Optimal coverage of an emission tax in the presence of monitoring, reporting, and verification costs

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Abstract

Environmental policies often include exemptions for some firms, e.g. the smallest emitters. This text explores the implications of such exemptions in the case of an emission tax, and in the presence of monitoring, reporting, and verification (MRV) costs. We develop an analytical framework capturing the trade-off between the cost-effectiveness of a broader tax base, and the savings on MRV costs enabled by a partial coverage. We characterize the optimal threshold below which firms should be exempted. Since determining this threshold is demanding in terms of information regarding firm-level MRV and abatement costs, we propose a simple approximation requiring knowledge of these costs only at the aggregate level. We apply this framework to assess the welfare implications of such an instrument in the case of greenhouse gas emissions from European agriculture. The findings indicate that exempting the smallest emitters may provide significant savings on MRV costs compared to the full coverage, while still incentivizing cost-effective reductions in emissions.

Keywords: Climate policy, Emission tax, Partial coverage, Greenhouse gas emissions, Agriculture.

JEL: Q58, Q54, Q15

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1. Introduction

Many policy instruments include provisions that leave some agents out of the scope of regulation. These provisions may involve exclusion of firms in specific sectors, or a threshold value of some characteristic above or below which the agents are granted exemption. A typical example is the income tax, which in many countries includes exemption provisions for households in the lowest income bracket. Examples can also be found in the field of environmental policy. The European Union Emissions Trading Scheme (EU-ETS)–currently the main instrument in EU climate policy–explicitly excludes emissions from the residential, agricultural, transport, and waste sectors. Within the sectors included in the EU-ETS, only the largest-emitting installations are subject to cap-and-trade. The EU-ETS covers almost 45% of total European emissions, but only some 11,200 installations (Vlachou, 2014; European Commission, 2015), a small number compared to the millions of car and home owners and farmers in Europe who contribute to most of the remaining 55% of emissions.

Arguably, excluding some emitters from the scope of policy comes at a social cost. The justification for adopting a partial coverage is often based on inequality considerations, as e.g. in the case of income-tax exemptions for lowest-income households. It may be based also on cost-effectiveness considerations. If the policy is costly to implement, administer, and/or enforce, and the related costs increase with the number of agents subject to the policy, the regulator faces a trade-off between the larger benefits from a broader coverage, and the cost savings associated with the monitoring of fewer agents.

In this paper, we examine this trade-off in the context of an emission tax. As is common in the context of climate policy, implementation, administration, and enforcement costs will be referred to as monitoring, reporting, and verification (MRV) costs (Bellassen et al., 2015).[1] The regulator must determine *ex ante* which firms should be subject to the emission tax, taking into account that the broader the coverage, the larger the overall reduction in emissions but also the larger the MRV costs. As suggested by Grosjean et al. (2016), the optimal coverage is related to the distribution

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[1] These costs correspond to the costs associated with (i) the collection of the relevant data (monitoring), (ii) their communication to the administration or the environmental agency (reporting), and the certification of the reports reliability (verification) that ensure the validity of the compliance with the regulatory requirements defined in the policy objective.

of emissions among firms. For instance, consider that firms' initial emissions are distributed as depicted in the Lorenz curve in Figure 1. In this situation, targeting only the top 20% emitters (i.e. those to the right of point A in Figure 1) covers almost three-quarters of total emissions.

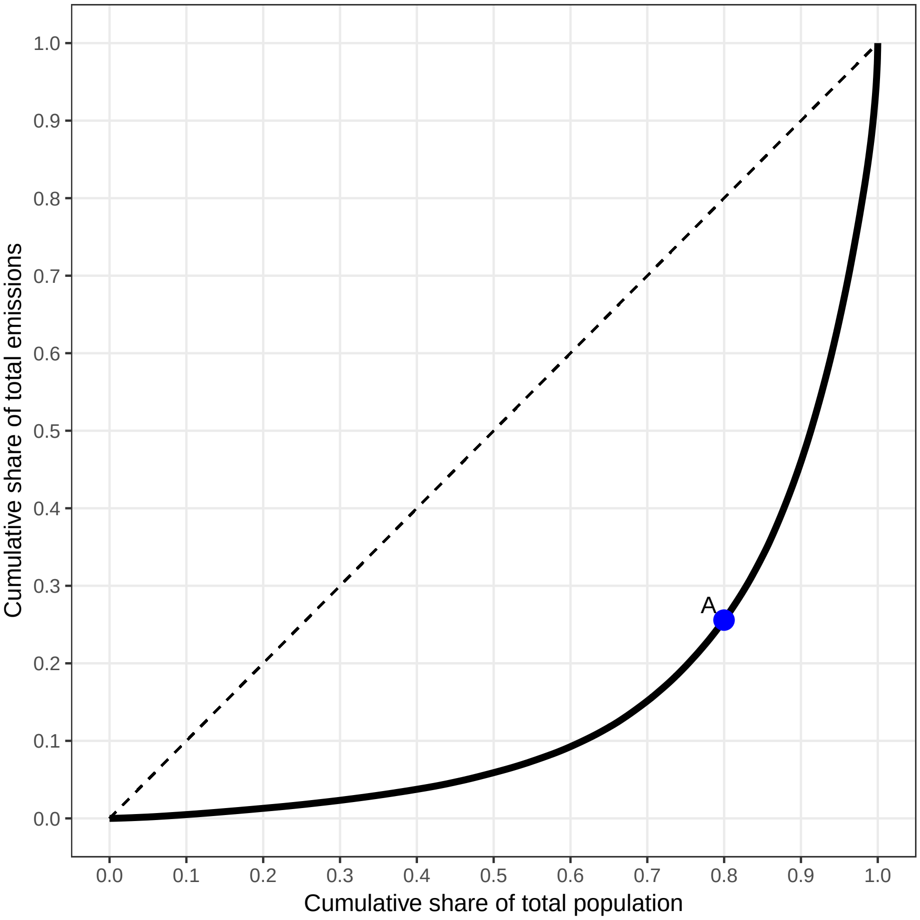

Figure 1: Lorenz curve of initial emissions

It may be that (some of) the smallest emitters are very efficient at reducing their emissions, while abatement may be very costly for (some of) the largest emitters. Thus, determining the optimal coverage requires the regulator to have *ex ante* access to detailed information about individual costs. This is a strong requirement, especially if a large number of heterogeneous firms are involved as is the case for many environmental issues.

Two strategies can be applied to address this issue. Since any firm's abatement and MRV costs may be known to that firm but unknown to the regulator, the first option is to design a truthful direct revelation mechanism that takes into account incentive constraints to address the issue of asymmetric information and/or moral hazard (Spulber, 1988; Macho-Stadler and Pérez-

Castrillo, 2006). Note that this would result in the transfer of information rents to some of the firms. In addition, the issue of costly monitoring and enforcement would remain (Bontems and Bourgeon, 2005; Stranlund et al., 2009). The alternative strategy is simpler in design and combines an emission tax with a threshold value of some known characteristic of the firm, above which the firm is liable for the tax, and below which the firm is exempt. We explore that latter strategy in this paper.

The oprtimal coverage of a policy instrument in the presence of administrative costs has been examined in optimal commodity taxation theory (e.g. Yitzhaki, 1979; Wilson, 1989; Dharmapala et al., 2011). Those works determine the tax base (i.e. taxed and untaxed goods) that maximizes welfare given the government's revenue requirement. A slightly different but related idea is developed in Keen and Mintz (2004), who study the turnover threshold above which firms are obliged to register for value-added tax. Although developed in a different context, the simple rule proposed by Keen and Mintz results from a similar trade-off to that discussed in the present paper.

In the field of environmental economics, the nature of transaction costs[2] and their implications for the design of environmental policy have resulted in a large body of theoretical and empirical literature (see e.g. Krutilla and Krause, 2011). Two questions addressed in the recent empirical literature on this topic are of particular interest for the present paper. The first is how transaction costs vary with firm size. Evidence from this literature suggests that these costs are characterized by economies of scale which can be explained by the presence of fixed costs (Betz et al., 2010; Becker et al., 2013; Bellassen et al., 2015). The second question is how the policy instrument choice influences the level of transaction costs. Coria and Jaraitė (2015) and Joas and Flachsland (2016) provide empirical evidence showing that transaction costs are lower under an emission tax than under a cap-and-trade system.

How transaction costs affect the design and efficiency of an environmental policy instrument was studied by Polinsky and Shavell (1982) in the case of an emission tax, and by Stavins (1995) in the case of an emissions trading scheme. Since we focus on an emission tax, the present research is related to Polinsky and Shavell (1982). An important difference between this early research and

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[2] The use of the term 'transaction costs' is somewhat vague in the literature as it may refer to a wide variety of costs. In this paper, we focus on '*ex post* transaction costs' in the categorization proposed in the review by Krutilla and Krause (2011), *i.e.* the costs of a policy's implementation, administration, and enforcement, which we group under 'MRV costs'.

the present study is that in the latter the emission tax coverage–i.e. who is liable for the tax and who is not–is chosen endogenously by the regulator.

The present paper contributes to this literature by characterizing the optimal coverage in the context of an emission tax when the pollution is caused by a set of heterogeneous firms in the presence of MRV costs. Determining the optimal coverage requires *ex ante* knowledge of firm-level abatement and MRV costs. To circumvent this difficulty, we propose a simple formula approximating the optimal threshold. As this formula relies only on aggregate (rather than firm-level) results, it is less demanding in terms of information requirements. We show how aggregate information obtained from e.g. sectoral applied models can be used in practice to approximate the optimal threshold. This formula gives rise to a convenient graphical interpretation based on a Lorenz curve such as the one depicted in Figure 1.

Agricultural greenhouse gas (GHG) emissions provide an interesting application case for the analytical framework developed here. First, agricultural emissions–despite their weight in total GHG emissions (Smith et al., 2014; Wollenberg et al., 2016)–are excluded from the scope of the main climate policy instruments currently in place in Europe and elsewhere in the world. Second, these emissions result from the activity of a large number of heterogeneous farms, which makes monitoring costly (Garnache et al., 2017). Third, there is debate in the literature about whether MRV costs in this sector are such that they would more than offset the social benefits of including of agricultural GHG emissions in the scope of existing climate policy instruments (Ancev, 2011; De Cara and Vermont, 2011).

The empirical application relies on a supply-side model of the European agricultural sector. This model has two main advantages. First, it provides sectoral level aggregate results, such as the abatement that can be achieved at a given emissions price and the corresponding total abatement costs to the farmers. These results are combined with the findings from a recent review of MRV costs in the field of climate policy conducted by Bellassen et al. (2015) to approximate the optimal threshold. Second, the model provides insights into individual marginal abatement costs for a large number of representative farms operating in a wide variety of contexts across Europe. Based on this farm-level information, the optimal threshold can be computed, and the cost-effectiveness implications of a simple approximation of the optimal threshold can be assessed in various configurations with regard to the marginal damage from GHG emissions, the overall magnitude of the

MRV costs, and how MRV costs vary with farm size.

The remainder of the article is structured as follows. The framework is presented in Section 2 and the optimal threshold is characterized analytically in Section 3. The results of the sectoral model of EU agriculture, and the assumptions with regard to MRV costs are presented in Section 4. The cost-effectiveness implications of implementing partial coverage are assessed in Section 5. Section 6 concludes.

2. Analytical framework

Consider a continuum of firms characterized by a parameter θ distributed according to a cumulative distribution function $F(\theta)$ with $\theta \in \Theta = [\theta_l, \theta_h]$ with $0 \leq \theta_l < \theta_h$. The parameter θ can represent any characteristic of the firm, such as e.g. level of output, use of inputs, or initial emissions. Without loss of generality, the total population of firms is normalized to unity. Therefore, aggregate values over the entire support can be interpreted alternatively as total (denoted by uppercase letters) or per-firm averaged (signaled with a bar) values. The average value of θ over the entire population is denoted $\bar{\theta} = \int_{\Theta} \theta \, \mathrm{d}F(\theta)$.

In the unregulated situation, the activity of each firm causes emissions which are denoted $e_0 \in [e_{0l}, e_{0h}]$. Reducing emissions below this level entails an abatement cost $c(a, \theta)$ for the firm of type θ, where a denotes abatement. There are no fixed costs of abatement. The function $c(.,.)$ is assumed to be twice differentiable with respect to both arguments. Abatement costs are assumed to be increasing and strictly convex with respect to a. Thus, the following standard assumptions are made for all θ in Θ: $c(0, \theta) = 0$, $c_a(0, \theta) = 0$, $c_a(a, \theta) \geq 0$ for all $a > 0$, $c_{aa}(a, \theta) > 0$ where the subscripts indicate partial derivatives.

Each unit of emissions causes an environmental damage which is assumed to be constant[3] and valued at level δ. The regulator considers a tax scheme where each unit of emissions is taxed at rate τ. Implementing the emission tax involves MRV costs. Some of these costs are borne by the firm (e.g. those related to compliance and reporting), and some by the regulator (e.g. those related

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[3] The damage function is therefore assumed to be linear. This assumption may be interpreted as a first-order approximation of the damage function, which is satisfactory when the total level of abatement remains small relative to global concentrations. In the case of a stock pollutant, such as GHG emissions, and in particular when addressing emissions from only one among many emitting sectors (as is the case in the empirical application presented in Section 4), this approximation appears to be satisfactory.

to enforcement and verification). For simplicity and contrary to e.g. Keen and Mintz (2004), the opportunity cost of public funds is assumed to be zero. Therefore, we do not distinguish between the costs borne by the firm and the regulator. Moreover, MRV costs are assumed to be firm-specific and do not depend on the abatement level making them akin to fixed (sunk) costs on a per-firm basis. Per-firm MRV costs are denoted by $m(\theta)$, which is assumed to be twice differentiable with respect to θ.

Note that the assumption that MRV costs $m(\theta)$ do not depend on the firm's level of abatement contrasts with the assumption made by Stavins (1995). However, it is supported by (i) the choice to study an emission tax rather than a cap-and-trade scheme (no trading costs), and (ii) empirical evidence which suggests that MRV requirements and the related costs depend primarily on the size of the regulated entity rather than on how much is abated (Bellassen et al., 2015). In addition, total (abatement and MRV) costs are assumed to remain sufficiently small relative to the firms' profit so that all firms subject to the emission tax continue to produce.[4] These two assumptions ensure that MRV costs do not interfere with the optimal firms' abatement choice. Under these assumptions, the level of abatement that maximizes any firm's profit is such that the marginal abatement cost is equal to the level of the emission tax, i.e.:

$$c_a(a, \theta) = \tau \text{ for all } \theta \in \Theta. \tag{1}$$

Equation (1) implicitly defines the individual abatement supply $a(\tau, \theta)$ for any θ type firm. As a direct consequence of the assumptions regarding abatement costs, the abatement supply for any firm of type θ is monotone increasing with respect to the emission tax and is equal to zero if the emission tax is zero. Thus, for all θ in Θ, $a(0, \theta) = 0$ and $a_\tau(\tau, \theta) > 0$ for all $\tau \geq 0$.

The regulator's objective is to minimize the total social loss, given by the sum of total environmental damage (total emissions–i.e. initial emissions minus abatement–valued at the marginal damage δ) and abatement and MRV costs. Since initial emissions are fixed, this is equivalent to maximizing the social benefit of implementing the tax defined as:

$$B(\tau) = \int_{\Theta} b(\tau, \theta) \, \mathrm{d}F(\theta), \tag{2}$$

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[4] This assumption is different to that made by Polinsky and Shavell (1982), where some firms may exit the market upon implementation of the environmental policy. Relaxing this assumption is possible at the expense of some additional complexity.

$$\text{where } b(\tau,\theta) \equiv \delta a(\tau,\theta) - c(a(\tau,\theta),\theta) - m(\theta) \text{ for all } \theta \in \Theta. \tag{3}$$

Consider first that all firms are subject to the emission tax ('full-coverage'). The regulator chooses the tax rate that maximizes $B(\tau)$. Under our assumptions regarding MRV costs, it is straightforward to see that the standard Pigouvian result is not affected by the presence of MRV costs. Thus, emissions should be taxed at the marginal damage, i.e. $\tau = \delta$. However, under full coverage, total MRV costs may outweigh the aggregate social value of abatement net of abatement costs, thereby deteriorating social welfare compared to the initial situation ($B(\delta) < 0$).

This difficulty can be overcome if the regulator is able to exempt some firms from the emission tax. Exempted firms have no incentive to reduce their emissions so their abatement is zero. At the same time, no MRV costs are incurred for those firms. Firms characterized by individual MRV costs greater than the social value of their abatement net of abatement costs should be exempt, and only firms such that $b(\tau,\theta) \geq 0$ (if any) should be liable for the emission tax. In this case, the regulator's objective function becomes:

$$B^*(\tau) = \int_\Theta \mathbb{1}_{b(\tau,\theta)\geq 0} b(\tau,\theta)\,\mathrm{d}F(\theta) \tag{4}$$

where $\mathbb{1}_{b(\tau,\theta)\geq 0}$ denotes an indicator function equal to 1 when $b(\tau,\theta) \geq 0$, and 0 otherwise.

Under the MRV and abatement costs assumptions underlying Eq. (1), it can be shown easily that the standard Pigouvian result still holds in this context, i.e. $\tau^* \equiv \arg\max_\tau B^*(\tau) = \delta$ (as long as at least some firms are such that $b(\delta,\theta) > 0$). In other words, emissions from firms subject to the emission tax should be taxed at the marginal damage.

By construction, the optimal value of the social benefit given by Eq. (4) is greater than or equal to that associated to full coverage (Eq. (2)), i.e. $B^*(\delta) \geq B(\delta)$, with an equality sign when $\delta a(\delta,\theta) - c(a(\delta,\theta),\theta) \geq m(\theta)$ for all θ. Moreover, it is greater than or equal to that in the *laissez-faire* situation (equal to 0 by construction), i.e. $B^*(\delta) \geq 0$, with an equality sign when $\delta a(\delta,\theta) - c(a(\delta,\theta),\theta) < m(\theta)$ for all θ. This situation is described as 'first-best'.

Implementing the first-best situation requires the regulator to have perfect knowledge of individual abatement and MRV costs, and the ability to 'cherry-pick' firms subject to the emission tax. In practice, this may be both very demanding in terms of information requirements, and at odds with the basic principles of taxation law. Therefore, although useful as a benchmark, this situation does not appear to be a realistic policy option.

3. Optimal threshold

We turn now to a more realistic–and more common in practice–exemption scheme based on a single threshold value θ_s. Only firms characterized by the largest θ, i.e. $\theta \geq \theta_s$, are subject to the emission tax. Firms characterized by θ lower than the threshold are granted exemption, and thus, have no incentive to mitigate their emissions. Note that such a scheme requires that θ is non-manipulable by firms (based on some historic level for instance) and that it can be observed by the regulator. As abatement and MRV costs are zero for exempt firms, the regulator's objective function becomes:

$$B^s(\tau, \theta_s) = \int_{\theta_s}^{\theta_h} b(\tau, \theta)\, \mathrm{d}F(\theta) \tag{5}$$

Any partial coverage should achieve at least a higher social benefit than both the *laissez-faire* and the full-coverage situations, i.e.:

$$B^s(\tau, \theta_s) \geq \max\{B(\tau); 0\} \tag{6}$$

The following proposition goes further than the minimal cost-benefit test given by inequality (6).

Proposition 1 (Optimal threshold). *Consider that the regulator can choose the level of the emission tax ($\tilde{\tau}$) and the threshold value ($\tilde{\theta}_s$) so as to maximize $B^s(\tau, \theta_s)$.*

1. *The pair $(\tilde{\tau}, \tilde{\theta}_s)$ such that $\theta_l < \tilde{\theta}_s < \theta_h$ (if it exists) must verify: (i) $\tilde{\tau} = \delta$, (ii) $b(\delta, \tilde{\theta}_s) = 0$, and (iii) $b_\theta(\delta, \tilde{\theta}_s) > 0$.*
2. *If $b(\delta, \theta_l) < 0$ and $b(\delta, \theta_h) > 0$, then the optimal threshold is interior (i.e. $\theta_l < \tilde{\theta}_s < \theta_h$).*
3. *If $\theta_l < \tilde{\theta}_s < \theta_h$, then the larger the marginal damage δ, the lower the optimal threshold $\tilde{\theta}_s$ all other things being equal.*

Proof. See Appendix A.1.

The first part of the proposition characterizes the interior optimal threshold if it exists. Again, the standard Pigouvian result holds for firms subject to the emission tax (condition (i)). Under the optimal level of the tax $\tilde{\tau} = \delta$, condition (ii) is equivalent to:

$$\delta a(\delta, \tilde{\theta}_s) - c(a(\delta, \tilde{\theta}_s), \tilde{\theta}_s) = m(\tilde{\theta}_s). \tag{7}$$

The 'pivotal' firm should be such that the social value of the abatement of this firm net of abatement costs (left-hand side) compensates the MRV cost associated to this firm (right-hand side). Although slightly different in its presentation, this condition is similar to that obtained by Keen and Mintz (2004) in the context of the turnover threshold above which a firm must register for value-added tax, or by Betz et al. (2010) in the context of a cap-and-trade scheme. It illustrates the trade-off faced by the regulator when setting the exemption threshold: including one additional firm in the scheme–i.e. marginally lowering θ_s–achieves a higher environmental benefit net of abatement costs but comes with additional MRV costs. Condition (iii) ensures that the second-order conditions of the regulator's program are satisfied. Differentiating Eq. (3) with respect to θ and using Eq. (1) with $\tau = \delta$, this condition is equivalent to:

$$c_\theta(a(\delta, \tilde{\theta}_s), \tilde{\theta}_s) + m'(\tilde{\theta}_s) < 0. \tag{8}$$

Therefore, individual costs (abatement plus MRV) must be decreasing with respect to θ in the neighborhood of an interior optimum.

Note that corner solutions are possible since no interior value of θ_s may exist satisfying conditions (ii) and (iii) of Proposition 1. If MRV costs are sufficiently small, full coverage ($\tilde{\theta}_s = \theta_l$) may be optimal. Conversely, the *laissez-faire* situation ($\tilde{\theta}_s = \theta_h$) may be preferable to any taxation scheme if MRV costs outweigh the environmental benefits of covering (even a fraction of the) firms.[5] The second part of Proposition 1 provides the sufficient conditions for optimal coverage to be partial coverage.

The third part of the proposition indicates that, in the case of an interior solution, the greater the marginal damage δ, the larger the proportion of firms that will be subject to the emission tax.

Without any further assumptions about how abatement and MRV costs vary with respect to θ, there may be several interior solutions satisfying conditions (i)-(iii) of Proposition 1. Therefore, the use of a single threshold may lead to tax emissions from firms such that $b(\delta, \theta) < 0$ and grant exemption to firms such that $b(\delta, \theta) \geq 0$. Thus, the optimal threshold $\tilde{\theta}_s$ characterized in Proposition 1 is only a second-best instrument. Proposition 2 provides the sufficient condition under which the optimal threshold corresponds to a first-best instrument.

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[5] Note that, in that case, the tax rate is irrelevant as no firm is subject to the tax, and the social benefit is by construction equal to zero.

Proposition 2. *If* $b_\theta(\delta, \theta) > 0$ *for all* $\theta \in \Theta$*, then an emission tax* δ *affecting only the firms characterized by* $\theta \geq \tilde{\theta}_s$ *yields the first-best social benefit, i.e.* $B^s(\delta, \tilde{\theta}_s) = B^*(\delta)$.

Proof. See Appendix A.2

The condition that $b(\delta, \theta)$ is monotone increasing with respect to θ over the entire support is equivalent to monotone decreasing individual costs (abatement plus MRV, see Eq. (8)). It ensures that the use of a (well-chosen) single threshold is sufficient to perfectly discriminate between the least and the most efficient firms. If this condition is satisfied, implementing the threshold $\tilde{\theta}_s$ leads to the first-best partition of the population as in Eq. (4).

Determining the optimal threshold as characterized in Proposition 1 requires that the regulator has *ex ante* access to detailed information about the firm-level values of $b(\delta, \theta)$. This is a strong requirement, especially when the number of emitters is large. Nevertheless, the regulator may have access to some information at the *aggregate* level prior to policy implementation. In particular, estimates of the aggregate abatement supply curve under full coverage $A(\tau) = \int_\Theta a(\tau, \theta)\, \mathrm{d}F(\theta)$ are often available. The curve $A(\tau)$ is a typical output of applied models aimed at assessing mitigation potential and costs (see e.g Vermont and De Cara, 2010, for a review in the case of GHG emissions from agriculture). Similarly, *ex ante* assessments of the overall magnitude of MRV costs under full coverage ($M = \int_\Theta m(\theta)\, \mathrm{d}F(\theta)$) may be available, e.g. based on data gathered from previous regulations.

If total MRV costs exceed the total social value of abatement net of abatement costs–i.e. if $M > \delta A(\delta) - C(A(\delta))$–, it is clear that *laissez-faire* should be preferred to full coverage. Provided that M and $A(\tau)$ are known, the comparison between the full coverage and the *laissez-faire* can be summarized in the ratio[6] (see Appendix A.3):

$$\hat{k} = \frac{M}{\int_0^\delta A(v)\, \mathrm{d}v}, \tag{9}$$

which is increasing with respect to M and decreasing with respect to δ. The following proposition

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[6] Some studies provide a functional specification for $A(\tau)$ (e.g. De Cara and Jayet, 2011; Vermont and De Cara, 2010). Other studies report only point estimates for some emission prices (e.g. Wollenberg et al., 2016). If the whole curve $A(\tau)$ is not known but only a point estimate of $A(\delta)$ is available, the denominator in Eq. (9) can be computed as $\delta A(\delta) - C(A(\delta))$, provided that the regulator also knows an estimate of the corresponding total abatement cost under full coverage $C(A(\delta))$.

shows how, under some additional assumptions, the ratio $\hat{k}$ can be used to compute the optimal threshold via a simple formula.

Proposition 3. *If (i) $a(\tau, \theta) = \theta\alpha(\tau)$ and (ii) $m(\theta) = \bar{m}$ for all $\theta \in \Theta$, then the optimal threshold is equal to $\tilde{\theta}_s = \hat{k}\bar{\theta}$ and $B(\delta, \hat{k}\bar{\theta}) = B^*(\delta)$.*

Proof. See Appendix A.3.

Assumption (i) is equivalent to assuming that the abatement supply *per unit of* θ ($a(\tau, \theta)/\theta$) is identical across all firms for any given emission price τ.[7] In other words, the abatement supply curve of any individual firm characterized by θ is equal to the aggregate abatement supply curve $A(\tau)$ up to the scaling factor $\theta/\bar{\theta}$. Along with assumption (ii) of constant per-firm MRV costs, this implies that for any given value of δ (see Appendix A.3):

$$b(\delta, \theta) = \frac{\theta}{\bar{\theta}} \int_0^{\delta} A(v)\,\mathrm{d}v - M \text{ for all } \theta \in \Theta. \tag{10}$$

The findings presented in Proposition 3 follow directly from Eq. (10). Proposition 3 offers a simple formula that allows computation of the optimal threshold using only aggregate results under full coverage ($A(\tau)$, M, and $\bar{\theta}$). In addition, if the two conditions of Proposition 3 hold, setting the threshold at this level corresponds to the first-best situation. A direct implication of the formula given in Proposition 3 is that the optimal threshold is greater than $\bar{\theta}$ if and only if the laissez-faire situation is preferable to full coverage ($\hat{k} > 1$). Moreover, the lower the overall magnitude of the MRV costs (M) or the greater the marginal damage (δ), the larger the number of firms that should be liable for the emission tax.

Eq. (10) gives rise also to a convenient graphical interpretation, provided that the regulator knows the Lorenz curve $L(F(\theta)) = \frac{1}{\bar{\theta}} \int_{\theta_l}^{\theta} t\,\mathrm{d}F(t)$. Plugging Eq. (10) into Eq. (5), the total social benefit for any threshold $\theta_s \in \Theta$ under conditions (i) and (ii) of Proposition 3 can be expressed as:

$$B^s(\delta, \theta_s) = [1 - L(F(\theta_s))] \int_0^{\delta} A(v)\,\mathrm{d}v - [1 - F(\theta_s)]M \tag{11}$$

In this context, the inequality (6) reduces to:

$$\frac{L(F(\theta_s))}{F(\theta_s)} \leq \hat{k} \leq \frac{1 - L(F(\theta_s))}{1 - F(\theta_s)} \tag{12}$$

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[7] By analogy with the results in the aggregation literature, assumptions (i) and (ii) can be interpreted as exact aggregation restrictions (see e.g. Blundell and Stoker, 2005).

The inequalities in (12) provide, for any given value θ_s of the threshold, a range for the ratio $\hat{k}$ within which taxing only the emissions from firms such that $\theta \geq \theta_s$ passes the minimal cost-benefit test (6). This is depicted in Figure 2 for a value of θ_s equal to the 80th percentile which corresponds to a cumulative share of about 26% of the total value of θ (point A). In that case, the lower and upper limits of $\hat{k}$ are given by the slopes of the two blue lines passing through A ($0.26/0.8 \approx 0.3$ and $0.74/0.2 \approx 3.7$, respectively).

The Lorenz curve depicted in Figure 2 can be used also to determine the optimal proportion of exempted firms for a given value of $\hat{k}$. Using the well-known property of the Lorenz curve that $L'(F(\theta)) = \theta/\bar{\theta}$, this proportion can be obtained at the point where the slope of the Lorenz curve is equal to $\hat{k}$. This is illustrated in Figure 2 for the case where total MRV costs are approximately three times (slope of the red line) higher than the total social value of abatement net of total abatement costs under full coverage (point B).

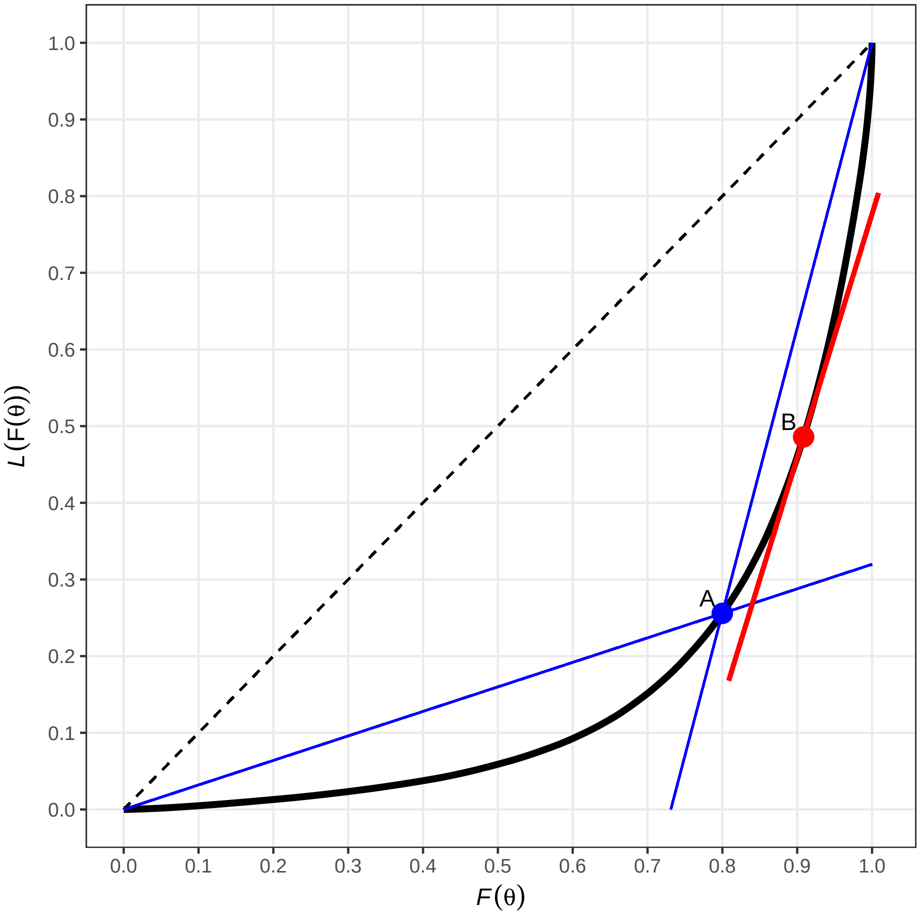

Figure 2: Graphical interpretation of the results of Proposition 3 on the Lorenz curve.

The assumptions of Proposition 3 may seem restrictive. In the absence of detailed information about firm-level abatement and MRV costs, Eq. (10) can be interpreted as a first-order approximation. Applying the formula from Proposition 3 to more general contexts–in particular if per-firm MRV costs are not constant and/or individual abatement supply is non-linear with respect to θ–may result in taxing emissions from firms that should not be subject to the emission tax (if $\hat{k}\bar{\theta} < \tilde{\theta}_s$), or, conversely, in granting exemption to some firms that should be subject to the emission tax (if $\hat{k}\bar{\theta} > \tilde{\theta}_s$).

The findings presented in this section underscore the importance of several factors when determining the threshold above which firms should be subject to the emission tax. First are the value of the marginal damage (δ) and the overall magnitude of per-farm MRV costs (M). These findings highlight also the importance of how abatement and MRV costs vary with the chosen firm characteristic (θ) on which exemption is based. In the following section, these factors are investigated empirically in the context of EU agricultural GHG.

4. MRV and abatement costs of GHG in the EU agricultural sector

The agricultural sector is an important contributor to global anthropogenic GHG emissions mainly through emissions of methane (CH_4) and nitrous oxide (N_2O). Both crops (use of organic and synthetic nitrogen fertilizers, rice cultivation) and livestock (enteric fermentation, manure management) production activities contribute to agricultural GHG emissions (Smith et al., 2014). However, agriculture is excluded from the scope of most current climate policy instruments. The presence of MRV costs has been advanced as one justification for excluding agricultural emissions from the scope of climate policy instruments (Ancev, 2011). The main argument is that high MRV costs in this sector are likely to offset the net social benefits of abatement in this sector if *all* farms were subject to the regulation.

The empirical application rests on the results from a sectoral model of the European agricultural sector. For a general presentation of (a previous version of) the model, see e.g. De Cara and Jayet (2011). The main changes compared to that previous version include a wider geographic coverage (27 EU member states, i.e. all current member states except Croatia), the use of more recent farm-level data from the European Union Farm Accountancy Data Network (EU-FADN for the year 2009), inclusion of the EU Common Agricultural Policy instruments prevailing in 2009, and updated relationships for the computation of GHG emissions based on the information reported by all member states in their GHG inventory reports.

The model is an annual supply-side model which describes the optimal economic decisions of a set of representative farms regarding land allocations and livestock management. Representative farms are clusters of the real farms surveyed by the EU-FADN. This data set provides economic and structural information on approximately 80,000 professional farms in the EU-27 for the year 2009. The typology relies on automatic classification techniques that combine the information provided by the EU-FADN on farm location (134 regions and three altitude classes within the EU-27), economic size, and main farming type. The model covers crop- and livestock-oriented farming systems as well as mixed-farming systems. Farms specialized in perennial crops (orchards, vineyards) are excluded from the analysis. The typology results in 1,802 clusters, representing approximately 3.7 million existing farms.

Each representative farm is associated with a micro-economic gross-margin maximization model subject to resource availability (e.g. land, stable places), agronomy (e.g. crop rotations, animal feeding requirements, livestock demography), and policy constraints. The main choice variables for each farmer are the areas allocated to different crops (the model accounts for the 24 main annual crops grown in Europe, and for temporary and permanent grassland), livestock numbers in each animal category (dairy and non-dairy cattle broken down into age and sex, sheep, goats, swine, poultry), and animal feed (e.g. on-farm produced vs. purchased feed, forage vs. concentrates) given animal-specific protein and energy minimum requirements and maximal ingested matter constraints. Most input parameters (input and output prices, yields, variable costs) are farm-specific and estimated using EU-FADN data. A restricted set of technical parameters, for which farm-level observations are lacking, are calibrated so that the model reproduces FADN observations at the representative farm level for the year 2009.

The model covers the major non-CO_2 GHG sources caused by farming activities: N_2O emissions from agricultural soil and manure management, and CH_4 emissions from manure management, enteric fermentation and rice cultivation. The emissions accounting method uses country-specific emission factors taken from national GHG inventory reports. The emission factors are linked to each farm's relevant activity variables, so that emissions for all categories are computed endogenously. CH_4 and N_2O emissions are converted into CO_2 equivalent using the respective

Global Warming Potential (25 for CH_4, 298 for N_2O). Total initial emissions amount to about 407 MtCO_2eq, or about 96% of agricultural emissions reported by the European Environment Agency (2016) for year 2009.

Initial emissions vary markedly among farms. Computed per-farm emissions at the representative farm level range from 0.3 tCO_2eq to about 7,700 tCO_2eq per year, an average of approximately 109.8 tCO_2eq (see Table B.3 in Appendix). The corresponding Lorenz curve of initial emissions is depicted in Figures 1 and 2, with 20% of the farms responsible for almost 75% of total emissions.[8]

When faced with an emission tax τ, each representative farmer endogenously adjusts the land allocation among crops, animal feed, and/or animal numbers until the marginal abatement cost is equal to τ. Plotting the resulting individual reductions in emissions against the emission tax (from 0 to 200 €/tCO_2eq in steps of 1 €/tCO_2eq) provides the abatement supply curve for each representative farm. The corresponding EU-wide aggregated abatement supply curve is provided in appendix (Figure B.6).

For simplicity, the analysis focuses on four emission prices: 5, 25, 50, and 100 €/tCO_2eq. The lowest value corresponds approximately to the average price of CO_2 emissions allowances in the EU ETS in 2016.[9] The highest value corresponds to the price required to maintain a sufficiently large probability of limiting the global temperature increase to below 2°C above pre-industrial levels (Rogelj et al., 2013). At these prices, aggregate abatement represents approximately 2%, 7%, 11%, and 20% of total initial EU agricultural emissions, respectively. The corresponding EU-wide abatement costs range from 18 million to almost 3.6 billion euros, while the social value of abatement net of abatement costs ranges from 22 million to 4.5 billion euros (see Table 1).

In a recent review, Bellassen et al. (2015) compile the available information on the MRV costs related to various climate policy instruments (ETS, clean development mechanism projects, inventories), and at various scales (jurisdiction, entity, project). The authors fit a log-linear relationship between per-ton MRV costs (μ) and initial per-entity emissions (e_0). Over the range explored by

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[8] Note that, as (i) the EU-FADN data does not provide information about non-professional farms, (ii) some farming activities (vineyard, orchards) are excluded from the analysis, (iii) emissions are computed for representative farms that result from the grouping of real farms, the Lorenz curve presented in Figure 2 may not fully reflect the actual concentration of emissions among farms.

[9] See `https://www.eex.com/en/market-data/environmental-markets/auction-market`, (last checked on December 23, 2016).

Table 1: Aggregate results under full coverage (Total farm population: $F = 3.7.10^6$ farms).

Emission price δ [€/tCO$_2$eq]	Emissions $E(\delta)$ [10^6tCO$_2$eq]	Abatement $A(\delta)$ [10^6tCO$_2$eq]	Abatement cost $C(A(\delta))$ [10^6€]	Net social value of abatement $\delta A(\delta) - C(A(\delta)) = \int_0^\delta A(v)\mathrm{d}v$ [10^6€]
0	406.8	-	-	-
5	398.8	8.0	18.0	22.0
25	379.9	26.9	271.9	399.7
50	361.0	45.8	979.4	1310.3
100	326.0	80.8	3557.4	4524.0

the authors, per-ton MRV costs are found to be decreasing with respect to initial emissions.[10] The estimated relationship implies increasing and concave per-entity MRV costs, suggesting the presence of economies of scale in MRV. However, note that the data collected for that review pertain mainly to firms in energy-intensive sectors, where emissions often exceed those of a typical farm by several orders of magnitude. For example, the initial emissions of the smallest emitting entity in Bellassen et al. (2015) are more than 12% larger than the emissions from highest emitting representative farm, and about 80 times larger than the average per-farm emissions.

Three scenarios are considered in relation to the magnitude of MRV costs. The high-MRV-costs scenario is based on direct extrapolation from the fitted curve proposed by Bellassen et al. (2015) using initial emissions from the representative farms as the independent variable. When aggregated at the EU-level, total MRV costs amount to more than 6 billion euros, or more than 15 €/tCO$_2$eq (see Table 2). The low-MRV-costs scenario assumes average per-ton MRV costs of $\bar{\mu}$=1.56 €/tCO$_2$eq which is the highest value in the range explored by Bellassen et al. (2015), i.e. that associated with the smallest emitter. The medium-MRV-costs scenario is based on average per-ton MRV costs that are twice that ($\bar{\mu}$=3.12 €/tCO$_2$eq). This figure is about 25% higher than that proposed by Ancev (2011) for mandating agricultural emissions to enter the EU-ETS. It corresponds to an overall average of about 343 € per farm.

These three scenarios are combined with three assumptions regarding the specification of per-farm MRV costs: (A) constant, (B) increasing and concave based on extrapolation of the relation-

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[10] Expressing per-ton MRV costs (μ) in €/tCO$_2$eq and per-entity initial emissions (e_0) in tCO$_2$eq, the fitted relationship obtained by Bellassen et al. (2015) is $\log(\mu) = 6.062 - 0.662\log(e_0)$. Per-entity MRV costs ($m = \mu.e_0$, in €) can thus be expressed as $m(e_0) = 429.4(e_0)^{0.338}$.

ship fitted by Bellassen et al. (2015), rescaled (where necessary) so that total MRV costs under full coverage match the respective M values, and (C) increasing and linear. The implications for total, per-farm, and per-ton MRV costs are presented in Table 2. Note that only the first specification satisfies condition (ii) in Proposition 3. The first two specifications imply that MRV costs exhibit economies of scale.

Table 2: Assumptions regarding MRV costs.

Specification and magnitude	Total M [10^6 €]	Per farm $m(e_0)$ [€/farm]			Per ton $\mu(e_0) = m(e_0)/e_0$ [€/tCO$_2$eq]		
		$\bar{m}$	min	max	$\bar{\mu}$	min	max
(A) Constant per-farm MRV costs: $m(e_0) = \bar{m}$							
Low	635	171	171	171	1.56	0.02	669.93
Medium	1270	343	343	343	3.12	0.04	1339.85
High	6138	1657	1657	1657	15.09	0.22	6475.11
(B) Increasing, concave per-farm MRV costs: $m(e_0) = \frac{M}{6138}\left[429.4(e_0)^{0.338}\right]$							
Low	635	171	28	916	1.56	0.12	109.50
Medium	1270	343	56	1831	3.12	0.24	219.00
High	6138	1657	271	8850	15.09	1.15	1058.39
(C) Increasing, linear per-farm MRV costs: $m(e_0) = \bar{\mu}e_0$							
Low	635	171	0	11998	1.56	1.56	1.56
Medium	1270	343	1	23995	3.12	3.12	3.12
High	6138	1657	4	115962	15.09	15.09	15.09

As shown in Section 3, the optimal emission threshold is a second-best instrument. Moreover, given the nature of the model used to elicit marginal abatement costs and the heterogeneity of farms with regard to production conditions and sources of GHG emissions, nothing ensures that farm-level abatement supply curves are all linear with respect to e_0. Therefore, it can be expected that the implementation of the emission threshold based on the formula from Proposition 3 yields a lower social benefit than that associated to the optimal emission threshold, which is itself lower than the first-best social benefit. This is investigated empirically in the next section.

5. Optimal threshold in the case of GHG emissions from the European agricultural sector

In this section, we start by considering that only the largest emitters are subject to the emission tax (i.e. $\theta \equiv e_0$). Note that this requires that farm-level initial emissions can be observed by the regulator. In the context of GHG emissions from European agriculture, this is supported by the fact that individual emissions can be approximated quite well using some standardized computation rules–such as e.g. those used in national GHG inventories–based on input data (area, yields, animal numbers, and synthetic and organic nitrogen management) which are readily available.[11]

It is possible also to base exemption on alternative criteria that require no prior computations by the regulator. Two additional criteria are investigated in this section: the farm's total agricultural area, and number of animals (expressed in livestock units –LU). Information regarding these variables is reported routinely by farmers for fiscal or agricultural policy purposes. Note that to determine the tax base still requires farms' emissions to be computed but only for the farms liable for the emission tax, not necessarily the entire farm population. All three criteria are based on historic levels of the respective characteristic–i.e. prior to the implementation of the emission tax–to ensure that they are not manipulable by farmers. The summary statistics for all three criteria are reported in appendix Table B.3.

For clarity, the results are presented first for a benchmark configuration characterized by a marginal damage equal to 25 €/tCO$_2$eq, constant per-farm MRV costs amounting to 343 € per farm (medium MRV costs), and an exemption criterion based on initial emissions ($\theta \equiv e_0$). In this configuration, all the information needed to approximate the optimal emission threshold using the formula from Proposition 3 can be retrieved from Tables 1 and 2. Total MRV costs under full coverage are about 3.18 times higher than the net social value of abatement. Thus, the corresponding threshold is given simply by $\hat{k}\bar{\theta} = 3.18 \times 109.8 \approx 349$ tCO$_2$eq. Setting the threshold at this level implies that only the emissions from the top 9.1% emitting farms are taxed for an emission coverage of about 51.4% (point B in Figure 2).

How accurate is this approximation of the optimal emission threshold and what are its welfare implications? To answer these questions, we make full use of the information contained in the model result, which provide marginal abatement costs at both the EU-wide level and the (representative) farm level. This information can be used to compute total social benefit in the first-best situation (as in Eq. (4)), and in the optimal emission threshold case (characterized by Proposition 1).

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[11] As argued by De Cara and Vermont (2011), existing Common Agricultural Policy (CAP) provisions demand that farmers–as soon as they benefit from CAP payments–collect and/or report this information.

Figure 3 depicts how MRV costs, the net social value of abatement, and the resulting total social benefit vary with respect to the emission threshold in the benchmark configuration. To ease comparison between Figures 2 and 3, these variables are plotted against the cumulative share of the total farm population, with farms sorted by increasing initial emissions. The x-axis in Figure 3 thus gives the share of exempted farms in the total population for all values of the threshold.

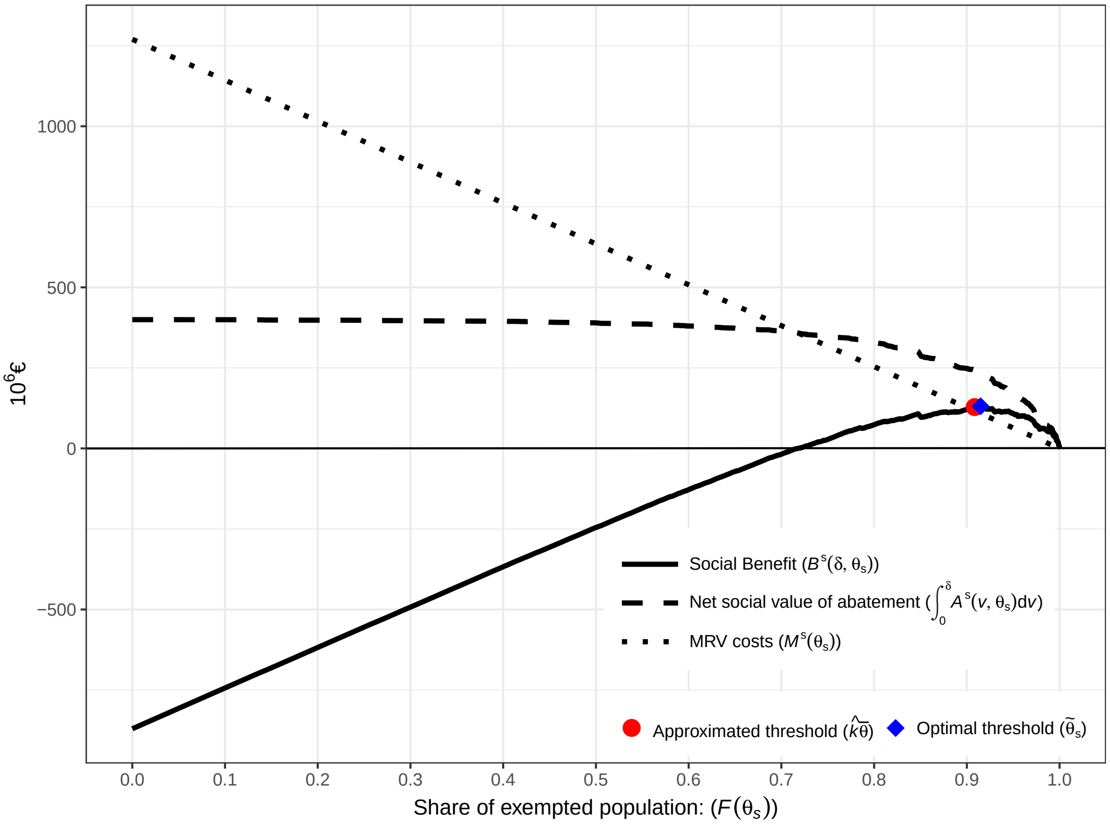


Figure 3: Total social benefit (solid curve) and its components in the benchmark configuration. *Note:* δ = *25 €/tCO$_2$eq, constant per-farm MRV costs equal to 343 € per farm (medium MRV costs), and only the largest emitting farms are subject to the emission tax ($\theta \equiv e_0$).*

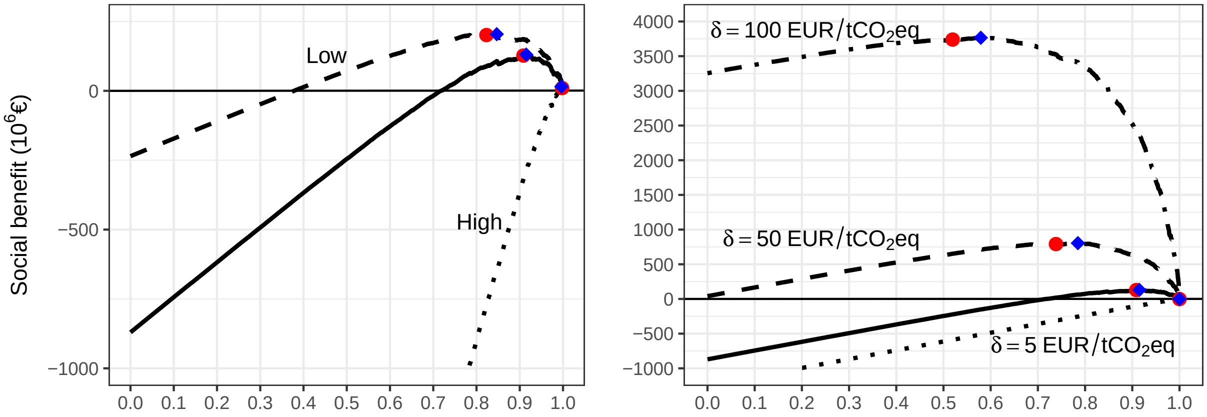
In the benchmark configuration, taxing emissions from all farms (i.e. $F(\theta_s) = 0$) leads to a net social loss of about 870 M€. This configuration corresponds to the situation put forth by Ancev (2011): under full coverage, MRV costs are markedly higher than the net social value of abatement. Figure 3 indicates also that the *laissez-faire* situation is preferable to an emission tax for any emission threshold below the 72nd percentile. The optimal emission threshold is equal approximately to 370 tCO$_2$eq. This would entail exemption of around 91.5% of farms (but only 50.7% of emissions) for a corresponding total social benefit of about 131 M€ (blue diamond in

Figure 3). In this configuration, the social loss associated with implementation of the approximated (red dot) rather than the optimal emission threshold is small (about 3 M€).

Figure 4 depicts how the total social benefit in the benchmark configuration is affected by alternative assumptions regarding the magnitude of MRV costs, the level of marginal damage, the MRV cost specification, and the choice of the exemption criterion. The full results for the first-best, optimal emission threshold, and approximated emission threshold configurations are reported in Tables B.4 to B.6 in Appendix.

a. Sensitivity to the MRV costs magnitude (δ = 25 €/tCO$_2$eq; $m(e_0) = \bar{m}$; $\theta \equiv e_0$)

b. Sensitivity to the marginal damage ($m(e_0) = \bar{m}$ = 343 €, $\theta \equiv e_0$)



c. Sensitivity to the MRV costs specification (δ = 25 €/tCO$_2$eq; $\bar{m}$ = 343 €; $\theta \equiv e_0$)

d. Sensitivity to the choice of the criterion (δ = 25 €/tCO$_2$eq; $m(e_0) = \bar{m}$ = 343 €)

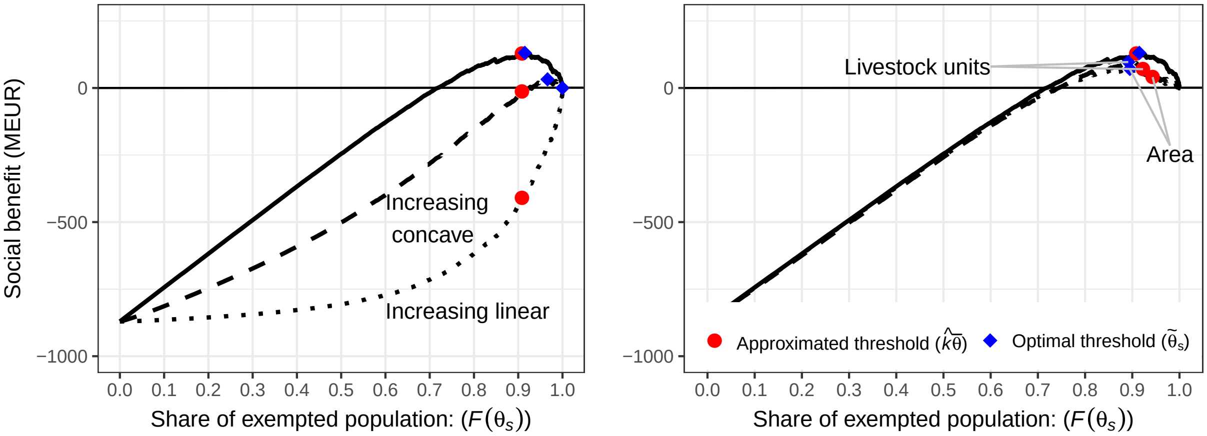


Figure 4: Total social benefit under alternative assumptions. *Note: The solid curve is the same as in Figure 3 and corresponds to the social benefit in the benchmark configuration:* δ = 25 €/tCO$_2$eq, $m(e_0) = \bar{m}$ *(constant per-farm MRV costs),* $\bar{m}$ = 343 € *per farm (medium MRV costs), and* $\theta \equiv e_0$ *(only the largest emitting farms are subject to the emission tax).*

As Propositions 1 and 3 underscored, the overall magnitude of the MRV costs is an important determinant of both the optimal and the approximated thresholds. This is illustrated by Figure 4.a which depicts the social benefit associated with three values of the (constant) per-farm MRV costs, holding constant the value of the marginal damage ($\delta = 25$ €/tCO_2eq). The optimal emission threshold under high MRV costs (1295 tCO_2eq) would lead to the exemption of about 99.6% of the farms. Under low MRV costs, the optimal threshold is only 211 tCO_2eq, leading to 84.7% of the farms being exempted. In all three configurations, the social loss associated to the approximated emission threshold does not exceed 5.1 M€ (see appendix Tables B.5 and B.6).

Figure 4.b illustrates the role of the marginal damage under constant per-farm MRV costs of 343 €. The optimal emission threshold involves farm exemption rates ranging from about 58% (if $\delta = 100$ €/tCO_2eq) to almost 100% (if $\delta = 5$ €/tCO_2eq). Note that the gap between the exemption rates under the optimal and approximated thresholds is wider for the two largest values of δ (50 and 100 €/tCO_2eq). For all the values of δ explored in Figure 4.b, the social loss from approximating the emission threshold remains relatively small (from 0.3 to 26.6 M€, see Tables B.5 and B.6).

Figure 4.c highlights the effect of the specification of per-farm MRV costs. For the same value of total MRV costs under full coverage (medium, $M = 1270$ M€) and the same value of the marginal damage ($\delta = 25$ €/tCO_2eq), the optimal emission threshold leads to 96.6% of the farms being exempted in the increasing and concave case, and to all farms (i.e *laissez-faire*) being exempted in the linear increasing case. By construction, the formula from Proposition 3 only depends on aggregate results under full coverage. Therefore, for any given values of M and δ, the approximated emission threshold is the same regardless of the distribution of MRV costs among farms. Therefore, direct application of this formula might lead to coverage that does not pass the minimal cost-benefit test (6). Figure 4.c depicts such a situation where the approximated emission threshold based on Proposition 3 (red dots) leads to a net social loss of about 14 M€ if per-farm MRV costs are increasing and concave with respect to initial emissions, and 409 M€ if they are increasing and linear.

Figure 4.d depicts how the total social benefit is affected if exemption is based on initial area or livestock numbers rather than on emissions in the benchmark configuration. The respective values of the total social benefit under the three criteria are fairly close. This is true in particular, for thresholds below the respective medians. This can be explained by the fact that the smallest farms, measured in terms of area or number of animals, are also the smallest emitters. Nevertheless,

for any given value of the threshold θ_s, the social benefit is larger if exemption is based on the farm's initial emissions rather than on area or number of animals. This suggests that the level of individual initial emissions is a better predictor of the sign of the respective social value of abatement net of abatement and MRV costs ($b(\delta, \theta_s)$) than farm area or number of animals. The optimal area threshold is about 82 ha, while the optimal animal number threshold is about 68 LU. The respecting corresponding social benefit is 60 M€ and 34 M€ lower than under the optimal emission threshold.

Figure 5 summarizes the social benefit under various exemption regimes (first-best, optimal threshold, approximated threshold) for the 36 scenarios described in Section 4 (4 values of the marginal damage, 3 levels of per-farm average MRV costs, and 3 specifications of per-farm MRV costs). For clarity, we focus only on the case of an emission threshold (i.e. $\theta \equiv e_0$).[12] The upper set of graph in Figure 5 compares the total social benefit if only firms above the optimal emission threshold are subject to the emission tax (on the x-axis) with the first-best social benefit (y-axis) under the three assumptions regarding the specification of per-farm MRV costs. In all situations except those where the first-best situation leads to a 100% exemption rate, the differences between the first- and second-best social benefit are strictly positive. This implies that the abatement supply at the representative farm level does not satisfy condition (i) of Proposition 3.[13] However, the formula provided in Proposition 3 appears to offer a satisfactory approximation of the second-best emission threshold if per-farm MRV costs are constant (specification (A), bottom row). This is the case also–although to a lesser extent–under specification (B). Only under specification (C), does the approximated threshold lead to a substantial social loss compared to the second-best social benefit.

6. Concluding remarks

When pollution is caused by a large number of heterogeneous firms and each firm's actions are costly to monitor and verify, the question that naturally arises is whether MRV costs more

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[12] All other things being equal, the use of area or number of animals as the exemption criterion (not shown here) yields a social benefit very close to that under the emission threshold.

[13] This is easily confirmed by the examination of the simulation results at the individual level, which show a large variability of abatement rates ($a(\delta, e_0)/e_0$) for the same emission tax. For example, if $\delta = 25$ €/tCO$_2$eq, farm-level abatement rates range from 0 to about 60% of initial emissions.

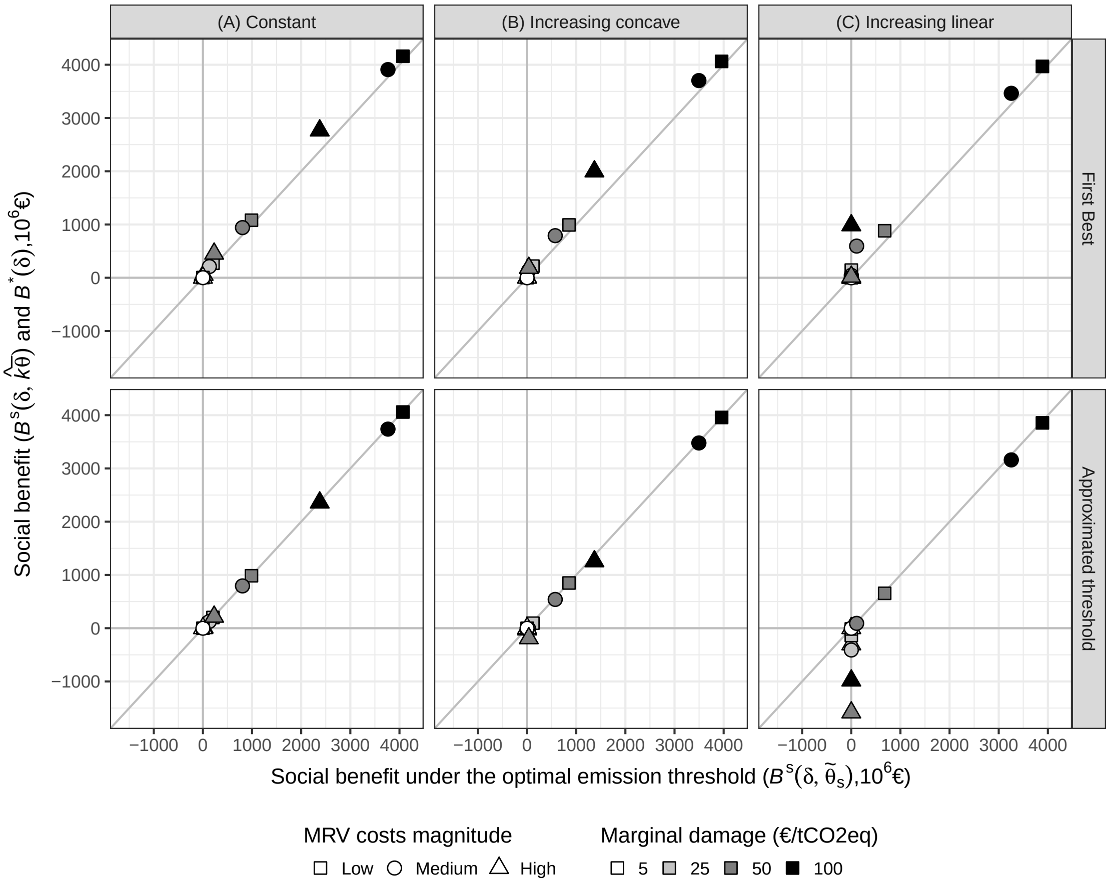

Figure 5: Comparison of the total social benefit under various exemption schemes (upper three graphs: First-best vs. optimal emission threshold, bottom row: Approximated vs. optimal emission threshold), three specifications of per-farm MRV costs (columns), and various assumptions regarding the magnitude of MRV costs and marginal damage.

than offset the social benefit that can be expected from the environmental policy, and therefore, whether implementing a policy instrument makes economic sense. Our findings emphasize that the choice faced by the regulator is not necessarily restricted to choosing between *laissez-faire* and full coverage. Targeting only a fraction of the firms may limit MRV costs, while simultaneously incentivizing cost-effective reductions in emissions.

Designing a partial coverage regulation requires to determine which agents will be subject to the environmental instrument, and which should be outside of its scope. The policy design examined in this paper is simple insofar as it relies on a single threshold value of some known firm characteristic. This corresponds to a second-best approach. Partial coverage may also involve issues related to information if individual abatement and MRV costs remain unknown to the regulator. Our analytical findings show how knowledge related to aggregate (rather than individual) abatement and MRV costs can be used effectively to approximate the optimal threshold. This demonstrates that in practice, the results from applied aggregate models could inform policymakers involved in designing a second-best exemption scheme, even in the absence of detailed firm-level information on abatement costs. Our results also reveal the relationship between the social gains that can be expected from partial coverage, and the concentration of the chosen firm characteristic among firms.

The empirical application to the issue of GHG emissions from European agriculture sheds some new quantitative light on whether emissions from the agricultural sector should be included in the scope of climate policy instruments. Our empirical findings indicate that under a wide range of assumptions regarding the marginal damage and the overall magnitude of MRV costs, targeting only the largest emitting farms could enable significant savings on MRV costs as well as allowing sufficient abatement to ensure higher social benefit than in a *laissez-faire* scenario.

Although data on MRV costs are lacking for the agricultural sector, evidence from other sectors, and the nature of GHG emissions and mitigation options in agriculture, tend to support the assumption that MRV costs are in large part akin to fixed costs. In this context, our findings show that the formula proposed in the paper to approximate the optimal threshold performs satisfactorily. Thus, this formula could become a useful basis for the design of more comprehensive–in terms of sectoral coverage–climate policies.

In this text, the motivation for adopting partial coverage was based on cost-effectiveness arguments. It might also have consequences for the income distribution among agents. For example, in the benchmark configuration proposed in the text (emission tax of 25 €/tCO_2eq, constant per-farm MRV costs of 343 €) and in the absence of any other redistribution mechanism, an emission tax affecting all farms (full coverage) would increase farm income inequalities compared to the *laissez-faire* situation (Gini index up from 0.700 to 0.707). By contrast, taxing only those farms emitting above the approximated emission threshold (in this case 349 tCO_2eq) would slightly reduce these inequalities (Gini index down to 0.695).

This work could be extended in several directions. First, the analysis of an emission tax could be adapted to examine a cap-and-trade mechanism. Although the fundamental mechanisms at play would remain, this might allow the costs related to the trading of permits to be taken into account. Since these costs are likely to depend on the level of abatement, this would likely introduce a wedge between marginal abatement cost and the emission price. Second, the simple second-best approach developed here could be compared to a more complex mechanism design aimed at revealing individual information. The empirical model used in this text could serve as a basis to quantify the associated information rent. Third, the introduction of partial coverage might cause leakage effects, and/or induce strategic behavior from firms in response to implementation of partial coverage. This is left to further research.

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Appendix A. Proofs

Appendix A.1. Proof of Proposition 1

The Lagrangian of the regulator's maximization problem is:

$$\mathcal{L} = B^s(\tau, \theta_s) - \rho_l(\theta_l - \theta_s) - \rho_h(\theta_s - \theta_h), \tag{A.1}$$

where ρ_l and ρ_h are the (non-negative) multipliers associated with the constraints $\theta_s \geq \theta_l$ and $\theta_s \leq \theta_h$, respectively. The corresponding first-order conditions with respect to τ and θ_s are:

$$B^s_\tau(\tau, \theta_s) = \int_{\theta_s}^{\theta_h} b_\tau(\tau, \theta)\, \mathrm{d}F(\theta) = 0 \tag{A.2}$$

$$B^s_{\theta_s}(\tau, \theta_s) + \rho_l - \rho_h = -b(\tau, \theta_s) + \rho_l - \rho_h = 0 \tag{A.3}$$

1. (i) Differentiating Eq. (3) with respect to τ and using Eq. (1), we have that for all $\theta \in \Theta$:

   $$b_\tau(\tau, \theta) = \delta a_\tau(\tau, \theta) - c_a(a(\tau, \theta), \theta) a_\tau(\tau, \theta) = (\delta - \tau) a_\tau(\tau, \theta). \tag{A.4}$$

   As $a_\tau(\tau, \theta) > 0$ for all θ and all $\tau > 0$, Eq. (A.2) is therefore equivalent to $\tilde{\tau} = \delta$ as soon as $\tilde{\theta}_s < \theta_h$.

   (ii) The complementarity slackness conditions imply that if $\theta_l < \tilde{\theta}_s < \theta_h$ then $\rho_l = \rho_h = 0$. Condition (ii) thus directly results from Eq. (A.3) in the case of an interior solution.

   (iii) For an interior solution ($\theta_l < \tilde{\theta}_s < \theta_h$), the second-order conditions are verified when the Hessian matrix of $B^s(\tau, \theta_s)$ evaluated in $(\tilde{\tau}, \tilde{\theta}_s)$ is negative definite. Differentiating B^s twice with respect to τ and θ_s and using Eq. (1), it comes:

   $$B^s_{\tau\tau}(\tau, \theta_s) = \int_{\theta_s}^{\theta_h} b_{\tau\tau}(\tau, \theta)\, \mathrm{d}F(\theta) = \int_{\theta_s}^{\theta_h} [(\delta - \tau) a_{\tau\tau}(\tau, \theta) - a_\tau(\tau, \theta)]\ \mathrm{d}F(\theta) \tag{A.5}$$

   $$B^s_{\theta_s\tau}(\tau, \theta_s) = -b_\tau(\tau, \theta_s) = -(\delta - \tau) a_\tau(\tau, \theta_s) \tag{A.6}$$

   $$B^s_{\theta_s\theta_s}(\tau, \theta_s) = -b_\theta(\tau, \theta_s) \tag{A.7}$$

   Evaluating Eqs. (A.5) to (A.7) in $\tau = \tilde{\tau} = \delta$ and $\theta_s = \tilde{\theta}_s$, and using that $a_\tau(\tau, \theta) > 0$ for all θ and all $\tau > 0$, we thus have that $B^s_{\tau\tau}(\delta, \tilde{\theta}_s) < 0$ and that $B^s_{\tau\tau}(\delta, \tilde{\theta}_s) B^s_{\theta_s\theta_s}(\delta, \tilde{\theta}_s) - (B^s_{\theta_s\tau}(\delta, \tilde{\theta}_s))^2 > 0$ if and only if $b_\theta(\delta, \tilde{\theta}_s) > 0$.

2. As $m(\theta)$, $c(a, \theta)$, and $a(\tau, \theta)$ are all differentiable with respect to θ, we have that $b(\tau, \theta)$ is continuous with respect to θ. Therefore, if $b(\delta, \theta_l) < 0$ and $b(\delta, \theta_h) > 0$, there is at least one interior value of θ_s satisfying conditions (ii) and (iii).

Moreover, if $\tilde{\theta}_s = \theta_l$ (full coverage) then $\tilde{\theta}_s < \theta_h$, which implies that $\rho_h = 0$ (complementarity slackness condition relative to the constraint $\theta_s \leq \theta_h$). Eq. (A.3) thus reduces to $b(\delta, \theta_l) = \rho_l$. As $\rho_l \geq 0$ in the optimum, a full coverage cannot maximize social benefit if $b(\delta, \theta_l) < 0$. Using the same line of reasoning for $\tilde{\theta}_s = \theta_h$ (*laissez-faire*), the condition $b(\delta, \theta_h) > 0$ implies that the *laissez-faire* situation cannot maximize social benefit. Therefore, the optimal threshold necessarily corresponds to an interior solution.

3. Differentiating condition (ii) with respect to $\tilde{\theta}_s$ and δ and using condition (iii) leads to:

$$\frac{d\tilde{\theta}_s}{d\delta} = -\frac{a(\delta, \tilde{\theta}_s)}{b_\theta(\delta, \tilde{\theta}_s)} < 0 \tag{A.8}$$

Appendix A.2. Proof of Proposition 2

If $b(\delta, \theta)$ is strictly monotone increasing with respect to θ, there is at most one value of θ satisfying conditions (ii) and (iii) of Proposition 1. In the case of an interior solution, we thus have that all exempted firms (i.e. $\theta < \tilde{\theta}_s$) are such that $b(\delta, \theta) < b(\delta, \tilde{\theta}_s) = 0$, and that all firms subject to the emission tax (i.e. $\theta \geq \tilde{\theta}_s$) are such that $b(\delta, \theta) \geq 0$. If the optimal threshold is equal to θ_l (full coverage), then necessarily $b(\delta, \theta_l) \geq 0$ (see Eq. (A.3)), and therefore $b(\delta, \theta) \geq 0$ for all $\theta \in \Theta$. Symmetrically, if the optimal threshold is equal to θ_h (*laissez-faire*), then necessarily $b(\delta, \theta_h) \leq 0$, and therefore $b(\delta, \theta) \leq 0$ for all $\theta \in \Theta$. In all cases, the partition of the firms is the same as in the first-best situation presented in Section 2.

Appendix A.3. Proof of Proposition 3

Using Eq. (1) for $\tau = \delta$, the formula of integration by parts and the change of variable $v = c_a(u, \theta)$, we can write for all $\theta \in \Theta$:

$$\begin{aligned} \delta a(\delta, \theta) - c(a(\delta, \theta), \theta) &= c_a(a(\delta, \theta), \theta) a(\delta, \theta) - \int_0^{a(\delta, \theta)} c_a(u, \theta) du \\ &= \int_0^{a(\delta, \theta)} c_{aa}(u, \theta) u \, \mathrm{d}u = \int_0^{\delta} a(v, \theta) \, \mathrm{d}v, \end{aligned} \tag{A.9}$$

which is positive as soon as $\delta > 0$. Integrating Eq. (A.9) over Θ yields:

$$\int_\Theta [\delta a(\delta, \theta) - c(a(\delta, \theta), \theta)] \, \mathrm{d}F(\theta) = \int_\Theta \left[\int_0^\delta a(v, \theta) \, \mathrm{d}v \right] \mathrm{d}F(\theta) = \int_0^\delta A(v) \, \mathrm{d}v. \tag{A.10}$$

Under assumption (i), Eq. (A.10) reduces to:

$$\int_0^\delta A(v) \, \mathrm{d}v = \int_0^\delta \left[\int_\Theta \theta \alpha(v) \, \mathrm{d}F(\theta) \right] \mathrm{d}v = \bar{\theta} \int_0^\delta \alpha(v) \, \mathrm{d}v \tag{A.11}$$

and Eq. (A.9) can be expressed as:

$$\int_0^\delta a(v,\theta)\,\mathrm{d}v = \theta \int_0^\delta \alpha(v)\,\mathrm{d}v = \frac{\theta}{\bar{\theta}} \int_0^\delta A(v)\,\mathrm{d}v. \tag{A.12}$$

As the mass of the total population is normalized to unity, assumption (ii) implies that $m(\theta) = M$ for all θ. Using Eq. (A.12), we therefore have under assumptions (i) and (ii):

$$b(\delta,\theta) = \frac{\theta}{\bar{\theta}} \int_0^\delta A(v)\,\mathrm{d}v - M \text{ for all } \theta \in \Theta. \tag{A.13}$$

As $\bar{\theta} > 0$ and $A(\tau) > 0$ for all $\tau > 0$, $b(\delta,\theta)$ is monotone increasing with respect to θ for all $\theta \in \Theta$. Therefore, the second-order conditions ((iii) in Proposition 1) and the condition of Proposition 2 are readily satisfied. Using Eq. (A.13) and solving $b(\delta,\theta_s) = 0$ for θ_s gives the interior optimal threshold (see Proposition 1). Last, corner solutions occur if $\hat{k}\bar{\theta} \leq \theta_l$ (full-coverage) or if $\hat{k}\bar{\theta} \geq \theta_h$ (*laissez-faire*).

Appendix B. Empirical application results

Table B.3: Descriptive statistics: per-farm characteristics in the reference situation (no emission tax).

	Emissions e_0 [tCO_2eq]	Agricultural area s_0 [ha]	Livestock numbers ℓ_0 [Livestock units]
Mean	109.81	35.10	27.54
Standard deviation	259.53	94.50	90.27
Min	0.26	0.05	0.00
Q1	11.25	6.09	1.82
Median	29.14	13.34	4.82
Q3	113.83	37.53	24.19
Max	7685.83	2696.22	5928.86

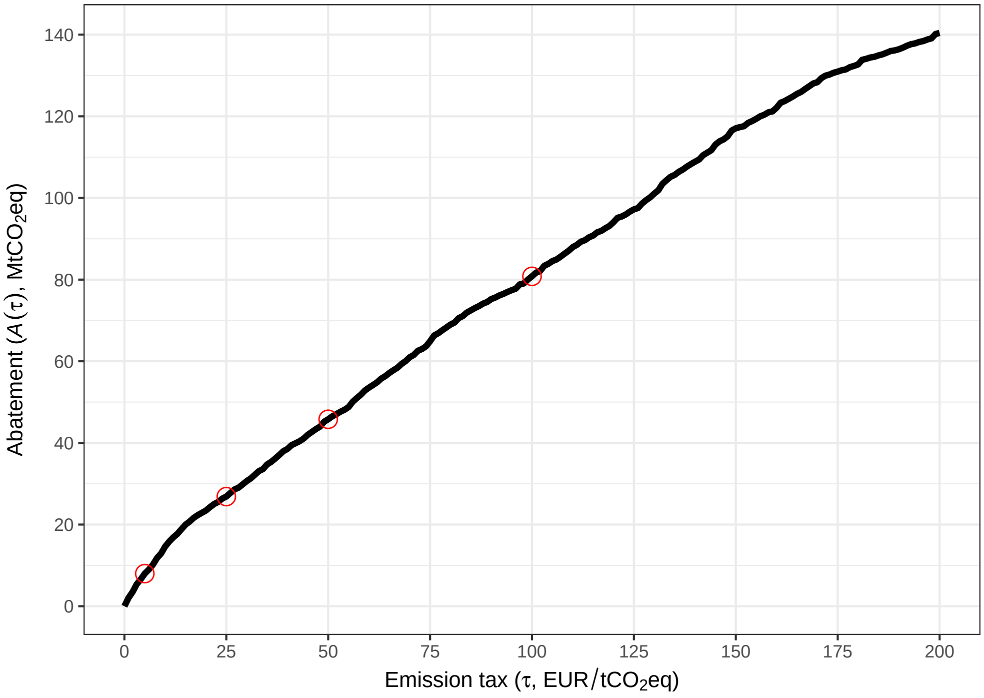

Figure B.6: Aggregate abatement supply for the EU-27 agriculture under full coverage.

Table B.4: First-best results

MRV costs specicification and magnitude	Emission tax δ [€/tCO$_2$eq]	Share of exempted		Abatement $A^*(\delta)$ [MtCO$_2$eq]	MRV costs $M^*(\delta)$ [10^6€]	Social benefit $B^*(\delta)$ [10^6€]
		Farms [1]	Emissions [1]			
(A) Constant per-farm MRV costs						
Low	5	0.995	0.957	2.5	3.4	4.1
	25	0.883	0.586	22.0	74.6	272.4
	50	0.748	0.345	42.4	159.9	1080.3
	100	0.554	0.164	79.0	283.5	4159.3
Medium	5	0.998	0.975	1.5	2.8	1.6
	25	0.920	0.673	19.3	101.1	210.8
	50	0.812	0.429	39.6	239.1	942.2
	100	0.645	0.220	77.3	451.0	3909.5
High	5	1.000	0.998	0.1	0.2	0.2
	25	0.990	0.912	6.5	59.5	55.5
	50	0.939	0.694	26.1	374.0	451.4
	100	0.824	0.401	67.1	1078.9	2765.2
(B) Increasing, concave per-farm MRV costs						
Low	5	0.999	0.989	0.7	1.8	1.0
	25	0.903	0.671	20.4	108.9	218.7
	50	0.753	0.398	41.6	239.9	991.8
	100	0.524	0.185	79.1	392.4	4062.7
Medium	5	1.000	0.998	0.1	0.4	0.2
	25	0.949	0.767	15.7	129.5	136.0
	50	0.838	0.523	37.1	341.3	790.8
	100	0.627	0.243	77.3	667.9	3703.4
High	5	1.000	1.000	-	-	-
	25	0.998	0.981	1.9	28.8	7.7
	50	0.977	0.864	14.3	306.9	184.1
	100	0.864	0.516	59.8	1504.8	1996.1
(C) Increasing, linear per-farm MRV costs						
Low	5	1.000	1.000	0.0	0.2	0.0
	25	0.868	0.755	18.4	155.4	144.0
	50	0.626	0.464	40.6	340.7	882.1
	100	0.304	0.172	80.0	526.1	3968.5
Medium	5	1.000	1.000	-	-	-
	25	0.953	0.914	9.1	109.6	45.9
	50	0.758	0.617	34.4	486.7	595.0
	100	0.403	0.243	78.1	961.1	3464.0
High	5	1.000	1.000	-	-	-
	25	1.000	1.000	-	-	-
	50	0.988	0.982	3.8	111.0	18.8
	100	0.834	0.710	43.6	1777.5	984.4

Table B.5: Optimal emission threshold

MRV costs specification and magnitude	Emission tax δ [€/tCO$_2$eq]	Threshold $\tilde{e}_{0s}$ [tCO$_2$eq]	Share of exempted		Abatement $A^s(\delta, \tilde{e}_{0s})$ [10^6tCO$_2$eq]	MRV costs $M^s(\delta, \tilde{e}_{0s})$ [10^6€]	Social benefit $B^s(\delta, \tilde{e}_{0s})$ [10^6€]
			Farms $F(\tilde{e}_{0s})$ [1]	Emissions $L(F(\tilde{e}_{0s}))$ [1]			
(A) Constant per-farm MRV costs							
Low	5	1675	0.998	0.944	0.5	1.4	0.4
	25	211	0.847	0.332	19.5	97.3	204.3
	50	61	0.647	0.116	42.0	224.0	987.9
	100	19	0.412	0.040	79.3	373.3	4069.7
Medium	5	5250	1.000	0.992	0.1	0.2	0.3
	25	370	0.915	0.507	15.0	108.1	130.8
	50	138	0.785	0.236	36.9	273.4	804.7
	100	42	0.579	0.084	76.7	534.7	3765.4
High	5	7686	1.000	1.000	-	-	-
	25	1295	0.996	0.924	2.3	23.2	15.4
	50	474	0.945	0.620	18.8	337.9	228.0
	100	163	0.811	0.271	63.6	1161.0	2376.6
(B) Increasing, concave per-farm MRV costs							
Low	5	5250	1.000	0.992	0.1	0.4	0.0
	25	370	0.915	0.507	15.0	121.2	117.8
	50	79	0.682	0.138	41.1	335.4	852.9
	100	17	0.386	0.035	79.6	499.1	3958.4
Medium	5	7686	1.000	1.000	-	-	-
	25	582	0.966	0.722	8.8	108.2	32.2
	50	163	0.811	0.272	35.3	461.8	572.0
	100	42	0.578	0.084	76.7	805.5	3495.8
High	5	7686	1.000	1.000	-	-	-
	25	5250	1.000	0.992	0.3	4.2	0.2
	50	1295	0.996	0.924	3.8	79.3	34.5
	100	212	0.847	0.333	59.2	1893.3	1369.6
(C) Increasing, linear per-farm MRV costs							
Low	5	7686	1.000	1.000	-	-	-
	25	7686	1.000	1.000	-	-	-
	50	12	0.256	0.018	45.5	623.4	679.2
	100	5	0.047	0.002	80.8	634.0	3889.7
Medium	5	7686	1.000	1.000	-	-	-
	25	7686	1.000	1.000	-	-	-
	50	163	0.811	0.272	35.3	925.2	108.7
	100	6	0.052	0.002	80.8	1267.7	3255.9
High	5	7686	1.000	1.000	-	-	-
	25	7686	1.000	1.000	-	-	-
	50	7686	1.000	1.000	-	-	-
	100	7686	1.000	1.000	-	-	-

Table B.6: Approximated emission threshold

MRV costs specification and magnitude	Emission tax δ [€/tCO_2eq]	Threshold $\hat{e}_{0s}$ [tCO_2eq]	Share of exempted		Abatement $A^s(\delta, \hat{e}_{0s})$ [$10^6 tCO_2eq$]	MRV costs $M^s(\delta, \hat{e}_{0s})$ [10^6€]	Social benefit $B^s(\delta, \hat{e}_{0s})$ [10^6€]
			Farms $F(\hat{e}_{0s})$ [1]	Emissions $L(F(\hat{e}_{0s}))$ [1]			
(A) Constant per-farm MRV costs							
Low	5	3168	0.999	0.977	0.1	0.3	0.1
	25	174	0.823	0.291	20.6	112.2	201.1
	50	53	0.623	0.103	42.5	239.7	984.8
	100	15	0.350	0.030	79.8	412.7	4059.0
Medium	5	6337	1.000	0.999	0.0	0.0	0.0
	25	349	0.909	0.486	15.4	116.2	127.7
	50	106	0.738	0.185	38.6	332.2	794.3
	100	31	0.520	0.064	77.6	610.0	3738.8
High	5	30624	1.000	1.000	-	-	-
	25	1686	0.998	0.947	1.5	12.5	10.3
	50	514	0.954	0.661	16.7	282.3	214.9
	100	149	0.799	0.254	64.7	1236.0	2359.2
(B) Increasing, concave per-farm MRV costs							
Low	5	3168	0.999	0.977	0.1	1.5	-1.0
	25	174	0.823	0.291	20.6	219.3	93.9
	50	53	0.623	0.103	42.5	375.7	848.9
	100	15	0.350	0.030	79.8	514.4	3957.3
Medium	5	6337	1.000	0.999	0.0	0.1	-0.0
	25	349	0.909	0.486	15.4	257.6	-13.7
	50	106	0.738	0.185	38.6	586.0	540.5
	100	31	0.520	0.064	77.6	870.1	3478.7
High	5	30624	1.000	1.000	-	-	-
	25	1686	0.998	0.947	1.5	47.0	-24.2
	50	514	0.954	0.661	16.7	686.6	-189.3
	100	149	0.799	0.254	64.7	2339.9	1255.3
(C) Increasing, linear per-farm MRV costs							
Low	5	3168	0.999	0.977	0.1	14.4	-14.0
	25	174	0.823	0.291	20.6	450.5	-137.2
	50	53	0.623	0.103	42.5	569.7	654.9
	100	15	0.350	0.030	79.8	616.1	3855.6
Medium	5	6337	1.000	0.999	0.0	1.2	-1.1
	25	349	0.909	0.486	15.4	652.8	-409.0
	50	106	0.738	0.185	38.6	1035.5	91.0
	100	31	0.520	0.064	77.6	1188.4	3160.5
High	5	30624	1.000	1.000	-	-	-
	25	1686	0.998	0.947	1.5	326.5	-303.7
	50	514	0.954	0.661	16.7	2080.5	-1583.3
	100	149	0.799	0.254	64.7	4578.2	-983.0