otherwise, their production is downgraded; that is, sold as regular at price p_r. In the absence of regulation, we assume that a proportion $0 \leq h_0 \leq 1$ of the IP crop is downgraded. There is no coexistence issue if $h_0 = 0$, that is, if the GMO content of non-GM crops is always below the regulatory threshold, even in the absence of any measures to limit gene flow. When $h_0 > 0$, an *ex ante* coexistence regulation mandates each GMO producer to undertake a level of effort $e \in [0, h_0]$ to reduce the gene flow towards non-GM crops. This level of effort represents the proportion of his or her land that must be planted with the non-GM variety and mixed with the GM production for sale as regular. This formulation captures in a stylized fashion *ex ante* regulations such as buffer zones, which prevent GMO producers from growing GMOs too close to non-GM fields.[5] For simplicity, we assume that the cost of effort for GMO farmers is solely the additional cost of the non-GM crop, v, on the proportion of land e planted with the non-GM variety, and that GMO farmers comply perfectly with the mandatory effort without costly enforcement. We discuss in the conclusion how relaxing this assumption would affect our results.

Noting the aggregate production of the GM good as Q_g, we model the probability of downgrading as a decreasing function of the effort undertaken by GMO producers:

$$h(e, Q_g) = (h_0 - e)Ind(Q_g), \tag{5}$$

where $Ind(Q_g)$ is an indicator function equal to zero if $Q_g = 0$, and equal to 1 otherwise.[6]

The functional form of $h(.)$, chosen for its simplicity, verifies several intuitive properties. First, the probability of downgrading is decreasing in the level of *ex ante* regulation, e. The higher this level, the lower the amount of GM gene flow towards non-GM fields. Second, none of the non-GM production is downgraded when the effort of GMO producers is maximal ($h(h_0, Q_g) = 0$). We assume that non-GMO producers do not undertake any effort on their own to reduce the probability

[5] 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 vary, making the proportion of land affected by the *ex ante* regulation heterogenous across producers. We abstract from these considerations for simplicity.

[6] 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.

of downgrading in their fields. They could, in fact, affect this probability. Separate harvesting of different field areas is one way this might be achieved: farmers could harvest and deliver the border rows of their fields as a regular crop, while dedicating the interior of their fields, less susceptible to gene flows from outside, to an IP supply channel. Allowing non-GMO farmers to undertake such activities would make the derivation of endogenous market effects excessively cumbersome.

The government may also implement an *ex post* regulation by setting up a compensation fund that exactly compensates the profit losses incurred by non-GMO producers if their production gets downgraded. We define this *ex post* regulation by an indicator function:

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

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

To keep the model as simple as possible, we do not account for administrative costs of setting up and managing the compensation fund. Such costs lower welfare when the compensation fund is in place. We assume, as well, that the only economic loss suffered by IP producers in the event of a product downgrade is the price difference between the IP good and the regular good. Downgrading may in fact entail additional costs for IP producers, such as the loss of an outlet, possible breach of contract, and the costs associated with finding a new outlet for the downgraded product. Accounting for such costs would increase the losses resulting from downgrading, and the benefits of avoiding downgrading through *ex ante* regulation would therefore be higher. Several countries in the European Union have set up, or envisage setting up, compensation funds or more complex schemes of ex post regulation. The compensation funds are financed either by GMO producers, through private liability insurance or through taxation, or by the state (Koch, 2012). Alternative schemes are designed to relax the normal causation requirements of a direct and definite link between the damage and the defendant, thus making it possible for several neighboring GMO farmers to be jointly liable for incurred losses in a non-GM field. These forms of ex post regulation are not modeled here and are discussed in the conclusion.

Beyond the farm stage, coexistence regulations no longer apply, therefore costly segregation and identity preservation actions have to be undertaken in order to maintain the integrity of IP products throughout the supply chain (Lapan and Moschini, 2004; Fulton and Giannakas, 2004; Moschini et al., 2005; Desquilbet and Bullock, 2009). Because this is not the topic of our paper, for simplicity reasons we do not model the related costs. We discuss the effects of introducing a positive unit cost of identity preservation in the conclusion.

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 e (*ex ante* regulatory effort imposed on GMO producers), L (*ex post* liability of GMO producers) and t (GM seed tax), omitting the argument v, the per-unit profit functions take the form:

$$\begin{aligned}
\pi^g(p_r, e, L, t; \alpha) &= p_r - ev - (1-e)Lt - \alpha = \alpha^g - \alpha, \\
\pi^i(p_r, p_i, Q_g, e, L; \alpha) &= p_i - v - (1-L)(p_i - p_r)h(e, Q_g) - \alpha = \alpha^i - \alpha
\end{aligned}$$

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. In this case, all producers with $\alpha \leq \alpha_i$ grow the IP crop, the GM good is not produced and there is neither coexistence nor downgrading. On the contrary, when $\alpha^i < \alpha^g$, the IP good is not produced, there is no coexistence and all producers with $\alpha \leq \alpha_g$ are GMO producers. Due to the *ex ante* regulation, a proportion $1-e$ of their production is GM while a proportion e is non-GM; however, all this production is sold as regular and there is no coexistence. All producers obtain the same profit from i and g when $\alpha^i = \alpha^g$. In this case, all producers with $\alpha \leq \alpha_g$ produce and are indifferent between growing the GM crop or the IP crop and coexistence will occur as long as there is a positive demand for both goods in equilibrium. In this case, individual supply functions cannot be defined for the regular and the IP good and only an aggregate supply function can be defined. Moreover, because a proportion h of IP production gets downgraded, the proportion of production accounted for by the IP good must be less than $(1-h)$ of the total production (while the regular good must account for least h of the total production). Let Q_s^g, Q_s^n and Q_s^i denote quantities supplied of goods g, n

and i. Omitting the argument v, the conditions above imply the following supply correspondence:

$$
\begin{aligned}
&S(p_r, p_i, Q_g, e, L, t) \equiv (S^g(p_r, p_i, Q_g, e, L, t), S^n(p_r, p_i, Q_g, e, L, t), S^i(p_r, p_i, Q_g, e, L, t)) \\
&= (Q_s^g, Q_s^n, Q_s^i) : \\
&\text{when } \alpha^i < \alpha^g, \begin{cases} Q_s^g = (1-e)\max(\alpha_g, 0), \\ Q_s^n = e\max(\alpha_g, 0), \\ Q_s^i = 0. \end{cases} \\
&\text{when } \alpha^i > \alpha^g, \begin{cases} Q_s^g = 0, \\ Q_s^n = 0, \\ Q_s^i = \max(\alpha_i, 0). \end{cases} \\
&\text{when } \alpha^i = \alpha^g, \begin{cases} Q_s^g + Q_s^n + Q_s^i = \max(\alpha_g, 0) \\ Q_s^g + Q_s^n \in (h(e, Q_g)(Q_s^g + Q_s^n + Q_i^s), Q_s^g + Q_s^n + Q_s^i), \\ Q_s^i \in (0, (1 - h(e, Q_g))(Q_s^g + Q_s^n + Q_s^i)). \end{cases}
\end{aligned}
\tag{6}
$$

2.3 Definition of equilibrium and benchmark cases

Given the model parameters a and v and given the policy instruments e, L, t, we have that p_r, p_i, $Q_g \in R_+^3$ is an *equilibrium* if: (a) $Q_g = Q_s^g$ (the production of the GM good in the downgrading function is equal to the quantity supplied of the GM good), (b) $(Q_s^g, Q_s^n, Q_s^i) \in S(p_r, p_i, Q_g, e, L, t)$ (each producer maximizes profits), (c) $Q_s^g + Q_s^n = D^r(p_r, p_i, s)$, and $Q_i^r = D^i(p_r, p_i, s)$ (each consumer maximizes utility and markets clear).

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 $\frac{h}{1-h}(1-\widetilde{\theta})$ of that total is downgraded. Given that $h = h_0 - e$, this downgraded production is:

$$Q_d = \frac{(h_0 - e)(1 - \widetilde{\theta})}{1 + e - h_0}. \tag{7}$$

The unit profit loss on this downgraded production is equal to the price difference $p_i - p_r$. Therefore, under coexistence, the total economic damage caused by downgrading is:

$$D = Q_d(p_i - p_r). \tag{8}$$

Maintaining the assumption of coexistence, the quantity of regular product consumed is $\widetilde{\theta} - \theta^r$. Since Q_d of this quantity is accounted for by the downgraded production of IP producers, the production of GMO producers must account for the remaining $\widetilde{\theta} - \theta^r - Q_d$. A proportion $(1-e)$ of this production is sown with GM seeds. As a result, the revenue from the GM seed tax is:

$$T = \left(\widetilde{\theta} - \theta^r - Q_d\right)(1-e)t. \tag{9}$$

Finally, it is useful to consider a benchmark case where GMOs are introduced without labeling and without coexistence regulations ($e = L = 0$). This benchmark is derived from a simplified version of the model. The GM and non-GM goods provide per-unit profits $\pi^g = p_r - \alpha$ and $\pi^i = p_i - v - \alpha$ respectively, while consumers demand only the cheapest product, with $D(p) = 1 - \frac{p}{1-a}$. In this situation, only the GM good is produced and consumed, and the equilibrium price is $p^0 = \frac{1-a}{2-a}$. The equilibrium quantity is $Q^0 = \frac{1}{2-a}$ and welfare is $W^0 = \int_0^{p_r^1}(p_r^0 - \alpha)d\alpha + \int_{1-p_r^0}^1(\theta(1-a) - p_r^0)d\theta = \frac{(1-a)^2}{2(2-a)}$.

3 The effects of coexistence regulations

In what follows we examine three possible forms of regulation: a labeling policy, *ex ante* regulation, and *ex post* liability.

3.1 Equilibrium characterization

Whether both, neither, or only one of the two types of goods is produced and consumed in equilibrium depends on the values of the supply and demand parameters (v and a) and on the policy instruments characterizing the *ex ante* and *ex post* regulations (e, L and t). Tables 1 and 2 below summarize the equilibrium prices in each type of equilibrium and the conditions under which each type of equilibrium may emerge, considering either *ex ante* regulation only (Table 1), or both *ex ante* and *ex post* regulations (Table 2) (the proof is given in Appendix A.1).[7]

[Insert Table 1]

[7] 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 buffer zones, or the non-GM IP good which is subject to some downgrading. Consumers characterized by $\theta^r \leq \theta \leq \widetilde{\theta}$ consume the regular good, while consumers characterized by $\theta > \widetilde{\theta}$ consume the IP good. In an equilibrium with only the regular 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 $\theta \geq \theta^r$ consume the regular 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 $\theta \geq \theta^i$.

[Insert Table 2]

Figure 1 illustrates the configuration of equilibrium domains when only *ex ante* regulation is in place. Areas with only regular production (r) and with coexistence (c) are separated by their common frontier v_2. The equilibrium with only the regular crop appears when consumers' aversion to GM products (a) is low and the additional cost of the non-GM crop (v) is high. As a rises and v falls, the equilibrium changes: first to coexistence, then to exclusively IP cultivation. For some parameter values, equilibria with both crops or with only regular cultivation coexist with an equilibrium with IP cultivation alone. These multiple equilibria arise because the profit obtained from IP cultivation depends on the presence of GMOs in other farmers' fields. With only ex ante regulation in place, IP producers are not compensated in the event of any downgrading.[8]

[Insert Figure 1]

With both *ex ante* and *ex post* regulations (Figure 2), IP producers are fully compensated for any crop downgrading they face. GMO producers, on the other hand, face the same regulations whether or not IP crops are actually cultivated. Starting from an equilibrium with regular cultivation alone, an increase in a and/or a decrease in v shifts the equilibrium towards coexistence, and then to IP-only cultivation. No stable equilibrium emerges between curves v_5 and v_7, because of the discontinuity in the downgrading of IP crops. The curve v_5 represents the limit equilibrium in which an infinitesimal amount of the GM crop is produced, resulting in the downgrade of a proportion h of the IP production. The curve v_7 is the limit equilibrium in which all producers are indifferent between GM or IP production, but there is no demand for the regular crop, and therefore all producers produce the IP crop.[9] Under both *ex ante* and *ex post* regulations no multiple equilibria emerge, because unit profit functions do not depend on the specific equilibrium.[10] *Ex post* regulation (which compensates IP producers for the profit losses caused by crop downgrading) favors IP production; the area with regular-only production is therefore smaller, and the area

[8]More precisely, the unit profit π_i is written $p_i - v - (p_i - p_r)(h_0 - e) - \alpha$ if GMOs are cultivated, and $p_i - v - \alpha$ if they are not, which allows for multiple equilibria.

[9]This area with no stable equilibrium would disappear if we assumed that downgrading was a function of the proportion of GM production, and not only of the presence or absence of this production. Such an assumption, however realistic, would prevent us from solving the model analytically.

[10]More precisely, the unit profit π_i is written $p_i - v - \alpha$ whether or not GMOs are cultivated, and the unit profit π_g is written $p_r - ev - (1 - e)t - \alpha$ whether or not IP crops are cultivated (in our model GMO producers have to implement the buffer zone e and to pay the tax t regardless of whether IP crops are actually cultivated).

of IP-only cultivation is larger, under joint *ex ante* and *ex post* regulations (Figure 2) compared with the case employing *ex ante* regulation alone (Figure 1).

[Insert Figure 2]

3.2 Coexistence regulations and the emergence of coexistence

We now analyze how changes in the 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 (EC, 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 (v and a), and of the parameter characterizing downgrading (h_0), 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 may remain a coexistence equilibrium, change to an unstable equilibrium or change to an equilibrium with only IP. A former equilibrium with only the regular crop may remain an equilibrium with only the regular crop or change to a coexistence equilibrium.

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

Proof. See Appendix A.2. □

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 causing the GM good to 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 in the literature, 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 is not an indicator that a policy favoring coexistence is not desirable.

To provide further insight on coexistence equilibria, we now study the quantity of each type of good consumed and the quantity of IP production downgraded in these equilibria, depending on the regulations in place. Table 3 summarizes the total quantities marketed in equilibrium (Q and Q'), as well as IP consumption (Q_i and Q'_i), regular consumption (Q_r and Q'_r), and IP downgrading (Q_d and Q'_d), under *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 3]

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 total consumption is lower (or equal when $t = 0$) ($Q' \leq Q$). This implies that regular consumption is also lower when both regulations are implemented ($Q'_r < Q_r$). The quantity of IP downgraded is necessarily higher under the combined regulations ($Q'_d > Q_d$), because *ex post* regulation encourages IP production, of which a fixed proportion is downgraded.

When the level of technical standards (e) increases, under either one or both coexistence regulations, IP consumption increases while regular consumption and total consumption decrease. This results from higher production costs for GM producers, as well as lower downgrading costs for IP producers with *ex ante* regulation alone. When the parameter h_0 (which characterizes the proportion of downgrading) increases, the total equilibrium quantity is unchanged. When only *ex ante* regulation is in place, an increase in h0 decreases revenues of IP producers, causing the IP equilibrium quantity to decrease and the regular quantity to increase. With both regulations in place, IP producers are compensated for losses due to downgrading, and an increase in h0 does not affect the equilibrium quantities of the IP and the regular good.

The more complex effects of an increase in e or h_0 on IP downgrading are detailed in the following equations. The equivalent holds in the mixed policy condition, with variables Q'_d and Q'_i

in place of Q_d and Q_i.

$$\frac{\partial Q_d}{\partial e} = \frac{h_0}{1 - h_0(1-e)} \left[\underbrace{-\frac{Q_i}{1 - h_0(1-e)}}_{\text{direct effect}} + \underbrace{(1-e)\frac{\partial Q_i}{\partial e}}_{\text{supply effect}} \right], \tag{10}$$

$$\frac{\partial Q_d}{\partial h_0} = \frac{1-e}{1 - h_0(1-e)} \left[\underbrace{\frac{Q_i}{1 - (1-e)h_0}}_{\text{direct effect}} + \underbrace{h_0 \frac{\partial Q_i}{\partial h_0}}_{\text{effect on } Q_i} \right]. \tag{11}$$

An increase in e results in a reduction in the proportion of downgrading (negative direct effect) and an increase of the supply of IP producers (indirect positive supply effect). The direct effect dominates the indirect supply effect when v is sufficiently low, that is, when the IP production level is sufficiently high. In this case, an increase in e results in a decrease in IP downgraded production. When v is high, a increase in e increases the amount of IP production that is downgraded.

With both *ex ante* and *ex post* regulations in place, an increase in h_0 only has the direct effect of increasing the proportion of downgrading: the quantity of IP production which is downgraded increases, with no effect on the level of IP production. With *ex ante* regulation alone, an increase in h_0 discourages IP production (negative indirect effect on Q_i), which counterbalances the positive direct effect. The positive direct effect dominates the negative indirect supply effect when v is sufficiently low, that is, when the IP production level is sufficiently high. In this case, an increase in h_0 has the same effect as it does under a mixed policy, that is, increasing the amount of IP production that is downgraded. When v is high, a increase in h_0 results in a decrease in the amount of IP production which is downgraded.

3.3 Market and welfare effects

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

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

Proposition 2 below details the effects of labeling on total welfare, absent any coexistence regulation. In other words, it compares the equilibrium without *ex ante* or *ex post* regulation ($e = L = 0$) to the benchmark equilibrium in which GMOs are introduced without labeling. When labeling allows the emergence of coexistence, it induces an increase in welfare by increasing the utility of consumers who turn to the IP good.

Proposition 2. *Absent any coexistence regulation ($e = L = t = 0$), the introduction of labeling, when it allows the emergence of coexistence, has no effect on any of the following: the price of the regular good, total production and consumption, producers' profits and the utility of consumers who consume the regular good both in the presence and the absence of labeling. The utility of consumers who consume the regular good in the absence of labeling and the (more expensive) IP good in the presence of labeling increases, and total welfare increases.*

Proof. See Appendix A.3. □

Market and welfare effects of *ex ante* regulation are summarized in Proposition 3 below.

Proposition 3. *In a coexistence equilibrium without ex post regulation, an increase in the level of ex ante regulation causes the price of the regular good to increase and the price of the IP good to decrease. Regular consumption decreases and IP consumption increases, resulting in a decrease in total (regular + IP) consumption. Consumers of the regular good and producers are hurt, while consumers of the IP good are better off. There exists $\tilde{v}$ such that the introduction of a low level of ex ante regulation is welfare-increasing if and only if $v_1 < v < \tilde{v}$, with $\tilde{v} \in (v_1, v_2)$ for $e = 0$.*

Proof. See Appendix A.4. □

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 buffer zones sown with non-GM seeds, decreasing their profitability while leaving their total production of regular 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 regular production decreases while IP production increases (total production remains unchanged). As a second effect, these changes tend to raise the price of the regular good and lower the price of the IP good, thereby increasing the profitability of the regular 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. This welfare-increasing effect arises when v is sufficiently low, that is, when IP consumption is sufficiently large compared to regular consumption.[11]

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 any downgrading they suffer is D (Equation (8)), of which T (Equation (9)) is paid by the GM seed tax revenue and $D - T$ by taxpayers. In a coexistence equilibrium aggregate welfare is given by:

$$W' = \int_0^{\alpha^g} (\alpha^g - \alpha) d\alpha + \int_{\theta^r}^{\widetilde{\theta}} (\theta(1-a) - p_r) d\theta + \int_{\widetilde{\theta}}^{1} (\theta - p_i) d\theta - D + T.$$

Proposition 4 below summarizes market and welfare effects in this case.

Proposition 4. *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 price of the regular good and a decrease in the price of the IP good. Producers' profits and regular consumers' utility decrease, while IP consumers' utility increases. The total production level decreases, with a decrease in the regular quantity and an increase in the IP quantity. 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 ($t = 0$). There exist $\tilde{v}'_1$ and $\tilde{v}'_2$ such that, absent ex ante regulation, the introduction of labeling is welfare-increasing if and only if $v_{5|e=t=0} < v$ and $v < \tilde{v}'_1$, and the introduction of a low level of ex ante regulation is welfare-increasing if and only if $v_{5|e=t=0} < v$ and $v < \tilde{v}'_2$ (where $\tilde{v}'_i$ may be higher or lower than $v_{5|e=t=0}$ and $\tilde{v}'_i \in (0, v_{6|e=t=0})$, $i = 1, 2$).

Proof. See Appendix A.5. □

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. Transferring part of this payment to GMO producers through a GM seed tax introduces a market distortion that impacts welfare negatively.

Compared with an unregulated equilibrium, the introduction of labeling and of *ex post* liability funded entirely by taxpayers may increase total welfare when the enforced regulations allow coexistence to emerge. These regulations do not change the price of the regular good, the producers'

[11] It can be shown that the lower v, the higher the IP consumption, and the lower the regular consumption.

profit or the utility of consumers who continue to buy the GM good (given that for $L = 1$ and $t = e = 0$, $p_r = p_0$). They allow some consumers to choose the IP good, which increases their utility, but impose a burden on taxpayers. The necessary condition for welfare to increase with the introduction of labeling, $v_{5|e=t=0} < \tilde{v}_1'$, is more likely to hold when the proportion of downgrading, h_0, is small (it can be shown that $v_{5|e=t=0}$ is increasing in h_0 while $\tilde{v}_1'$ is decreasing in h_0). In such a case, welfare increases with the introduction of labeling and *ex post* regulation when the overcost of producing the IP good, v, is sufficiently small.

When an *ex post* regulation funded by taxpayers' money protects IP producers from damages related to the externality, introducing 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 damage D under coexistence is decreasing with the level of the *ex ante* regulation, which allows such a regulation to increase total welfare.

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 coexistence; 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 regular production, the introduction of ex post regulation shifts the equilibrium towards coexistence.

Proposition 5. *For given values of the other parameters, the introduction of ex post regulation funded entirely by taxpayers maintains a coexistence equilibrium when $v_5 < v < v_2$. In this case, the price of the regular good does not change while the price of the IP good decreases. Total production and consumption are unchanged, with some former regular producers and some former regular consumers turning to the IP good. Producers' profits and the utility of consumers who continue to consume the regular 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.6. □

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 regular production alone (in which case the welfare level is simply $\int_0^{\alpha^g}(\alpha^g - \alpha)d\alpha + \int_{\theta^r}^1(\theta(1-a) - p_r)d\theta$) to coexistence, as indicated in Proposition 6.

Proposition 6. *For given values of the other parameters, the introduction of ex post regulation funded entirely by taxpayers causes the equilibrium to shift from regular production alone to coexistence when $Max(v_2, v_5) < v < v_6$. In this case, the price of the regular good does not change. Total production and consumption are unchanged, with some former regular producers and some former regular consumers turning to the IP good. Producers' profits and the utility of consumers who consume the regular good both in the presence and in the absence of ex post regulation are unchanged. The utility of consumers who consume the regular good in the absence of ex post regulation and the (more expensive) IP good in the presence of ex post regulation increases, but this increase is more than compensated by the cost to taxpayers. Total welfare therefore decreases.*

Proof. See Appendix A.7. □

With a relatively high supply parameter (v), the introduction of *ex post* regulation allows coexistence to emerge from a situation where only the regular crop was produced and consumed. In this case, 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 7. *For given values of the other parameters, the introduction of ex post regulation, funded entirely by taxpayers, shifts the equilibrium from coexistence to IP production alone when*

$v_1 < v < \min(v_2, v_7)$. *The new regulation results in a new price for IP goods which is above the former price of the regular good and below the former price of the IP good. Total production and consumption increase. Profit increases for every producer and utility increases for every consumer. As a result, total welfare increases.*

Proof. See Appendix A.8. □

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

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. The results in Propositions 6 to 8 show that *ex post* regulation is favorable to IP consumers but detrimental to taxpayers and welfare when it induces or maintains coexistence. This regulation improves welfare only when it removes coexistence in favor of an equilibrium with only the IP good, a situation that arises when consumer aversion to GMOs is high enough and the overcost of producing the non-GM good is sufficiently low.

4 Conclusion

In this paper we examine the effects of *ex ante* and *ex post* regulation of GM and non-GM crop 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 form of non-point source pollution and therefore GMO producers do not, individually, have the appropriate incentives to correct the externality that they exert on non-GMO producers. *Ex ante* technical measures such as buffer zones reduce GM gene flow, and therefore reduce the risk of downgrading the non-GM production. Such 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 gene flow. We study one form of *ex post* regulation: a fund aimed at compensating IP producers for any loss of profit due to downgrading, financed by GMO producers and/or the state.

GM and non-GM coexistence presents an interesting example of how ex ante and ex post regulations can interact to reduce externalities. We find that a GM seed tax, as a substitute to taxpayer funding for downgrading compensation, introduces a market distortion that always deteriorates welfare. When it maintains or induces coexistence, *ex post* regulation entirely funded by taxpayers favors IP consumers but reduces welfare overall, since it has no incentive effect on producers of the regular good. The *ex post* regulation improves welfare only when its introduction causes the market of the regular good, and therefore burdensome coexistence costs, to disappear. On the contrary, *ex ante* regulation reduces the potential damage, that is, the risk of IP crop downgrading. We find that *ex ante* technical measures may be welfare increasing, as long as consumers care sufficiently for non-GM goods,and the cost advantage of GM production is modest.

In our model, we assume that segregation and identity preservation beyond the farm stage are costless. With a positive unit cost of identity preservation beyond the farm stage, coexistence equilibria would appear for a smaller range of parameter values. The IP price would be higher, and therefore the utility of IP consumers lower, in coexistence equilibria. This positive cost of identity preservation would make it is less likely that the introduction of coexistence regulations increases welfare.

The results of this article hold under the assumption that the only cost imposed on GMO farmers by *ex ante* coexistence regulations is the additional cost of producing the non-GM crop on the area devoted to a buffer zone. These regulations would, in fact, impost additional operation costs on GMO farmers, who would have to buy two different types of seeds and plant them separately. These operations are inconvenient and can be time-consuming; furthermore, they may result in yield losses due to delayed planting and extra costs during the growing season, particularly if the GM and non-GM varieties have different characteristics. With such costs for GMO farmers, perfect compliance with *ex ante* regulations would be less likely in the absence of costly monitoring. As a result, the regular crop would be produced in equilibrium for a smaller range of parameter values. When it is produced, producers' profits would be lower, the regular price would be higher and the utility of regular consumers would be lower. Therefore, it would be less likely that the introduction of *ex ante* coexistence regulation increases welfare.

A related topic not covered in our article is the potential for cooperation between neighboring farmers to define more flexible *ex ante* coexistence measures. In particular, arrangements between neighbors whereby a GMO farmer compensates a neighbor who implements a buffer zone in his non-GM field may reduce the burdens on GMO farmers, as described above. The literature on flexible coexistence measures (Demont et al;, 2008 and 2009; Gray, 2011; Groeneveld et al., 2013) could be extended to assess the effects of such arrangements on market and welfare outcomes.

For tractability reasons, our model assumes that all producers are identical. In reality, producers are differentiated, and the degree to which regulation aligns with their interests varies greatly. We expect that our main results would hold, however, with heterogenous producers. Notably, because of the non-point nature of the externality exerted by GM producers towards IP producers, we expect that the introduction of a compensation fund would still decrease welfare with heterogenous producers. In this case, however, not only consumers but also producers of the IP good would benefit from *ex post* compensation.

Other types of *ex post* regulations than the compensation fund studied here may incentivize farmers. For example, tort law could be used to impose liability on the GMO farmer whose fields is the nearest to a downgraded IP harvest. Alternatively, under joint and several liability, all GMO farmers in a given area would be jointly liable for losses suffered by a non-GMO farmer, and it would be the responsibility of these farmers to sort out their respective proportions of liability and payment. This mechanism may lead defendants to apportion damages among themselves insofar as they can bargain easily at low transaction costs. Such liability schemes are more difficult to devise and involve higher enforcement costs than a compensation fund. They could induce excessive incentives for precaution, and reduce the profitability of the regular crop, causing the regular good to disappear from the market in a wider range of situations. They could also, however, induce farmers to adopt *ex ante* technical measures to prevent gene flow and therefore reduce the need for *ex ante* coexistence regulation. The effects of such liability schemes, which go beyond the scope of this paper, are discussed notably in Koch (2008), Koch (2010) and Koch (2012).

As a final point, labeling and coexistence regulations only partially address the market failure arising from the positive public-good attributes that some consumers associate with non-GM goods due, for example, to their perceptions about environmental issues, their attitudes towards interactions between man and nature, possible opposition to the concentration of the upstream agricultural sector, or questions on whether regulatory authorities have sufficient power to effectively regulate companies that develop GMOs. 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 may 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. If such policies are not implemented, it is likely that consumers who are strongly opposed to GMOs will not be satisfied with labeling and coexistence policies alone.

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Table 1: Prices and equilibrium conditions with *ex ante* regulation alone

$$v_1 = \frac{a(1+e-h_0)[1+(1-a)(h_0-e)]}{2(1-e)+ae(h_0-e)(2+e-h_0)-a}$$
$$v_2 = \frac{a(1+e-h_0)}{1-e}$$
$$v_3 = \frac{1-a}{e}$$
$$v_4 = \frac{a}{2(1-e)-a}$$
$$a_0 = \frac{1-e}{1-e(h_0-e)}$$

- Coexistence. $p_r^* = \frac{1-a}{2-a}(1+ev), \quad p_i^* = p_r^* + \frac{(1-e)v}{1+e-h_0}$

$$\begin{cases} a < a_0 \\ v_1 < v < v_2 \end{cases}$$

- Regular production alone. $p_r^* = \frac{1-a}{2-a}(1+ev)$

$$\begin{cases} a < a_0 \\ v_2 \leq v < v_3 \end{cases}$$

- IP production alone. $p_i^* = \frac{1}{2}(1+v)$

$$\begin{cases} \text{if } 2(1-e) \leq a, v < 1 \\ \text{if } 2(1-e) > a, v < v_4 \end{cases}$$

Table 2: Prices and equilibrium conditions with *ex ante* and *ex post* regulations

$$v_5 = \frac{a(1+(1-a)(h_0-e)) + (1-e)(2-a(h_0-e))t}{2(1-e)+ae(h_0-e)-a}$$
$$v_6 = \frac{a}{1-e} + t$$
$$v_7 = \frac{a+2(1-e)t}{2(1-e)-a}$$
$$a_1 = (1-e)(1-t)$$

- Coexistence. $p_r^* = \frac{1-a}{2-a}(1+ev+(1-e)t), \quad p_i^* = p_r^* + (1-e)(v-t)$

$$\begin{cases} a < a_1 \\ v_5 < v < v_6 \end{cases}$$

- Regular production alone. $p_r^* = \frac{1-a}{2-a}(1+ev+(1-e)t)$

$$\begin{cases} a < a_1 \\ v_6 \leq v \end{cases}$$

- IP production alone. $p_i^* = \frac{1}{2}(1+v)$

$$\begin{cases} \text{if } 2(1-e) \leq a, v < 1 \\ \text{if } 2(1-e) > a, v < v_7 \end{cases}$$

Note: When $t = 0$, v_7 is equal to v_4 .

Table 3: Quantities of each type of product 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	$Q = \frac{1-a-ev}{2-a}$ • $\frac{\partial Q}{\partial e} < 0$	$Q' = \frac{1-a-ev-(1-e)t}{2-a}$ • $\frac{\partial Q'}{\partial e} < 0$
Quantity of IP good consumed	$Q_i = 1 - \frac{(1-e)v}{a(1+e-h_0)}$ • $\frac{\partial Q_i}{\partial e} > 0$ • $\frac{\partial Q_i}{\partial h_0} < 0$	$Q'_i = 1 - \frac{(1-e)(v-t)}{a}$ • $\frac{\partial Q'_i}{\partial e} > 0$
Quantity of regular good consumed	$Q_r = \frac{2(1-e)v+av(1-e(h_0-e))-a(1+e-h_0)}{(2-a)a(1+e-h_0)}$ • $\frac{\partial Q_r}{\partial e} < 0$ • $\frac{\partial Q_r}{\partial h_0} > 0$	$Q'_r = \frac{2(1-e)(v-t)-a(1+v)}{(2-a)a}$ • $\frac{\partial Q'_r}{\partial e} < 0$
Quantity of IP production downgraded	$Q_d = \frac{h}{1-h}Q_i = \frac{(h_0-e)(a(1+e-h_0)-(1-e)v)}{a(1+e-h_0)^2}$ • $\frac{\partial Q_d}{\partial e} \begin{cases} \leq 0 & \text{if } v \leq v_8 \\ > 0 & \text{if } v > v_9 \end{cases}$ • $\frac{\partial Q_d}{\partial h_0} \begin{cases} > 0 & \text{if } v < v_9 \\ \leq 0 & \text{if } v \geq v_9 \end{cases}$	$Q'_d = \frac{h}{1-h}Q'_i = \frac{(h_0-e)(a-(1-e)(v-t))}{a(1+e-h_0)}$ • $\frac{\partial Q'_d}{\partial e} \begin{cases} \leq 0 & \text{if } v \leq v_{10} \\ > 0 & \text{if } v > v_{10} \end{cases}$ • $\frac{\partial Q'_d}{\partial h_0} > 0$

Note: $v_8 = \frac{a(1+e-h_0)}{1-e+(2-h_0)(h_0-e))}$, $v_9 = \frac{a(1+e-h_0)}{(1-e)(1-e+h_0}$, $v_9 = \frac{a}{1+(h_0-e)(1+e-h_0-e)}$. $v_8 < v_9$, both v_8 and v_9 are positive and smaller than v_2 and both may be higher or lower than v_1. v_9 is positive and smaller than v_6 and may be higher or lower than v_5.

A Appendixes

A.1 Characterization of equilibrium

The parameters α^g and α^i are given by $\alpha^g = p_r - ev$ and $\alpha^i = p_i - v - (p_i - p_r)(h_0 - e)Ind(Q_g)$ in the absence of *ex post* regulation ($L = 0$), and by $\alpha^g = p_r - ev - (1-e)t$ and $\alpha^i = p_i - v$ with *ex post* regulation ($L = 1$). We consider all possible equilibria which may arise in each of these two cases ($L = 0$ or 1).

A coexistence equilibrium arises when $\alpha^i = \alpha^g$, $0 < \alpha^g$, $\theta^r < \theta^i < \widetilde{\theta} < 1$ and $1 - \widetilde{\theta} < (1 - h(.))(1 - \theta_r)$ (so that $Q_s^i < (1-h)(Q_s^g + Q_s^n + Q_s^i)$). Equations ((a)-(c)), which define an equilibrium, imply that $\alpha^g = 1 - \theta^r$. Solving the system of equations $\alpha^i = \alpha^g$ and $\alpha^g = 1 - \theta^r$, when $L = 0$ and when $L = 1$, yields the equilibrium prices given in Tables 1 and 2 for the coexistence case. Equilibrium conditions $1 - \widetilde{\theta} < (1 - h(.))(1 - \theta_r)$ (which implies that $\theta^r < \theta^i < \widetilde{\theta}$) and $\widetilde{\theta} < 1$ (which implies that $\theta^r < 1$ and therefore $\alpha_g > 0$) respectively yield conditions $1 < \frac{v}{v_1}$ and $v < v_2$ when $L = 0$, $1 < \frac{v}{v_5}$ and $v < v_6$ when $L = 1$. It can be shown that conditions $1 < \frac{v}{v_1}$ and $v < v_2$ are compatible if and only if $a < a_0$, in which case v_1 is positive. Conditions $1 < \frac{v}{v_5}$ and $v < v_6$ are compatible if and only if $a < a_1$, in which case v_5 is positive.

An equilibrium with only the regular crop arises when $\max(\alpha^i, 0) < \alpha^g$, $\theta^r < \theta^i < \widetilde{\theta}$ and $\theta^r < 1 \leq \widetilde{\theta}$. The definition of equilibrium in ((a)-(c)) then implies that $\alpha^g = 1 - \theta^r$. Solving this equation when $L = 0$ and when $L = 1$ yields the equilibrium prices of the regular good given in Tables 1 and 2 for the case with regular production alone. Solving the equilibrium condition $\theta^r < 1$ yields $v < v_3$ when $L = 0$ and $v < v_8$, defined by $v_8 = \frac{1-a-(1-e)t}{e}$, when $L = 1$. This condition also guarantees that $0 < \alpha^g$. The condition $1 \leq \widetilde{\theta}$ is equivalent to $p_r + a \leq p_i$. Straightforward calculations show that this condition is more binding than the condition $\theta^r < \theta^i$ (which is equivalent to $\frac{1}{1-a}p_r < p_i$) as long as $v < v_3$ when $L = 0$ and $v < v_8$ holds when $L = 1$. The condition $\alpha^i < \alpha^g$ is equivalent to $p_i < p_r + \frac{(1-e)v}{1-h_0(1-e)}$ when $L = 0$ and to $p_i < p_r + (1-e)(v-t)$ when $L = 1$. When $L = 0$, the conditions $p_r + a \leq p_i$ and $p_i < p_r + \frac{(1-e)v}{1+e-h_0}$ imply $v_2 < v$. When $L = 1$, the conditions $p_r + a \leq p_i$ and $p_i < p_r + (1-e)(v-t)$ imply $v_6 < v$. Conditions $v_2 \leq v$ and $v < v_3$ and are compatible if and only if $a < a_0$. Conditions $v_6 \leq v$ and $v < v_8$ are compatible if and only if $a < a_1$, in which case v_8 always holds. When $v = v_2$ (when $L = 0$) or $v = v_6$ (when $L = 1$), we get a regular equilibrium at the limit with the coexistence equilibrium, where all producers are indifferent between the GM and the IP crops but no demand exists for the IP crop.

An equilibrium with only IP arises when $\alpha^g < \alpha^i$, $0 < \alpha^i$, $\widetilde{\theta} \leq \theta^i \leq \theta^r$ and $\theta^i < 1$. The definition of equilibrium in ((a)-(c)) then implies that $\alpha^i = 1 - \theta^i$ and $Q_g = 0$. Solving this equation yields the equilibrium price of the IP good given in Tables 1 and 2 for the case of IP alone. The condition $\theta^i < 1$ (which implies that $0 < \alpha^i$) is equivalent to $v < 1$. The condition $\theta^r \geq \theta^i$ is equivalent to $\frac{1-a}{2}(1+v) \leq p_r$. The condition $\alpha^g < \alpha^i$ is equivalent to $p_r < \frac{1+v}{2}-(1-e)v$ when $L = 0$ and $p_r < \frac{1-v}{2}+ev+(1-e)t$ when $L = 1$. When $L = 0$, the conditions $\frac{1-a}{2}(1+v) \leq p_r$ and $p_r < \frac{1+v}{2} - (1-e)v$ imply $(2(1-e)-a)v < a$. When $L = 1$, the conditions $\frac{1-a}{2}(1+v) \leq p_r$ and $p_r < \frac{1-v}{2} + ev + (1-e)t$ imply $(2(1-e)-a)v < a + 2(1-e)t$.

A.2 Proof of Proposition 1

We have that $v_2 < v_6$, therefore a former coexistence equilibrium cannot become an equilibrium with only the regular crop, but a former regular equilibrium may turn into a coexistence equilibrium. v_2 and v_5 are both increasing in a, and at $a = 0$, $\frac{\partial v_5}{\partial a} < \frac{\partial v_2}{\partial a}$ if and only if $3h_0(1-e) + t(1-(1-e)h_0) < 1$, which holds if h_0 and t are small enough. In this case, the curve v_5 lies below the curve v_2 close to $a = 0$ in a (a, v) plane and a former coexistence equilibrium may remain a coexistence equilibrium. v_1, v_5 and v_7 are increasing in a, and at $a = 0$, $\frac{\partial v_1}{\partial a} < \frac{\partial v_5}{\partial a} < \frac{\partial v_7}{\partial a}$. Therefore, the curve v_1 lies below the curves v_5 and v_7, and close to $a = 0$ in a (a, v) plane; a former coexistence equilibrium become an area with no stable equilibrium or an IP equilibrium.

Expressions v_2, v_6 and v_7 are increasing in e; v_1 is increasing in e as long as $a < a_0$; v_5 is increasing in e as long as $a < a_1$.

A.3 Proof of Proposition 2

From Table 1, given that $L = e = 0$, $p_r^* = \frac{1-a}{2-a} = p_r^0$: the regular price in the coexistence equilibrium with labeling only is identical to the regular price in the benchmark equilibrium where GMOs are introduced without labeling. The total quantity produced and consumed is unchanged. The welfare level with labeling only is $W_{|e=0} = \frac{1}{2(2-a)} + v\frac{v-2a(1-h_0)}{2a(1-h_0)^2}$. The difference in welfare levels with and without labeling is $W_{|e=0} - W^0 = \frac{(v-a(1-h_0))^2}{2a(1-h_0)^2} > 0$. Since the price of the regular good and total quantity are unchanged, welfare effects on producers and consumers are straightforward.

A.4 Proof of Proposition 3

Given the equilibrium prices in Table 1, we find that in a coexistence equilibrium with *ex ante* regulation alone, an increase in e causes the price of the regular good to increase ($\partial p_r/\partial e > 0$), total production and consumption as well as producers' profit to decrease ($\partial \alpha_g/\partial e < 0$), and IP consumption to increase ($\partial(1-\tilde{\theta})/\partial e > 0$). Using the conditions $a < a_0$ and $0 < e < h_0 < 1$, we also find that the increase in e results in an increase in the price of the IP good ($\partial p_i/\partial e > 0$) and a decrease in regular consumption ($\partial(\tilde{\theta} - \theta_r)/\partial e < 0$).

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

$$W = \frac{1}{2}\left(1 + {\alpha_g}^2 + \frac{(p_i - p_r)^2}{a} + \frac{{p_r}^2}{1-a}\right) - pi,$$

or equivalently:

$$\begin{aligned} W &= \frac{1}{2} + \frac{(1-a-ev)^2}{2(2-a)^2} + \frac{((1-e)v)^2}{2a(1+e-h_0)^2} + \frac{(1-a)(1+ev)^2}{2(2-a)^2} - \frac{(1-a)(1+ev)}{2-a} \\ &\quad - \frac{(1-e)v}{1+e-h_0}. \end{aligned}$$

We obtain: $\frac{\partial W}{\partial e}\ |_{e=0} = \frac{v(2-h_0)}{a(1-h_0)^3}(\tilde{v} - v)$, where $\tilde{v} = \frac{a(1-h_0)(3-(h_0)^2 - a(1+(1-h_0)h_0))}{(2-a)(2-h_0)}$. Therefore, the introduction of a low level of e is welfare-increasing if and only if $v < \tilde{v}$. When $e = 0$, we have that $v_1 = \frac{a(1-h_0)(1+(1-a)h_0)}{2-a}$ and $v_2 = a(1-h_0)$, with $v_1 < \tilde{v} < v_2$.

A.5 Proof of Proposition 4

Given the equilibrium prices in Table 2, we find that in a coexistence equilibrium with *ex ante* regulation alone, an increase in t causes the price of the IP good to decrease ($\partial p_i/\partial t < 0$), total production and consumption as well as producers' profit to decrease ($\partial \alpha_g/\partial t < 0$), regular consumption to decrease ($\partial(\tilde{\theta} - \theta_r)/\partial t < 0$), IP consumption to increase ($\partial(1-\tilde{\theta})/\partial t > 0$). Using the condition $a < 1 - e$, we also find that the increase in t results in an increase in the price of the regular good ($\partial p_r/\partial t > 0$). Changes in consumers' utility are straightforward given price changes.

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

$$\begin{aligned} W' &= \frac{1}{2}\left(1 + {\alpha_g}^2 + \frac{(p_i - p_r)^2}{a} + \frac{{p_r}^2}{1-a}\right) - pi + \left(\frac{p_i - p_r}{a} - \frac{p_r}{1-a}\right)(1-e)t \\ &\quad - \frac{(h_0 - e)(a - p_i + p_r)}{(1+e-h_0)a}(p_i - p_r - (1-e)t), \end{aligned}$$

or equivalently:

$$\begin{aligned} W' &= \frac{1}{2} + \frac{(1-a-ev-(1-e)t)^2}{2(2-a)^2} + \frac{((1-e)(v-t))^2}{2a} + \frac{(1-a)(1+ev+(1-e)t)^2}{2(2-a)^2} \\ &\quad - \frac{(1-a)(1+ev+(1-e)t)}{2-a} - (1-e)(v-t) \\ &\quad + \left(\frac{(1-e)(v-t)}{a} - \frac{1+ev+(1-e)t}{2-a}\right)(1-e)t \\ &\quad - \frac{(h_0-e)(a-(1-e)(v-t))}{(1+e-h_0)a}(1-e)v \end{aligned}$$

We have: $\frac{\partial W'}{\partial t} = -\frac{(1-e)^2}{a}\left[\frac{2t}{2-a} + \frac{(h_0-e)v}{1+e-h_0}\right] < 0$. Therefore, the optimal level of the per-unit tax on GM seeds (t) is zero.

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

When $e = t = 0$, we have $v_5 = \frac{a(1+(1-a)h_0)}{2-a}$ and $v_6 = a$. The difference in welfare levels with and without labeling is: $W'_{|e=0,t=0} - W^0 = \frac{(a-v)}{2a(1-h_0)}(a(1-h_0) - v(1+h_0))$. $v < v_6$ implies that $v < a$, therefore this welfare difference is positive if and only if $v < \tilde{v}'_1$, with $\tilde{v}'_1 = \frac{a(1-h_0)}{1+h_0}$. When $e = 0$, we have that $0 < \tilde{v}'_1 < v_6$ while $\tilde{v}'_1$ may be higher or lower than v_5.

When $t = 0$, we have: $\frac{\partial W'(t=0)}{\partial e} \mid_{e=0} = \frac{(2-(h_0)^2)v}{a(1-h_0)^2}(\tilde{v}'_2 - v)$, with $\tilde{v}'_2 = \frac{a(3-(h_0)^2-a(1+h_0-(h_0)^2))}{(2-a)(2-(h_0)^2}$. Therefore, the introduction of a low level of e is welfare-increasing if and only if $v < \tilde{v}'_2$. When $e = 0$, we have that $0 < \tilde{v}'_2 < v_6$ while $\tilde{v}'_2$ may be higher or lower than v_5.

A.6 Proof of proposition 5

The introduction of *ex post* regulation maintains a coexistence equilibrium when $v_1 < v < v_2$ and $v_5 < v < v_6$. Given $t = 0$ and $a < a_1$, we have that $v_2 < v_6$ and $v_1 < v_5$, while v_5 may be higher or lower than v_2. From Table 1, given that $t = 0$, p_r^* 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 prices of the IP good in these two equilibria is $p_i'^* - p_i = -\frac{(1-e)(h_0-e)v}{1+e-h_0} < 0$. 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: $W' - W = -\frac{(1-e)^2(e-h_0)^2v^2}{2a(1+e-h_0)^2} < 0$. Therefore the cost to taxpayers has to be larger than the utility gain for consumers.

A.7 Proof of proposition 6

The introduction of *ex post* regulation shifts the equilibrium from regular only to coexistence when $v_2 < v < v_3$ and $v_5 < v < v_6$. Given $t = 0$ and $a < a_1$, we have that $v_6 < v_3$ and $v_2 < v_6$ while v_5 may be higher or lower than v_2 and v_3. From Table 1, p_r^* is identical in the equilibrium with *ex ante* regulation alone and regular 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 $t = 0$. The welfare level with *ex ante* regulation and only the regular crop is given by $\frac{(1-a-ev)^2}{2(2-a)}$. After simplification, we obtain that the difference in welfare levels with and without *ex post* regulation , $W' \mid_{t=0} - W_{\text{r only}}$, is of the sign of $(v_6 - v)\left(\frac{v_2}{1-e+h_0} - v\right)$. Under the assumptions given above, the first parenthesis is positive while the second one is negative, therefore $W' \mid_{t=0} < W_{\text{r only}}$ for any $v \in (\max(v_2, v_5), v_6)$.

A.8 Proof of proposition 7

The introduction of *ex post* regulation shifts the equilibrium from coexistence to IP only when $v_1 < v < v_2$ (which implies that $a < a_0$ and therefore $a < 2(1-e)$) and $v < v_7$. Given $t = 0$ (which we assume throughout this proof), we have that $v_1 < v_7$ while v_2 may be higher or lower than v_7.

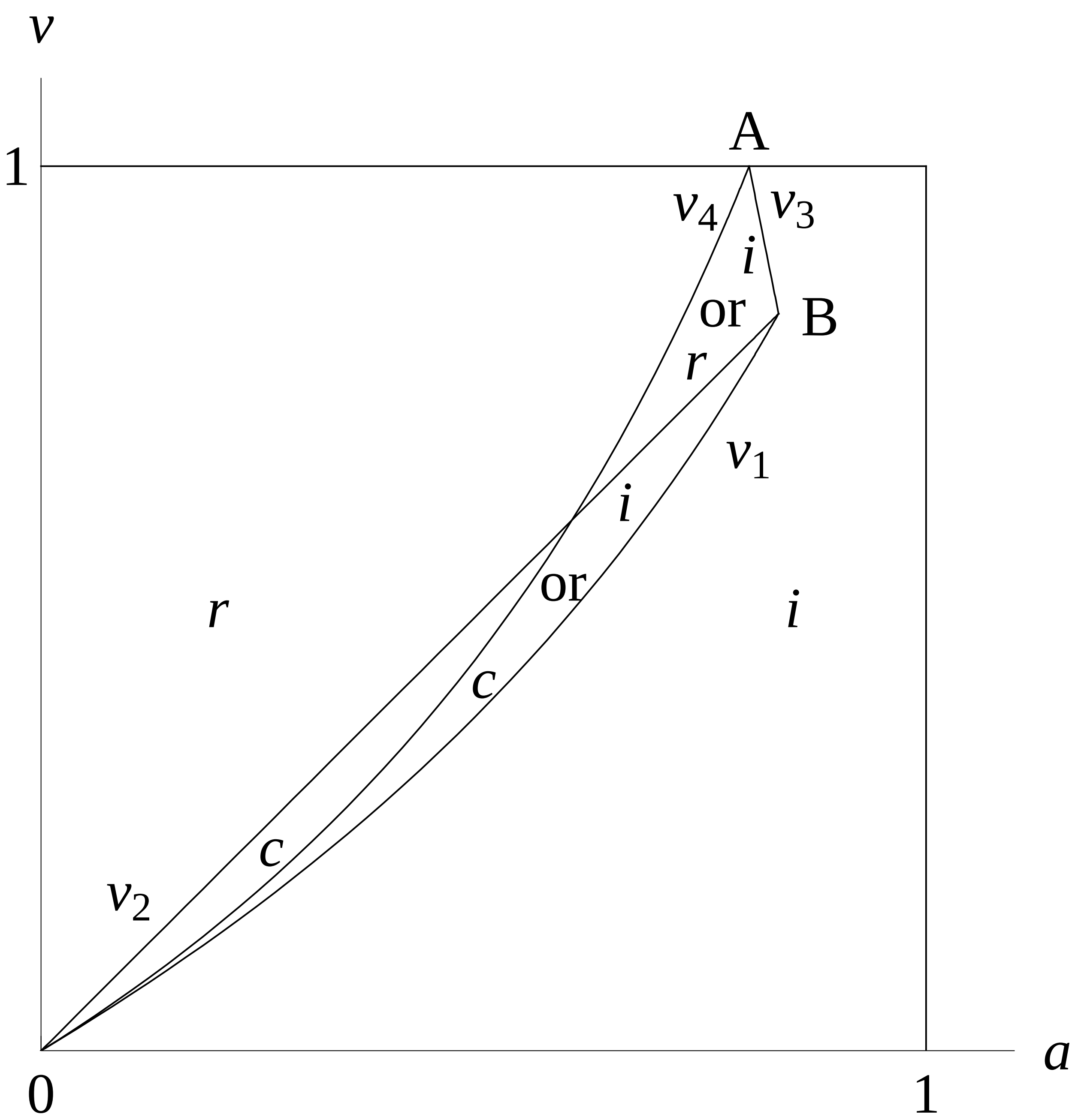
The equilibrium price of the IP good with *ex ante* regulation only in a coexistence equilibrium, $p_{i(c)}$, is equal to the equilibrium price of the IP good with *ex ante* and *ex post* regulations and IP only, $p'_{i(i)}$, if and only if $v = \hat{v}_1 = \frac{a(1+e-h_0)}{2(1-e)(1+e-h_0)-a(1-e(1+2(h_0-e))+h_0)}$. Given $a < a_0$ and $0 < e < h_0 < 1$, we obtain that $\hat{v}_1 < v_1$. Therefore, the relative levels of the two prices do not change on the interval $v \in (v_1, Min(v_2, v_7))$. Moreover, for $v = v_1$, we find that $p'_{i(i)} < p_{i(c)}$. Therefore, this inequality holds for $v \in (v_1, Min(v_2, v_7))$.

The equilibrium price of the regular good with *ex ante* regulation only in a coexistence equilibrium, $p_{r(c)}$, is equal to $p'_{i(i)}$ if and only if $v = \hat{v}_2 = -\frac{a}{2-a-2(1-e)a}$. Given $a < a_0$ and $0 < e < h_0 < 1$, we obtain that $\hat{v}_2 < v_1$. Therefore, the relative levels of the two prices do not change on the interval $v \in (v_1, Min(v_2, v_7))$. Moreover, for $v = v_1$, we find that $p_{r(c)} < p'_{i(i)}$. Therefore, this inequality holds for $v \in (v_1, Min(v_2, v_7))$.

The total production with *ex ante* regulation only in a coexistence equilibrium, $\alpha_{g(c)}$, is equal to the total production price of the IP good with *ex ante* and *ex post* regulations and IP only, $\alpha'_{i(i)}$, if and only if $v = v_7$. Moreover, for $v = v_1$, we find that $\alpha_{g(c)} < \alpha'_{i(i)}$. Therefore, this inequality holds for $v \in (v_1, Min(v_2, v_7))$.

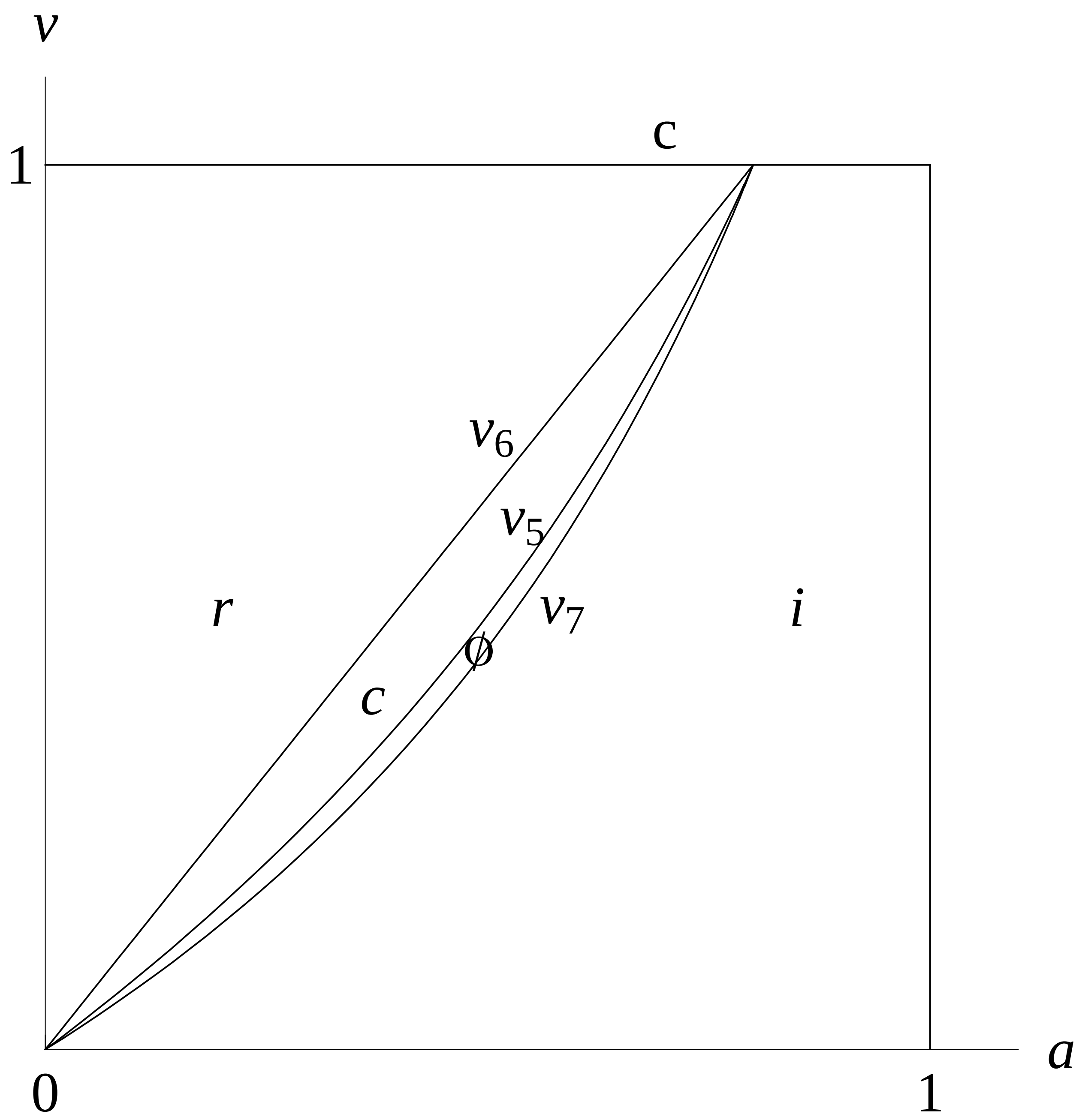
Since $\alpha_{g(c)} < \alpha'_{i(i)}$, all producers gain when the introduction of *ex post* regulation shifts the equilibrium from coexistence to IP only. All former consumers of the IP good necessarily win from the decrease in the price of the IP good. Given that total consumption increases, all former regular consumers turn to the IP good. Their individual utility changes from $\theta(1-a) - p_{r(c)}$ to $\theta - p'_{i(i)}$. Therefore, their individual utility increases if and only if $\theta > \frac{p'_{i(i)} - p_{r(c)}}{a}$. This inequality holds for $\theta = \theta_r$, that is for the former regular consumer characterized by the smallest θ, if and only if $v < v_7$. Therefore this inequality holds for any $\theta \geq \theta_r$ on the interval $v \in (v_1, Min(v_2, v_7))$; that is, all former regular consumers gain. Finally, all consumers who move from consuming nothing to consuming the IP good gain. Therefore, all consumers gain. Therefore total welfare increases.

Figure 1: Equilibrium diagram with *ex ante* regulation



Note. At A, $v = 1$ and $a = 1 - e$. At B, $v = \frac{1+e-h_0}{1+e(e-h_0}$

Figure 2: Equilibrium diagram with *ex ante* regulation



Note. At C, $v = 1$ and $a = a_1$

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