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Abstract

Environmental policies often include exemptions for some firms, e.g. the small emitters. This paper 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. Second-best partial coverage is defined by a threshold value of some characteristic of the firms below which firms are exempted. We characterize the optimal threshold and discuss its welfare implications. Since determining this threshold is demanding in terms of information regarding firm-level MRV and abatement costs, we show how limited knowledge about these costs at the aggregate level can be used in practice to approximate the optimal threshold. 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 small 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 agents are granted exemption. A typical example is 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 (Becker et al., 2013). 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 installations emitting more than a given amount 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 account for most of the remaining 55% of emissions.

The justification for adopting partial coverage is often based on considerations of inequality, as e.g. in the case of income-tax exemptions for lowest-income households. It may be based also on cost-effectiveness considerations, in particular when the implementation of the policy requires the regulator and/or the agents to engage in costly monitoring, reporting, and verification (MRV) procedures.[1] If the related costs increase with the number of agents subject to the policy, the regulator faces a trade-off between the larger benefits that may be expected from 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. The regulator must determine *ex ante* which firms should be subject to the emission tax, taking into account the fact that the broader the coverage, the larger the overall reduction in emissions but also the larger the MRV costs. Grosjean et al. (2016) suggest a relationship between the social interest of partial coverage and the distribution of emissions among firms. The intuition is that the more concentrated the emissions among agents, the larger the social interest of targeting only the larger emitters. As an illustration, consider that firms' initial emissions are distributed as depicted by the Lorenz curve in Figure 1.

In this situation, targeting only the top 25% emitters (i.e. those to the right of point A in Figure 1) saves the MRV costs associated with the remaining 75% of agents, while still covering almost 80% of total initial emissions. Of course, it may be that (some of) the smaller emitters are very efficient at reducing their emissions, while abatement and MRV are very costly for (some of) the larger emitters. Therefore, how such a partial coverage would perform in terms of social welfare depends on the distribution of abatement and MRV costs among agents, not just the distribution of emissions. Determining the optimal coverage thus requires detailed information about individual abatement and MRV costs. This is a strong requirement, especially if a large number of heterogeneous firms are involved, as is the case for many environmental issues.

Informational issues have given rise to a large body of literature in environmental economics. Most of this literature has focused on the design of truthful direct revelation mechanisms to tackle

[1] The term MRV is commonly used in the context of climate policy (Bellassen et al., 2015). The related 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 (iii) the certification of the reliability of reports (verification) that ensures the compliance with the regulatory requirements defined in the policy objective.

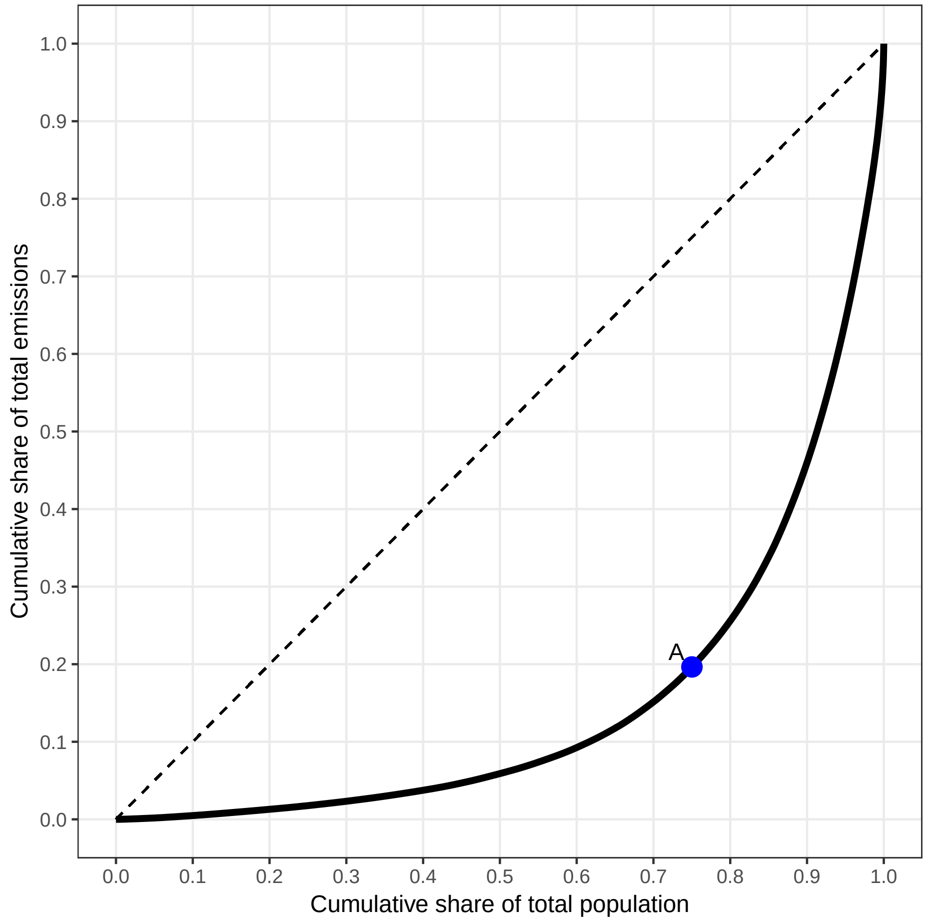

Figure 1: Lorenz curve of initial emissions. *Note: Point A corresponds to the third quartile of emissions. Emissions from firms emitting more than this value total approximately 80% of total emissions.*

adverse selection and/or moral hazard (see e.g. Spulber, 1988; Macho-Stadler and Pérez-Castrillo, 2006; Montero, 2008). A recent example can be found in Mason and Plantinga (2013). The authors address the additionality issue in carbon offset programs under asymmetric information about the agents' opportunity costs. They propose a two-part menu of contracts that combines an amount of land included in the program and a differentiated payment. The mechanism enables the regulator to identify to what extent emission reductions are truly additional. It thus avoids paying for reductions in emissions that would have been undertaken anyway. Note that such a mechanism involves the transfer of information rents to induce the agents to reveal their true type. It also requires *ex ante* knowledge of the distribution of agents' types. In addition, even if the mechanism can overcome adverse selection, the issue of costly monitoring and enforcement would remain (Bontems and Bourgeon, 2005; Stranlund et al., 2009).

In this paper, we explore a simpler design whereby firms below a given threshold are exempted, and emissions from firms above the threshold are all taxed at the same marginal rate. We circumvent the adverse selection problem by using a threshold based on some known and non-manipulable characteristic of the firms. Unlike Mason and Plantinga (2013), we explicitly account for the presence of administrative, transaction and other MRV costs involved by the implementation of the policy instrument.

The optimal 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 work (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 a less-than-linear increasing relationship, which can be explained by the presence of size-independent setup costs (Betz et al., 2010; Becker et al., 2013; Bellassen et al., 2015). The second question is how the choice of policy instrument 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 the present study is that in our study the emission tax coverage is determined endogenously.

The present paper makes three contributions to this literature. First, it characterizes the optimal threshold in the context of an emission tax when pollution is caused by a set of heterogeneous firms in the presence of MRV costs. This characterization allows us to discuss its performance in terms of social welfare in relation to the first-best, *laissez-faire*, and full-coverage situations. Second, our paper demonstrates how aggregate (rather than individual) information obtained from sectoral models can be used in practice to approximate the optimal threshold. The third contribution is empirical and consists of a quantitative assessment of the welfare implications of implementing the proposed threshold in the context of greenhouse gas (GHG) emissions from agriculture in the European Union. The empirical application covers a large and diverse agricultural sector. This contrasts with previous studies of GHG mitigation in agriculture that have focused on narrower areas and/or a limited set of activities and mitigation options (Dakpo et al., 2016; Garnache et al., 2017; Pellerin et al., 2017).

GHG emissions from European agriculture provide an interesting application case for the analytical framework developed in this paper. First, despite their weight in total European GHG emissions (about 10% of total net EU emissions according to the European Environment Agency, 2017a), non-CO_2 emissions from agriculture are excluded from the scope of the main climate policy instruments currently in place. This is the case for the EU-ETS, but also for the carbon tax

[2]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'.

policies implemented in an increasing number of European countries (World Bank, 2017).[3] The resulting limitation of inter-sectoral flexibility raises concerns about the possibility of meeting the ambitious EU mitigation targets in a cost-effective manner (Tol, 2009; De Cara and Vermont, 2011; European Environment Agency, 2017b). Second, agricultural GHG emissions result from a large number of heterogeneous farms, which makes monitoring costly (Garnache et al., 2017), a fact that has been used as a justification for excluding agricultural GHG emissions from the scope of climate policy in Europe (Ancev, 2011). Third, many provisions in the Common Agricultural Policy (CAP) are already based on a differentiated treatment of small and large farms. For instance, the requirements that farmers have to fulfill in order to be eligible for green direct payments are more stringent for farms above a certain size. The existence of such thresholds in current CAP provisions may ease the implementation of the optimal threshold proposed in this paper.

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 emission price, and the corresponding total abatement costs to the farmers. Second, the model provides insights into farm-level marginal abatement costs for a large number of representative farms operating in a wide variety of contexts across Europe. This information can be used to determine the optimal threshold, and assess the cost-effectiveness implications of the approximation of the optimal threshold proposed in the paper in various configurations with regard to the marginal damage from GHG emissions, the overall magnitude of 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 sectoral model of EU agriculture and its results in terms of abatement supply of GHG emissions are presented in Section 4. The assumptions about MRV costs are presented in Section 5. The simulation results with regard to the optimal threshold in the case EU GHG agricultural emissions are presented in Section 6. Section 7 concludes.

2. Analytical framework

Consider a continuum of firms characterized by a parameter θ distributed according to a cumulative distribution function $F(\theta)$ defined for all θ in $\Theta = [\theta_l, \theta_h]$ with $0 \leq \theta_l < \theta_h$. The associated probability distribution function, denoted $f(\theta)$, is such that $f(\theta) > 0$ for all θ in Θ and is equal to 0 everywhere else. The parameter θ can represent any characteristic of the firm observable by the regulator, such as the 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 (denoted with a bar) values.

In the unregulated situation, the activity of each firm causes emissions which are denoted e_0 in $[e_{0l}, e_{0h}]$. For any given value of the characteristic θ, reducing emissions below this level entails for the corresponding firm an abatement cost $c(a, \theta)$, where a denotes abatement. There are no fixed

[3] A carbon tax is currently implemented in ten EU countries: Denmark, Estonia, Finland, France, Ireland, Latvia, Poland, Portugal, Sweden, and the United Kingdom (World Bank, 2017). In none of these countries does the carbon tax apply to non-CO_2 GHG emissions from agriculture.

costs of abatement.[4] 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 individual firm values of θ in Θ: $c(0,\theta) = 0$, $c_a(0,\theta) = 0$, $c_a(a,\theta) > 0$ for all $a > 0$, $c_{aa}(a,\theta) > 0$ where the subscripts indicate partial derivatives.

Each unit of emissions causes an environmental damage $\delta > 0$, which is assumed to be constant.[5] The regulator considers an emission tax 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 to enforcement and verification). For simplicity and unlike 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 level of abatement. They are thus 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. Total MRV costs are denoted by $M \equiv \int_\Theta m(\theta)\,\mathrm{d}F(\theta)$.

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 of studying 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.[6] These two assumptions ensure that MRV costs do not interfere with the firms' optimal 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.:

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

Equation (1) implicitly defines the individual abatement supply $a(\tau,\theta)$ for any value of the characteristic θ. As a direct consequence of the assumptions regarding abatement costs, the abatement supply for any firm 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 $\tau > 0$. For a given level of the emission tax τ, the industry-wide aggregated abatement is denoted by $A(\tau) \equiv \int_\Theta a(\tau,\theta)\,\mathrm{d}F(\theta)$, and the corresponding total abatement cost is given by $C(\tau) \equiv \int_\Theta c(a(\tau,\theta),\theta)\,\mathrm{d}F(\theta)$.

[4]Fixed costs (in the form of MRV costs) are introduced later on in the paper. Accounting for fixed abatement costs would be possible at the expense of additional notations. The insights gained from the analytical model do not depend on this assumption.

[5]The damage function is therefore assumed to be linear. This simplifying 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. Relaxing this assumption is possible and does not fundamentally change the nature of the results.

[6]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.

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:

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

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

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. $\tau = \delta$. In this case, using Eq. (1) and a standard change of variable, the social value of any firm's abatement net of the corresponding abatement costs ($n(\delta, \theta)$) can be expressed as:

$$n(\delta, \theta) \equiv \delta a(\delta, \theta) - c(a(\delta, \theta), \theta) = \int_0^{\delta} a(v, \theta) \,\mathrm{d}v, \tag{4}$$

which is positive for all $\theta \in \Theta$. The aggregate net social value of abatement is defined as $N(\delta) \equiv \int_{\Theta} n(\delta, \theta) \,\mathrm{d}F(\theta)$ and can be computed either as $N(\delta) = \delta A(\delta) - C(\delta)$, or as $N(\delta) = \int_0^{\delta} A(v) \,\mathrm{d}v$.

Note that, under full coverage, total MRV costs may outweigh the aggregate net social value of abatement, thereby deteriorating social welfare compared to the initial situation ($B(\delta) < 0$). This occurs if and only if the ratio of aggregate MRV costs over the total net social value of abatement:

$$k(\delta) \equiv \frac{M}{N(\delta)} > 1 \tag{5}$$

Provided that M and $N(\delta)$ are known, $k(\delta)$ provides a synthetic indicator of whether *laissez-faire* should be preferred to full coverage.

If total MRV costs exceed the total net social value of abatement (i.e. if $k(\delta) > 1$), it may be tempting to stop any further cost-benefit investigation and rule out any regulation of emissions in the sector. The main point made in this paper is that, even if $k(\delta) > 1$, it may be possible to achieve a higher level of welfare than that associated with *laissez-faire* by taxing emissions only from a fraction of the firms.

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

$$B^*(\tau) = \int_{\Theta} \mathbb{1}_{b(\tau,\theta)\geq 0} b(\tau, \theta) \,\mathrm{d}F(\theta) \tag{6}$$

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), 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 $b(\delta, \theta) > 0$). Emissions from firms subject to the emission tax should thus be taxed at the marginal damage. By construction, when $\tau = \delta$, the social benefit given by Eq. (6) corresponds to the first-best situation. It is therefore greater than or equal to the social benefit under both full coverage ($B^*(\delta) \geq B(\delta)$) and *laissez-faire* ($B^*(\delta) \geq 0$).

Implementing the first-best situation requires that the regulator is able to 'cherry-pick' firms subject to the emission tax. In practice, this may be both unrealistic 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

3.1. Characterization of the 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 sufficiently large 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 this requires that θ is non-manipulable (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:

$$B^s(\tau, \theta_s) = \int_{\theta_s}^{\theta_h} b(\tau, \theta) \, \mathrm{d}F(\theta) \tag{7}$$

A minimal cost-benefit test that any partial coverage should pass is that it yields at least a higher social benefit than both the *laissez-faire* and the full-coverage situations, that is:

$$B^s(\tau, \theta_s) \geq \max\{B(\tau); 0\}. \tag{8}$$

The following proposition characterizes the interior optimal threshold (if it exists).

Proposition 1 (Interior optimal threshold). *Consider that the regulator chooses the level of the emission tax ($\tilde{\tau}$) and the threshold value ($\tilde{\theta}$) so as to maximize $B^s(\tau, \theta_s)$. The pair $(\tilde{\tau}, \tilde{\theta})$ such that $\theta_l < \tilde{\theta} < \theta_h$ (if it exists) must satisfy: (i) $\tilde{\tau} = \delta$, (ii) $b(\tilde{\tau}, \tilde{\theta}) = 0$, and (iii) $b_\theta(\tilde{\tau}, \tilde{\theta}) > 0$.*

Proof. See Appendix A.1.

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:

$$\delta a(\delta, \tilde{\theta}) - c(a(\delta, \tilde{\theta}), \tilde{\theta}) = m(\tilde{\theta}). \tag{9}$$

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 with 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 are satisfied. Differentiating Eq. (3) with respect to θ and using Eq. (1) with $\tau = \delta$, this condition is equivalent to:

$$c_\theta(a(\delta, \tilde{\theta}), \tilde{\theta}) + m'(\tilde{\theta}) < 0. \tag{10}$$

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

By totally differentiating Eq. (9) and using the second-order condition in Eq. (10), it can be shown that the interior optimal threshold $\tilde{\theta}$ (if it exists) is decreasing with respect to δ. Therefore, the greater the marginal damage, the larger the proportion of firms that should be subject to the emission tax.

Note that corner solutions are possible. There may exist no interior value of θ_s satisfying Eqs. (9) and (10). Even if such a solution exists, it may not satisfy the condition in inequality (8). Full coverage ($\tilde{\theta} = \theta_l$) may be optimal if the overall magnitude of MRV costs is sufficiently small. Conversely, the *laissez-faire* situation ($\tilde{\theta} = \theta_h$) may be optimal if MRV costs outweigh the environmental benefits of covering (even a fraction of the) firms.[7] The following proposition provides sufficient conditions that ensure that the optimal threshold corresponds to an interior solution.

Proposition 2. *If $b(\delta, \theta_l) < 0$ and $b(\delta, \theta_h) > 0$, then the optimal threshold is interior ($\theta_l < \tilde{\theta} < \theta_h$).*

Proof. See Appendix A.2

Without any further assumptions about how abatement and MRV costs vary with respect to θ, there may also be several interior solutions satisfying Eqs. (9) and (10). As a consequence, 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 $b(\delta, \theta) > 0$. Therefore, the optimal threshold $\tilde{\theta}$ characterized in Proposition 1 is only a second-best instrument. Proposition 3 provides a sufficient condition under which the optimal threshold corresponds to a first-best instrument.

Proposition 3. *If $b_\theta(\delta, \theta) > 0$ for all θ in Θ, then an emission tax δ affecting only the firms characterized by $\theta \geq \tilde{\theta}$ yields the first-best social benefit, i.e. $B^s(\delta, \tilde{\theta}) = B^*(\delta)$.*

Proof. See Appendix A.3

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. (10)). It ensures that the use of a (well-chosen) single threshold is sufficient to perfectly discriminate between the less and the more efficient firms. If this condition is satisfied, implementing the threshold $\tilde{\theta}$ leads to the first-best partition of the population as in Eq. (6).

[7]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.

3.2. Optimal threshold under constant-elasticity MRV costs and net social value of abatement

The findings presented in Propositions 1, 2, and 3 underscore the importance of two factors for the existence of an optimal interior threshold and its performances in terms of social benefit: (i) the overall magnitude of the net social value of abatement and MRV costs, and (ii) how firm-level net social value of abatement and MRV costs vary with respect to θ.

To illustrate this, further assumptions regarding the distribution of the net social value of abatement and MRV costs are useful. Assume that, for all θ in Θ, $n(\delta,\theta)$ and $m(\theta)$ are specified as follows:

$$n(\delta,\theta) = \alpha_1(\delta)\theta^{\alpha_2} \qquad\qquad m(\theta) = \beta_1\theta^{\beta_2}, \tag{11}$$

with $\alpha_1(\delta) > 0$ as soon as $\delta > 0$, and $\beta_1 > 0$. For clarity, we shall also assume that both the net social value of abatement and MRV costs are increasing with respect to θ (i.e. $\alpha_2 \geq 0$ and $\beta_2 \geq 0$).[8]

The specifications in Eqs. (11) allow the effects related to the overall magnitude of abatement and MRV costs and those related to their distribution among firms to be disentangled. $\alpha_1(\delta)$ and β_1 are scaling factors independent of θ. The greater $\beta_1/\alpha_1(\delta)$, the larger the ratio of aggregate MRV costs over the total net social value of abatement ($k(\delta)$). α_2 and β_2 represent the (constant) elasticity of the net social value of abatement and MRV costs with respect to θ, respectively. Under specifications (11), α_2 is also the elasticity of the firm-level abatement supply with respect to θ (see Eq. (4)). Note also that $b(\delta,\theta)$ may not be monotone increasing over the entire support Θ.

The following proposition gives the optimal threshold when the net social value of abatement increases faster than MRV costs with respect to θ.[9]

Proposition 4. *If the firm-level net social value of abatement and MRV costs are specified as in Eqs. (11) with $\alpha_2 > \beta_2$, then the optimal threshold is given by:*

$$\tilde{\theta} = \begin{cases} \theta_l & \text{if } \theta_i \leq \theta_l \text{ (full coverage)} \\ \theta_i & \text{if } \theta_l < \theta_i < \theta_h \text{ (interior optimal threshold)} \\ \theta_h & \text{if } \theta_i \geq \theta_h \text{ (laissez faire)} \end{cases} \tag{12}$$

where

$$\theta_i = \left(k(\delta) \frac{\int_\Theta \theta^{\alpha_2}\, \mathrm{d}F(\theta)}{\int_\Theta \theta^{\beta_2}\, \mathrm{d}F(\theta)} \right)^{\frac{1}{\alpha_2-\beta_2}}. \tag{13}$$

An emission tax δ affecting only the firms characterized by $\theta \geq \tilde{\theta}$ yields the first-best social benefit, i.e. $B^s(\delta,\tilde{\theta}) = B^*(\delta)$.

Proof. See Appendix A.4.

[8]These two assumptions are simply meant to simplify the discussion. They are not required to establish the results presented in Proposition 4.

[9]When the abatement supply increases slower than MRV costs with respect to θ (i.e. when $\alpha_2 < \beta_2$), the optimal coverage consists of taxing only emissions from the smaller firms (in terms of θ). The results of Proposition 4 can easily be extended to this case by considering $\tilde{\theta}$ as an upper (rather than lower) threshold. In the limit case $\alpha_2 = \beta_2$, it is straightforward to see that $b(\delta,\theta)$ is of the same sign as $(1 - k(\delta))$ for all θ in Θ, and therefore that the optimal coverage corresponds to either the full coverage (if $k(\delta) < 1$) or the *laissez-faire* (if $k(\delta) > 1$). Lastly, in the degenerate case where $\alpha_2 = \beta_2$ and $k(\delta) = 1$, the full coverage, *laissez-faire*, and any partial coverage all yield zero social benefit.

It is apparent from Eq. (13) that, holding everything else constant, the larger the ratio of aggregate MRV costs over the total social value of abatement net of abatement costs ($k(\delta)$), the larger the value of the (interior) optimal threshold, and therefore the smaller the fraction of firms that should be subject to the emission tax. It also appears clearly from Proposition 4 that, even in cases where *laissez-faire* is preferable to full coverage (i.e. if $k(\delta) > 1$), taxing emissions from only a fraction of the firms may be socially optimal. This requires that the abatement supply increases sufficiently faster than MRV costs with respect to θ, so that the net social value of abatement for the larger firms (in terms of θ) exceeds their MRV costs. Note also that, despite the possible non-monotonicity of $b(\delta, \theta)$ with respect to θ under specifications (11), the use of the threshold defined in Eq. (13) is able to perfectly discriminate between firms such that $b(\delta, \theta) < 0$ and those such that $b(\delta, \theta) \geq 0$, and therefore achieves the first-best solution.

The particular case where the firm-level net social value of abatement increases linearly with respect to θ ($\alpha_2 = 1$)[10] and MRV costs are constant across agents ($\beta_2 = 0$) illustrates the intuition discussed in the Introduction regarding the relationship between a partial coverage and the concentration of θ among firms. Denote by $L(.)$ the Lorenz curve defined as: $L(F(\theta)) \equiv \left(\int_{\theta_l}^{\theta} t \, \mathrm{d}F(t)\right)/\bar{\theta}$, where $\bar{\theta} \equiv \int_{\Theta} \theta \, \mathrm{d}F(\theta)$ denotes the average value of θ over the entire population. Plugging specifications (11) with $\alpha_2 = 1$ and $\beta_2 = 0$ into Eqs. (2), (3), and (7), the inequality (8) reduces to:

$$\frac{L(F(\theta_s))}{F(\theta_s)} \leq k(\delta) \leq \frac{1 - L(F(\theta_s))}{1 - F(\theta_s)} \tag{14}$$

The inequalities in (14) provide, for any given value θ_s of the threshold, a range for the ratio $k(\delta)$ within which taxing the emissions only from firms such that $\theta \geq \theta_s$ passes the minimal cost-benefit test in inequality (8). This is depicted in Figure 2 (point A). In this case, the lower and upper limits of $k(\delta)$ are given by the slopes of the two blue lines passing through point A. Moreover, the Lorenz curve depicted in Figure 2 can be used to determine the optimal proportion of exempted firms for a given value of $k(\delta)$. If $\alpha_2 = 1$ and $\beta_2 = 0$, Eq. (13) reduces to:

$$\theta_i = k(\delta)\bar{\theta}. \tag{15}$$

Using Eq. (15) and the property of the Lorenz curve that $L'(F(\theta)) = \theta/\bar{\theta}$, this proportion is obtained at the point where the slope of the Lorenz curve is equal to $k(\delta)$. This is illustrated in Figure 2 for the case where total MRV costs are almost twice as large as the total net social value of abatement under full coverage (point B).

3.3. Discussion: Informational requirements and incentives

How can the findings presented in this section inform the regulator about the optimal coverage in practice? The answer to this question very much depends upon the information that the regulator has access to prior to setting the threshold. It is therefore worth examining the informational requirement involved by the various formulas proposed in this section.

[10]Recall that α_2 is also the elasticity of the firm-level abatement supply with respect to θ (see Eq. (4)). Therefore, the assumption $\alpha_2 = 1$ is equivalent to assuming that the abatement supply *per unit* of θ ($a(\tau, \theta)/\theta$) is identical across all firms for any given marginal emission tax rate τ. When θ is taken as initial emissions ($\theta \equiv e_0$), $a(\tau, e_0)/e_0$ simply represents the abatement rate, i.e. the relative change in emissions for a given value of τ.

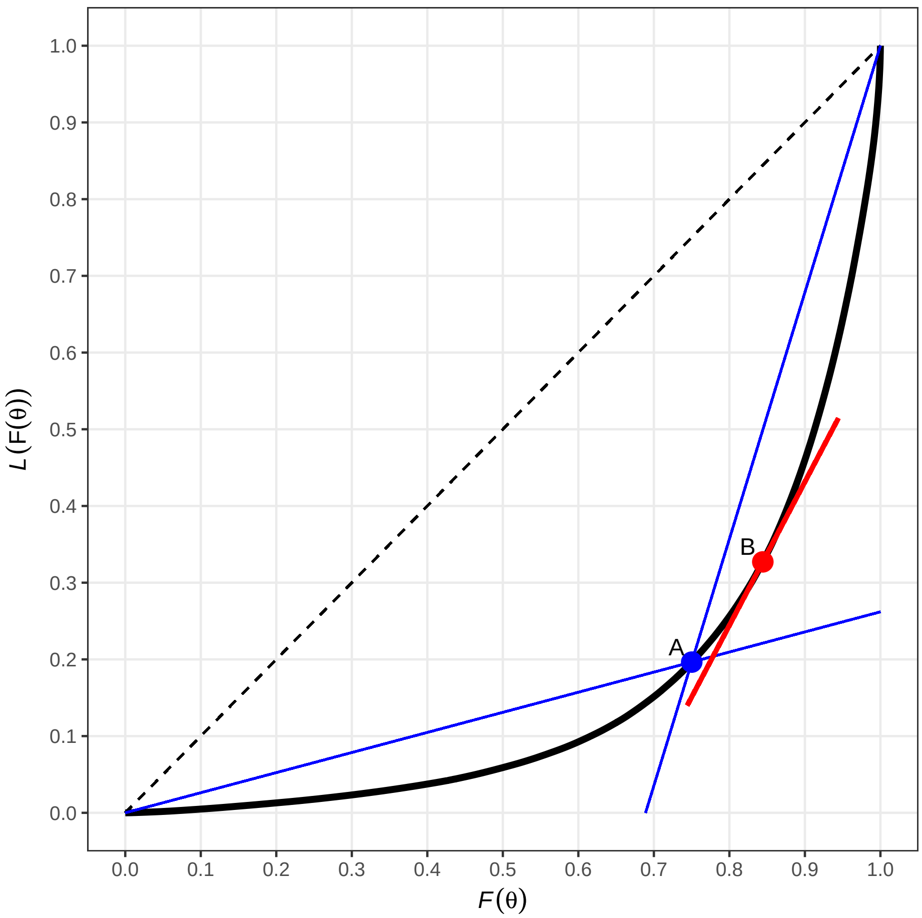

Figure 2: Graphical interpretation of the results of Proposition 4 in the case $\alpha_2 = 1$ and $\beta_2 = 0$. *Note: The slopes of the two blue lines passing through point A give the lower and upper limits of* $k(\delta)$ *within which a partial coverage covering only the top 25% emitters performs better than both laissez-faire and full coverage (i.e. satisfies inequality 8). Point B corresponds to the optimal threshold when* $k(\delta) = 1.87$ *(slope of the red line).*

In order to implement the optimal coverage, the regulator must be able to determine whether each firm falls below or above the threshold. This requires that θ is known to the regulator, and that it is non-manipulable by firms. Moreover, *ex post* emissions of the firms above the threshold must also be known in order to determine the applicable tax base. The costs of collecting this information are included in MRV costs.

If the regulator has perfect *ex ante* knowledge about all individual abatement supply curves $a(\tau, \theta)$ and MRV costs $m(\theta)$, the conditions provided in Proposition 1 can be used to determine the optimal coverage. However, assuming full and perfect information is admittedly a strong requirement, especially when a large number of heterogeneous emitters are involved.

It may be the case that the regulator has access only to aggregate evaluations of the costs and benefits of implementing an emission tax under full coverage. For instance, $N(\delta)$ may be derived from simulations of aggregate models of the sector-level response to an emission tax, either based on the full curve $A(\tau)$ or on point-estimates of $A(\delta)$ and the corresponding total abatement costs

$C(\delta)$.[11] The overall magnitude of MRV costs (M) may be evaluated based on similar regulations in the sector, or on observations on a representative sample of the population. If M and $N(\delta)$ are known, Eq. (15) provides a rule-of-thumb approximation of the optimal threshold, which is valid if both the firm-level abatement supply *per unit of* θ and MRV costs can be reasonably assumed to be constant across firms. In more general cases where $\alpha_2 \neq 1$ and/or $\beta_2 \neq 0$, Eq. (13) of Proposition 4 may be used to determine the optimal threshold provided that (i) the regulator has prior knowledge of the elasticities of the firm-level abatement supply and MRV costs with respect to θ, and (ii) those elasticities can reasonably be assumed to be constant with respect to θ.

In practice, it is possible that specifications such as those proposed in (11) reflect only imperfectly the specificities of each individual firm. To illustrate this, consider the modified versions of Eqs. (11):

$$n(\delta, \theta, \varepsilon) = \alpha_1(\delta)\theta^{\alpha_2}\varepsilon \qquad\qquad m(\theta, \eta) = \beta_1\theta^{\beta_2}\eta, \tag{16}$$

where ε and η are two independent random error terms such that $\mathbb{E}[\varepsilon] = \mathbb{E}[\eta] = 1$, where $\mathbb{E}$ represents the expectation operator over the joint distribution of ε and η. In this case, the objective of a (risk-neutral) regulator is to maximize $\mathbb{E}[B^s(\delta, \theta_s)]$. Under these assumptions, the linearity of the expectation operator then implies that $\mathbb{E}[B^s(\delta, \theta_s)] = \int_{\theta_s}^{\theta_h} \left[\alpha_1(\delta)\theta^{\alpha_2} - \beta_1\theta^{\beta_2}\right] \mathrm{d}F(\theta)$.[12] Therefore, the formula given in Eq. (13) can still be used, provided that unbiased estimates of the elasticities α_2 and β_2 have been obtained, for instance from an econometric estimation of Eqs. (16) over a representative sample of the total population. Replacing α_2 and β_2 by their respective (unbiased) estimates in Eq. (13) gives the threshold value that maximizes $\mathbb{E}[B^s(\delta, \theta)]$. Note however that because of the local non-monotonicity due to the error terms ε and η, the *ex post* social benefit may not correspond to the first-best.

Lastly, imposing a differentiated treatment of small and large firms may raise issues regarding the incentives to escape taxation. It may be argued that, under a partial coverage, firms above the threshold face incentives either to pretend to be below the threshold, or to set their output at a sub-optimal level. In the context of the model presented above, this difficulty is circumvented by the assumption that the threshold hinges on an observable and non-manipulable characteristic. This is nevertheless a valid concern if, for instance, firms expect the threshold to be revised over time. The policy design may mitigate this concern, e.g. by taxing only the emissions that are above that of the pivotal firm. Such a design would be equivalent to a lump-sum transfer to all firms above the threshold, and it would not affect their abatement levels (see Eq. (1)) compared to the situation where all their emissions are taxed.

4. Abatement costs of greenhouse gas emissions in the EU agricultural sector

The empirical application is based on the results from a supply-side sectoral model of the European agricultural sector (AROPAj). This model has been used in several empirical assessments of

[11] 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. Pérez Domínguez et al., 2016).

[12] Note that the same argument would apply under a specification with independent, zero-mean additive error terms. The choice of multiplicative error terms in Eqs. (16) is motivated by the estimation on the log-transformed specification conducted in the empirical application (see Section 4 and Appendix B.3).

agricultural and/or climate policies in Europe (e.g. De Cara et al., 2005; De Cara and Jayet, 2011; Leclère et al., 2013; Lungarska and Jayet, 2016). For a general presentation of (a previous version of) the model, see e.g. De Cara and Jayet (2011).[13]

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. An important data source is the European Union Farm Accountancy Data Network (EU-FADN) data set, which provides economic and structural information on approximately 80,000 professional farms in the EU-27 for the year 2009. Based on this information, representative farms are constructed as clusters of the real farms surveyed by the EU-FADN. 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 types of farming. 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 representative farms, 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, size of cattle operation facilities), agronomy (e.g. crop rotations, animal feeding requirements, livestock demography), and policy constraints. These constraints depend on the conditions of production and type of farming, and thus vary from one representative farm to the other. The main decision 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 by 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. It excludes CO_2 emissions from agriculture,[14] as well as carbon sources and sinks related to agricultural soils.[15] The emissions accounting method

[13]The main changes compared to this 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 (pertaining to 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. A full technical presentation of the model is available at `https://www6.versailles-grignon.inra.fr/economie_publique/Media/fichiers/ArticlAROPAj`.

[14]Non-energy related sources of CO_2 in agriculture are much smaller than that of methane and nitrous oxide emissions. They are mainly caused by the use of carbon-containing fertilizers (lime, urea) for a EU total of about 9 $MtCO_2eq$ in 2009. The European Environment Agency (2017a) reports the emissions due to fossil fuel use in agriculture together with those of fisheries and forestry. These emissions represent slightly less than 77 $MtCO_2eq$, a figure to be compared to a total of non-energy related agricultural emissions of about 431 $MtCO_2eq$.

[15]Accounting for soil carbon sinks and sources would introduce additional complexity because of the dynamic

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 94% of agricultural emissions reported by the European Environment Agency (2017a) for the year 2009.

Initial emissions vary markedly among farms.[16] Computed per-farm emissions at the representative farm level range from 0.3 tCO_2eq to about 7,700 tCO_2eq per year, with 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 25% of the farms responsible for about 80% of total emissions.[17]

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. Note that these adjustments depend on the set of active capacity constraints at the representative farm level, and therefore vary from one representative farm to the other. 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 the Appendix (Figure B.6).

For simplicity, the analysis focuses on four emission tax rates: 5, 30, 50, and 100 €/tCO_2eq. The lowest value corresponds approximately to the average price of CO_2 emissions allowances in the EU ETS in 2016-2017.[18] A price of 30 €/tCO_2eq is the 2017 level of the carbon tax in France, the largest emitting country of agricultural emissions in Europe (World Bank, 2017). 50 and 100 €/tCO_2eq correspond to the lower and upper values of the carbon price range recommended by the Stern-Stiglitz Commission for 2030 in the aftermath of the Paris Agreement (High-Level Commission on Carbon Prices, 2017). At these prices, aggregate abatement represents approximately 2%, 7.5%, 11%, and 20% of total initial EU agricultural emissions, respectively.[19] 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).

The model results at the representative farm level are used to compute the individual net social value of abatement $n(\delta, \theta)$ over the full explored range of emission prices and for each representative farm. These values are then regressed on the corresponding emission price (in the form of a

nature of natural processes involved and because of the importance of land-use changes from and to agricultural uses (forestry, urban, etc.).

[16] Complete model results at the representative farm level (initial emissions, abatement, abatement costs, etc.), along with the R code necessary to reproduce all graphs and calculations reported in the paper can be retrieved from the online supplemental material available at: `https://doi.org/10.17632/w4ygt38p86.1`.

[17] Note that, as (i) the EU-FADN data does not provide information about non-professional farms, (ii) some farming activities (vineyards, 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.

[18] See `https://www.eex.com/en/market-data/environmental-markets/auction-market`, (last checked on November 21, 2017).

[19] As a comparison, Pérez Domínguez et al. (2016, see table 35, p. 117) report abatement rates in EU agriculture of 3.5%, 5%, 10%, and 16% for carbon prices of 10, 20, 50, and 100 €/tCO_2eq, respectively.

Table 1: Aggregate results under full coverage (Total farm population: $F = 3.7 \times 10^6$ farms).

Emission price δ [€/tCO_2eq]	Emissions $E(\delta)$ [$10^6 tCO_2$eq]	Abatement $A(\delta)$ [$10^6 tCO_2$eq]	Abatement cost $C(\delta)$ [10^6€]	Net social value of abatement $N(\delta)$ [10^6€]
0	406.8	-	-	-
5	398.8	8.0	18.0	22.0
30	376.2	30.6	375.6	543.5
50	361.0	45.8	979.4	1310.3
100	326.0	80.8	3557.4	4524.0

smooth non-parametric term), and on a measure of farm size using a Generalized Additive Model (Wood, 2006) on the log-transformed model presented in Eq. (16). Three alternative measures of farm size are used: initial emissions (e_0), initial area (s_0), and initial number of livestock (ℓ_0). The estimated results are reported in Appendix (Table B.4). For all three measures, the estimated elasticity α_2 is larger than 1, suggesting that the abatement supply increases more than proportionally with respect to size. The estimated elasticity ranges from 1.11 (for $\theta \equiv e_0$) to 1.48 (for $\theta \equiv \ell_0$). The quality of the fit is the highest using initial emissions as the measure of farm size.

5. MRV costs data and assumptions

MRV costs correspond to the costs of (public and private) resources needed to (i) determine whether each farm is above or below the threshold, (ii) measure *ex post* emissions for farms above the threshold, and (iii) implement and collect the emission tax.

The magnitude of the costs associated with each of the above items depends on how MRV activities are deployed in practice. The costs of determining which farms are above the threshold depends on the characteristic upon which exemption is based. In the context of the present study, we assume that this characteristic can be readily observed by the regulator, and we therefore assume that the related costs are negligible.[20] Emissions may be computed using standardized emission factors and equations linking the level of emissions with activity data retrieved from farm-level book-keeping information; or they may be directly measured, through e.g. sensors, monitoring devices, or satellite observations. MRV costs are also likely to depend on the type of mitigation technologies adopted by farmers. Some of these methodologies may be easier to monitor and verify than others. Another important determinant of the magnitude of MRV costs is the extent to which the implementation of the emission tax can build on existing policy instruments. The European agricultural sector has a long history of regulation, most notably through the Common Agricultural Policy (CAP). Many CAP provisions require that farmers collect and report data about their farm operations on a regular basis to be eligible for CAP payments. They also include standardized

[20]Note that the model can be generalized to incorporate the cost of determining whether each firm is above or below the threshold. As this would require to collect information for the entire population, which size is given, the related cost can be considered as fixed (i.e., independent of θ_s). Incorporating such a fixed cost in the regulator's objective function would not change the results presented in Proposition 1. This would however affect the conditions under which an interior solution prevails (inequality (8)).

control and verification procedures of the reported data. Arguably, relying on already-collected data and existing information systems to process and verify it may significantly reduce MRV costs.

The calibration of MRV costs is all the more challenging in that MRV costs data pertaining to the mitigation of GHG emissions in European agriculture are scant. The vast majority of the estimates available in the literature pertain to firms in energy-intensive sectors (see e.g. Bellassen et al., 2015), or to carbon projects in the forestry sector (see e.g. Phan et al., 2017). Some estimates in the agricultural sector are available, but they often pertain to policy instruments not directly related to GHG emissions (e.g. OECD, 2007), and/or have been obtained in non-European contexts (e.g Cacho et al., 2013).

Based on a compilation of available estimates and taking into account the specificities of the EU agricultural sector, Ancev (2011) proposes a figure of 2.5 € per ton of CO_2eq initially emitted. Extrapolating this figure to the entire European sector using the total emissions reported in Table 1 leads to total MRV costs (M) slightly above 1 billion € and to a per-farm average of 275 €. Based on the average hourly labor cost in the EU,[21] the corresponding workload is about 11 hours per farm, which is in line with the assumptions made by Cacho et al. (2013) in the context of the Australian carbon farming program.

To our knowledge, Foucherot (2015) is the only reference that provides an in-depth analysis of MRV costs in an actual agricultural GHG mitigation project in the European context. The Joint Implementation project analyzed in this work aims at reducing N_2O emissions from nitrogen fertilizer use through the introduction of legume crops in 316 farms in France.[22] The author reports a total of 40,000 € in MRV costs for the project as a whole, or an average of approximately 127 € per farm. Extraploted to the entire farm population represented in the model, this corresponds to total MRV costs of about 470 million €.

Given the scarcity of empirical information about MRV costs, a range of calibrations for MRV costs will be explored. As underscored in Section 3, two features are important: (i) the overall magnitude of MRV costs (M), and (ii) how these costs are distributed among farms.

As for the magnitude of MRV costs, three scenarios will be explored. The "low" and "medium" scenarios are based on the figures reported by Foucherot (2015) and Ancev (2011), respectively. The "high" scenario draws from a compilation of the estimated implementation costs of agri-environmental programs in the EU by (OECD, 2007, Table I.1.4), which reports an average per-farm implementation costs of 1,522 € in France. When upscaled to the entire population, this figure corresponds to total MRV costs of about 5.6 billion €.

These three scenarios are combined with three contrasted assumptions regarding the distribution of per-farm MRV costs: (A) constant across farms, (B) increasing and concave with respect to initial emissions, and (C) increasing and linear with respect to initial emissions. Assumption (B) builds on the results reported by Bellassen et al. (2015). In this recent review, the authors compile the available information on MRV costs within energy-intensive sectors related to various climate policy instruments (ETS, clean development mechanism projects, inventories), and at various scales (jurisdiction, entity, project). Their estimation results indicate a constant elasticity of per-entity MRV costs with respect to initial emissions equal to about 0.34.

[21]This information is extracted from Eurostat, see: http://ec.europa.eu/eurostat/statistics-explained/index.php/Hourly_labour_costs

[22]A detailed description of the project is available from the UNFCCC website: http://ji.unfccc.int/JIITLProject/DB/B62UQB13Z82B384RU4SBK14JR7P9RS/details.

The implications of these various assumptions for total, per-farm, and per-ton MRV costs are presented in Table 2.

Table 2: Assumptions regarding MRV costs: $m(e_0) = \beta_1 e_0^{\beta_2}$

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]		
	β_1		$\bar{m}$	min	max	$\bar{\mu}$	min	max
(A) Constant per-farm MRV costs ($\beta_2 = 0$)								
Low	126.58	469	127	127	127	1.15	0.02	494.80
Medium	274.52	1017	275	275	275	2.50	0.04	1073.09
High	1522.00	5639	1522	1522	1522	13.86	0.20	5949.37
(B) Increasing, concave per-farm MRV costs ($\beta_2 = 0.34$)								
Low	32.81	469	127	28	916	1.15	0.09	80.87
Medium	71.15	1017	275	56	1831	2.50	0.19	175.39
High	394.47	5639	1522	271	8850	13.86	1.06	972.40
(C) Increasing, linear per-farm MRV costs ($\beta_2 = 1$)								
Low	1.15	469	127	0	8860	1.15	1.15	1.15
Medium	2.50	1017	275	1	19215	2.50	2.50	2.50
High	13.86	5639	1522	4	106528	13.86	13.86	13.86

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

In this section, we start by considering that the threshold is defined as a minimum level of initial emissions above which farms are subject to the emission tax (i.e. $\theta \equiv e_0$). Note that this requires that farm-level initial emissions be observed by the regulator.[23]

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 determining 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).

[23] In the context of GHG emissions from European agriculture, this appears to be a reasonable assumption insofar as individual emissions can be approximated quite well using standardized computation rules–such as those used in national GHG inventories–based on farm-level data (area, yields, animal numbers, and synthetic and organic nitrogen management). As argued by De Cara and Vermont (2011), existing CAP provisions demand that farmers–as soon as they benefit from CAP payments–collect and/or report this information.

For clarity, the results are presented first for a benchmark configuration characterized by a marginal damage equal to 30 €/tCO_2eq, total MRV costs under full coverage equal to 1,017 M€ (medium MRV costs), increasing and concave per farm MRV costs with respect to initial emissions ($\beta_2 = 0.34$), 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 simple formula from Eq. (15) can be retrieved from Tables 1 and 2. Total MRV costs under full coverage are about 1.87 times higher than the net social value of abatement. Thus, the corresponding threshold is given simply by $k(30) \times \bar{\theta} = 1.87 \times 109.8 \approx 205$ tCO_2eq. Setting the threshold at this level implies that only the emissions from the top 15.6% of emitting farms are taxed, for an emission coverage of about 67.3% (point B in Figure 2). The use of the formula in Eq. (13) requires additional information, in particular with regard to elasticities α_2 and β_2. Plugging the values of $N(30)$, M, α_2 and β_2 reported in Tables B.4 and 2 into Eq. (13) yields a threshold value of about 391 tCO_2eq. Only 7.7% of the farms emit more than this value initially.

How accurate are these approximations of the optimal emission threshold? And what are their welfare implications? To answer these questions, we make full use of the model results, which provide marginal abatement costs at both the EU level and the (representative) farm level. This information can be used to compute total social benefit in the first-best situation (as in Eq. (6)), and in the optimal emission threshold case (characterized by Proposition 1).

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 make it easier to compare 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. Therefore, the full-coverage situation is obtained when $F(\theta_s) = 0$, and the *laissez-faire* situation when $F(\theta_s) = 1$.

In the benchmark configuration, taxing emissions from all farms (full coverage) leads to a net social loss of about 474 M€. This configuration corresponds to the situation described by Ancev (2011): under full coverage, MRV costs are markedly higher than the net social value of abatement. Figure 3 shows also that the *laissez-faire* situation is preferable to a partial coverage for any emission threshold below the 73rd percentile. The optimal emission threshold is equal approximately to 370 tCO_2eq. This would entail exemption of around 91.5% of farms (but only 50.7% of emissions) for a corresponding abatement of approximately 16.7 MtCO_2eq and abatement costs of about 184 M€ . The latter figure is to be compared with a sector-wide gross margin of about 140 billion € initially. The resulting total social benefit in the benchmark configuration is approximately equal to 124 M€ (blue diamond in Figure 3). In this configuration, the social benefit associated with the implementation of the threshold approximated by Eq. (13) (red square) is about 7 M€ smaller than under the optimal threshold. The use of the simple approximation given in Eq. (15) would yield a social benefit about 37 M€ smaller than under the optimal threshold.

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.5 to B.8 in the Appendix.

As underscored in Section 3, 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

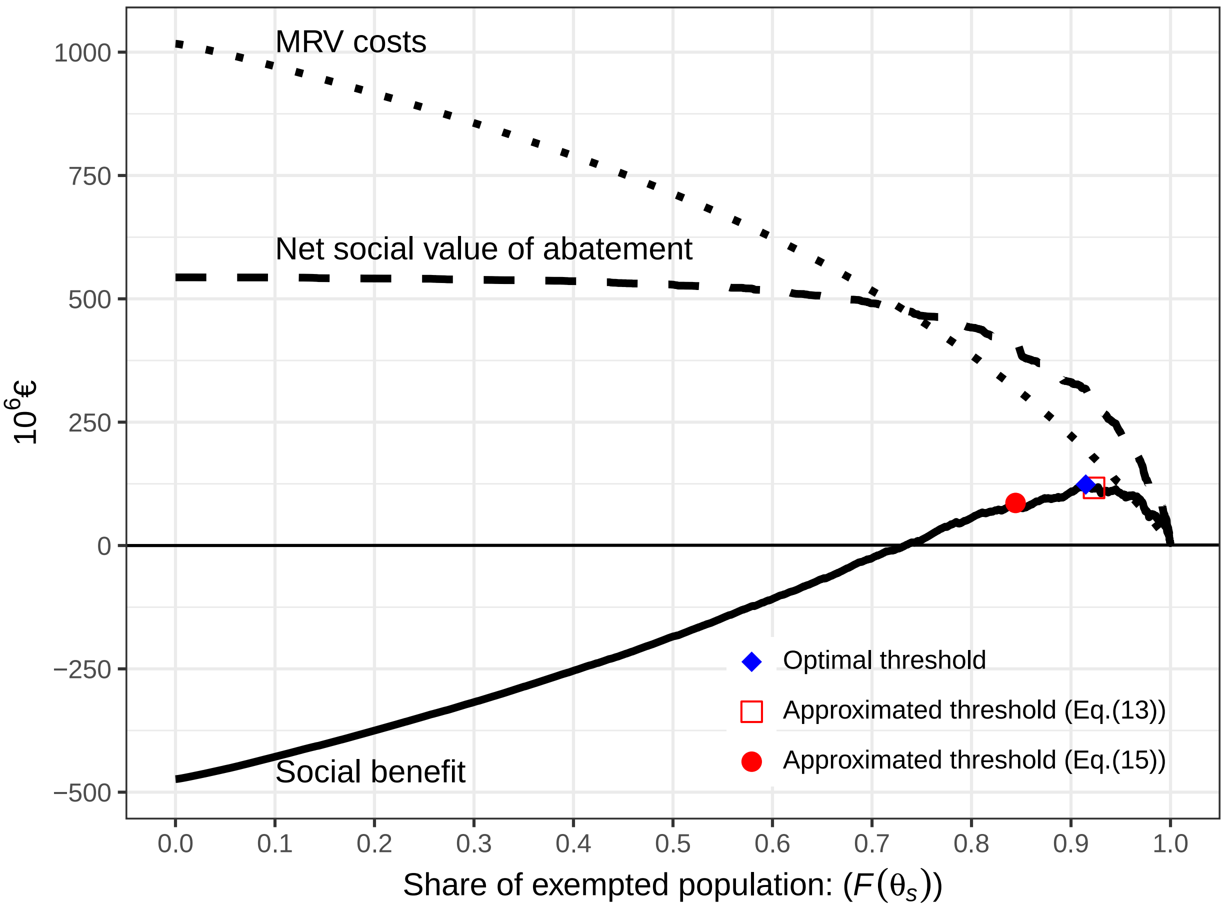

Figure 3: Total social benefit (solid curve) and its components in the benchmark configuration. *Notes:* δ = 30 €/tCO$_2$eq, $m(e_0) = 71.15(e_0)^{0.34}$ *(medium, increasing and concave per-farm MRV costs), and only the largest emitting farms are subject to the emission tax* ($\theta \equiv e_0$).

depicts the social benefit associated with three values of total MRV costs under full coverage, holding constant the value of the marginal damage (δ = 30 €/tCO$_2$eq) and the elasticity of per-farm MRV costs with respect to initial emissions (β_2 = 0.34). The optimal emission threshold under high MRV costs (5250 tCO$_2$eq) would lead to the exemption of about 99.99% of the farms. Under low MRV costs, the optimal threshold is only 138 tCO$_2$eq, leading to 78.5% of the farms being exempted. In all three configurations, the social loss when the emission threshold is approximated based on Eq. (13) does not exceed 7 M€; while the social loss using the approximation based on Eq. (15) amounts at most to 40 M€ (see Appendix, Tables B.6 to B.8).

Figure 4.b illustrates the role of the marginal damage. The magnitude and distribution of MRV costs ($m(e_0) = 71.15(e_0)^{0.34}$, i.e. medium, increasing and concave per-farm MRV costs) are held constant. The optimal emission threshold involves farm exemption rates ranging from about 41% (if δ = 100 €/tCO$_2$eq) to 100% (if δ = 5 €/tCO$_2$eq). For all the values of δ explored in Figure 4.b, the social loss from approximating the emission threshold using Eq. (13) does not exceed 7 M€, see Tables B.6 and B.7). The use of the simpler approximation given in Eq. (15) would yield to a social loss up to 37 M€.

Figure 4.c highlights the effect of the specification of per-farm MRV costs. For the same value

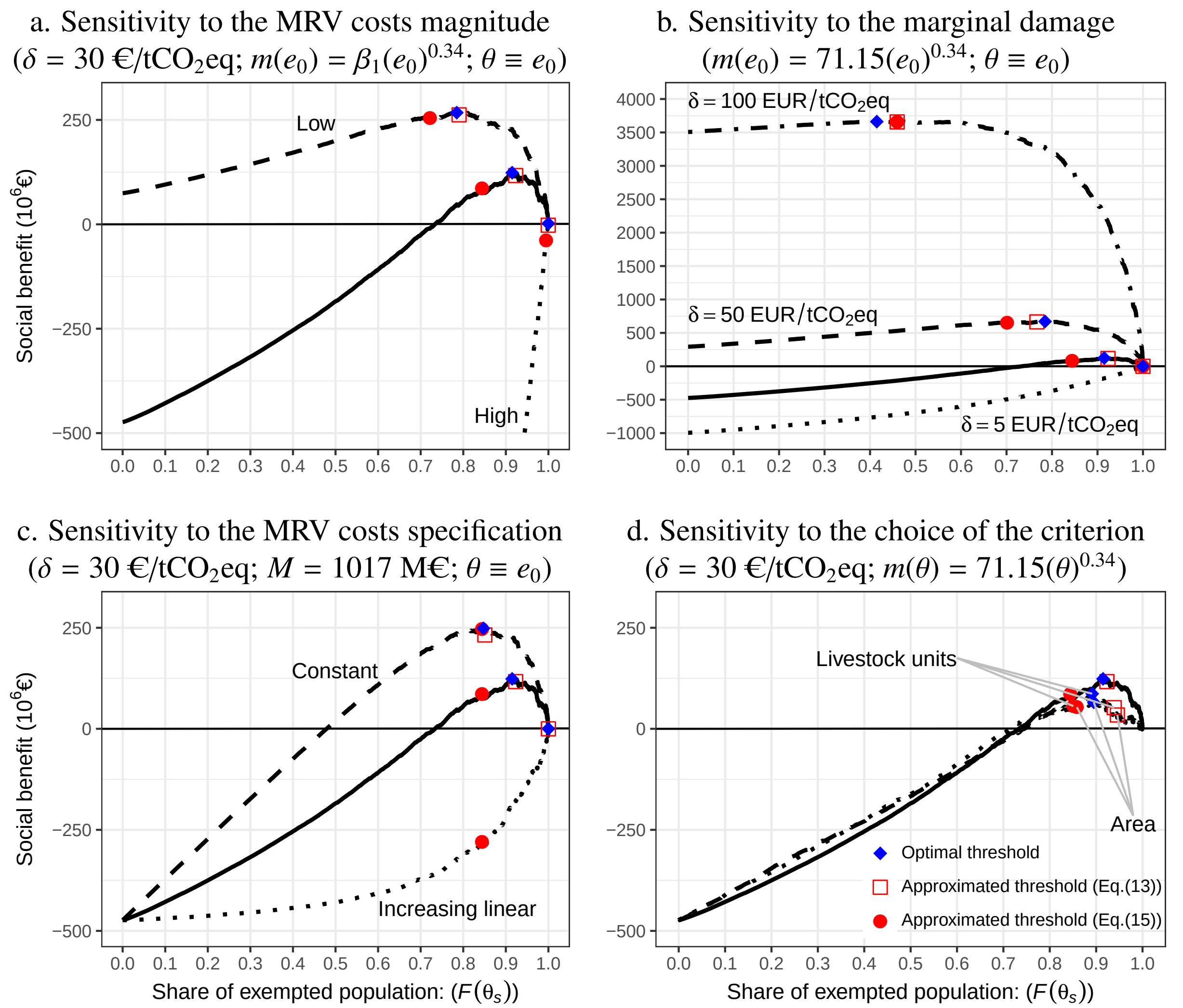

Figure 4: Total social benefit under alternative assumptions. *Note: The solid curve is the same as in Figure 3 and corresponds to the social benefit in the benchmark configuration:* $\delta = 30$ *€/tCO*$_2$*eq,* $m(e_0) = 71.15(e_0)^{0.34}$ *(medium, increasing and concave per-farm MRV costs), and* $\theta \equiv e_0$ *(only the largest emitting farms are subject to the emission tax).*

of total MRV costs under full coverage (medium, $M = 1017$ M€) and the same value of the marginal damage ($\delta = 30$ €/tCO$_2$eq), the optimal emission threshold leads to 84.7% of the farms being exempted in the constant per-farm MRV costs case, and to all farms (i.e *laissez-faire*) being exempted in the linear increasing case. By construction, the formula in Eq. (15) only depends on aggregate results under full coverage. Therefore, for any given values of M and δ, the associated threshold (205 tCO$_2$eq) is the same regardless of the actual distribution of MRV costs among farms. This approximation performs fairly well when per-farm MRV costs are constant, but deteriorates social welfare by 279 M€ compared to *laissez-faire* in the increasing linear case. By contrast, the approximation from Eq. (13) yields a non-negative social benefit in all three configurations.

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 third quartile. This can be explained by the fact that the smaller farms, be they measured in terms of area or the number of animals, are also the smaller 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 the 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/farm, while the optimal animal number threshold is about 68 LU/farm. The respective corresponding social benefit is 58 M€ and 37 M€ lower than under the optimal emission threshold.

Figure 5 summarizes the implications of the optimal threshold for social welfare for the 36 scenarios explored in the paper (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. $\theta \equiv e_0$).[24] 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 (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. The approximation using Eq. (13) appears to offer a satisfactory approximation of the second-best emission threshold under the three assumptions regarding the distribution of MRV costs (middle row). The simple formula provided in Eq. (15) performs satisfactorily if per-farm MRV costs are constant (specification (A), bottom row). However, this simple formula may lead to a substantial social loss, and even deteriorate welfare compared to the *laissez-faire* situation, when per-farm MRV costs are increasing with respect to initial emissions.

7. Concluding remarks

When pollution is caused by a large number of heterogeneous firms and firms' actions are costly to monitor and verify, the question that naturally arises is whether MRV costs more than offset the social benefit that can be expected from 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. A partial coverage may thus be welfare-improving, even in situations where total MRV costs outweigh the social benefit of including all firms into the environmental policy.

Designing a partial coverage regulation requires determining 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 such as size. This corresponds to a second-best approach. Partial coverage may also involve informational issues with regard to firm-level abatement and MRV costs. To circumvent this issue, a simple rule-of-thumb formula is proposed. This formula only requires knowledge of

[24] 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.

the aggregate (rather than individual) magnitude of abatement and MRV costs. Note that this information is also needed for the *ex ante* cost-benefit analysis under full coverage. This simple formula is however valid only under rather restrictive assumptions (constant per-firm MRV costs and abatement supply proportional to initial emissions), and may perform poorly if these assumptions are not satisfied. We also propose a more general formula, which performs better under a wider range of cases, but requires some additional information with regard to the structure of MRV and abatement costs. Our findings show how in practice the results from applied aggregate models could inform policymakers about the design of a second-best exemption scheme, even in the absence of detailed firm-level information.

The empirical application to the issue of GHG emissions from European agriculture sheds new light on whether emissions from the agricultural sector should be included within the scope of climate policy instruments. Our results indicate that the social interest of taxing emissions from *all* farms very much depends on the value of the marginal damage. For low emission prices, such as those that have prevailed in the EU-ETS in recent years (around 5 €/tCO_2eq), a full coverage deteriorates welfare relative to *laissez-faire* as soon as the average value of MRV costs is greater than 6 € per farm. By contrast, if the marginal damage reaches 100 €/tCO_2eq, a full coverage can be welfare-improving as long as average per-farm MRV costs stay below 1220 €. Furthermore, even if total MRV costs exceed the net social value of abatement under full coverage, our findings indicate that targeting only the large emitting farms may increase welfare relative to *laissez-faire* under a wide range of assumptions regarding the marginal damage and the overall magnitude of MRV costs. These findings depend on how per-farm MRV cost and farm-level abatement supply vary with respect to size, e.g. measured as initial emissions. Our empirical findings suggest that, in the EU agricultural sector, farm-level abatement increases slightly more than proportionally with initial emissions. Therefore, if per-farm MRV costs increase less than proportionally with initial emissions, this leaves room from implementing an emission tax that targets only large emitting farms, while still improving social welfare.

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 work would remain, this would require to take into account the costs related to the trading of allowances. Since these costs depend on the level of abatement, this would 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 paper could serve as a basis for quantifying the associated information rent. Third, the introduction of a partial coverage might cause leakage effects, and/or induce strategic behavior from firms in response to implementation of partial coverage.

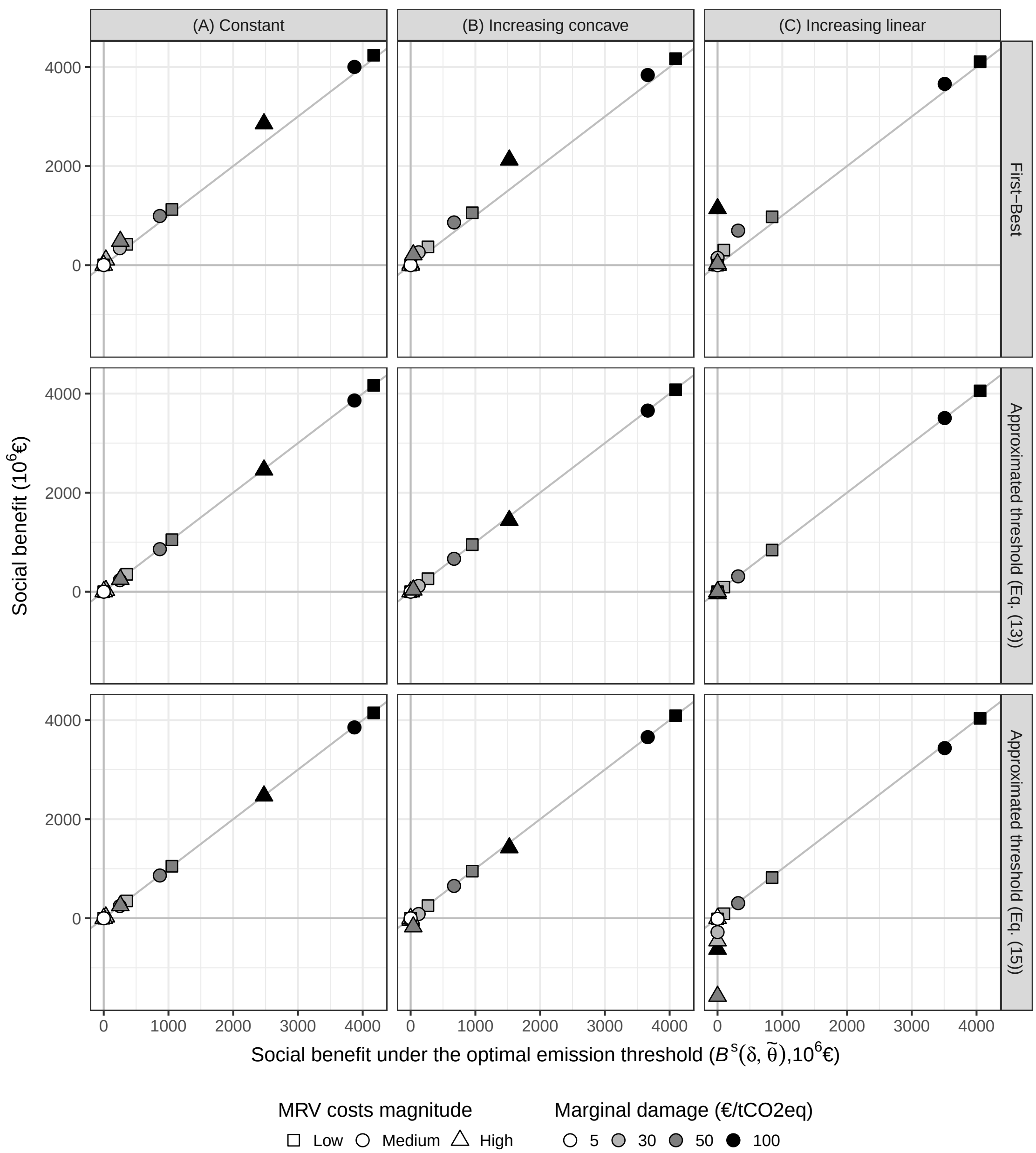

Figure 5: Summary results: Comparison of the total social benefit under the optimal emission threshold (*x* axis) with the first-best (upper row), the approximated optimal threshold based on Eq. (13) (middle row), and approximated optimal threshold based on Eq. (15) (bottom row), under three specifications of per-farm MRV costs (columns), and various assumptions regarding the magnitude of MRV costs and marginal damage.

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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:

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

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

(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 $\tilde{\theta} < \theta_h$.

(ii) The complementarity slackness conditions imply that if $\theta_l < \tilde{\theta} < \theta_h$ 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 ($\theta_l < \tilde{\theta} < \theta_h$), the second-order conditions are verified when the Hessian matrix of $B^s(\tau, \theta_s)$ evaluated in $(\tilde{\tau}, \tilde{\theta})$ is negative definite. Differentiating B^s twice with respect to τ and θ_s and using Eq. (1), it comes:

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

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

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

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

Appendix A.2. Proof of Proposition 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) of Proposition 1.

Moreover, if $\tilde{\theta} = \theta_l$ (full coverage) then $\tilde{\theta} < \theta_h$, which implies that $\rho_h = 0$ (complementarity slackness condition relative to the constraint $\theta_s \leq \theta_h$). Eq. (A.3) thus reduces to $b(\delta, \theta_l) f(\theta_l) = \rho_l$. 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 $\tilde{\theta} = \theta_h$ (*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.

Appendix A.3. Proof of Proposition 3

If $b(\delta,\theta)$ is strictly monotone increasing with respect to θ for all $\theta \in \Theta$, there is at most one value of θ satisfying conditions (ii) and (iii) of Proposition 1. In the case of an interior solution, all exempted firms (i.e. $\theta < \tilde{\theta}$) are such that $b(\delta,\theta) < b(\delta,\tilde{\theta}) = 0$, and all firms subject to the emission tax (i.e. $\theta \geq \tilde{\theta}$) 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.4. Proof of Proposition 4

Denote by θ_i the value of θ that solves $b(\delta,\theta_i) = n(\delta,\theta_i) - m(\theta_i) = 0$ (conditions (i) and (ii) of Proposition 1). Under specification in Eq (11) with $\alpha_2 > \beta_2$, this value is:

$$\theta_i = \left(\frac{\beta_1}{\alpha_1(\delta)}\right)^{\frac{1}{\alpha_2-\beta_2}} \tag{A.8}$$

It is straightforward to verify that $b_\theta(\delta,\theta_i) > 0$ (condition (iii) of Proposition 1) as soon as $\alpha_2 > \beta_2$. Moreover, combining Eqs (3), (11), and (A.8) and rearranging, we have:

$$b(\delta,\theta) = \beta_1\theta^{\beta_2}\left[\left(\frac{\theta}{\theta_i}\right)^{\alpha_2-\beta_2} - 1\right]. \tag{A.9}$$

From Eq. (A.9), it appears clearly that $b(\delta,\theta) < 0$ for all $\theta < \theta_i$ and $b(\delta,\theta) > 0$ for all $\theta > \theta_i$. If $\theta_l < \theta_i < \theta_h$, then $b(\delta,\theta_l) < 0$ and $b(\delta,\theta_h) > 0$, and therefore the optimal threshold corresponds to the interior solution $\tilde{\theta} = \theta_i$. In addition, using the definition of M and $N(\delta)$ under specifications (11):

$$N(\delta) = \alpha_1(\delta)\int_\Theta \theta^{\alpha_2} dF(\theta) \qquad\qquad M = \beta_1\int_\Theta \theta^{\beta_2} dF(\theta). \tag{A.10}$$

The expression given in Proposition 4 is obtained by combining Eqs. (A.8) and (A.10).

If $\theta_i < \theta_l$, then $b(\delta,\theta) < 0$ for all $\theta \in \Theta$, which implies that $\rho_h > 0$ (see Eq. (A.3)), and therefore that the optimal solution is the *laissez-faire* ($\tilde{\theta} = \theta_h$). Conversely, if $\theta_i > \theta_h$, then $b(\delta,\theta) > 0$ for all $\theta \in \Theta$, $\rho_l > 0$, and the optimal solution is the full coverage ($\tilde{\theta} = \theta_l$).

Appendix B. Empirical application results

Appendix B.1. Descriptive statistics

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

Appendix B.2. Aggregate abatement supply

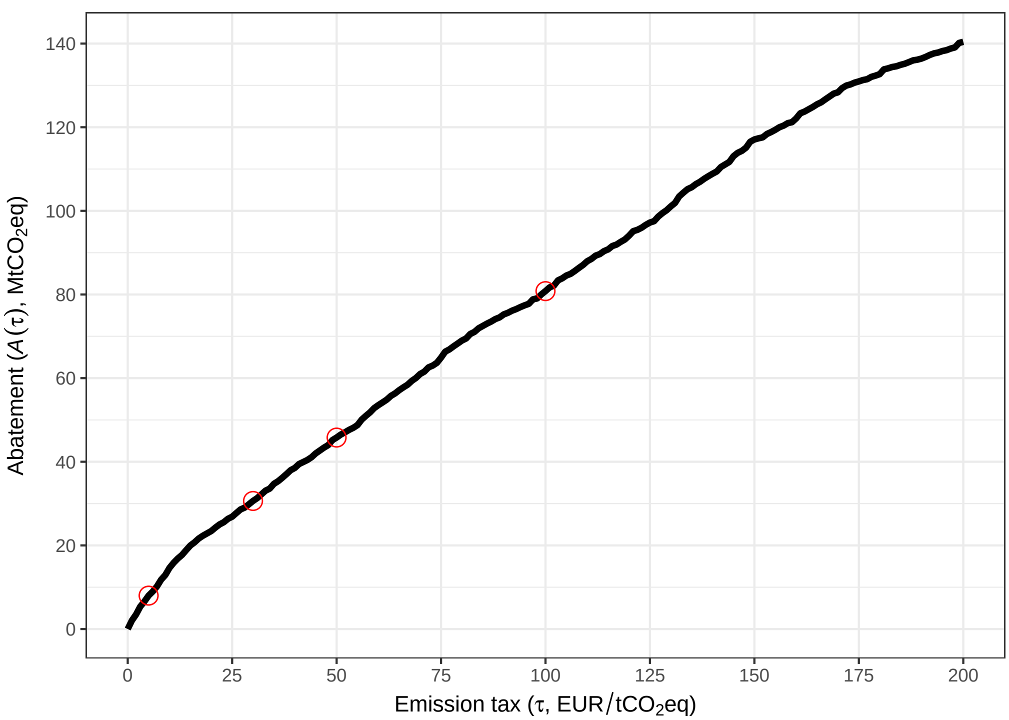

Figure B.6: Aggregate abatement supply for the EU-27 agriculture under full coverage.

Appendix B.3. Farm-level net social value of abatement: Estimation results

The net social value of abatement is computed for each representative farm k (representing f_k real farms) and each value of δ (from 1 to 200 €/tCO_2eq by steps of 1 €/tCO_2eq) as:

$$n_k(\delta) = \delta a_k(\delta) - c(a_k(\delta)) \tag{B.1}$$

The following discrete version of the log-transformed version of Eq (16) is estimated:

$$\log(n_k(\delta)) = \log(\alpha_1(\delta)) + \alpha_2 \log(\theta_k) + \epsilon_k \tag{B.2}$$

where $\log(\alpha_1(\delta))$ is introduced as a smooth non-parametric term, α_2 is the elasticity with respect to θ, and θ_k alternatively represents initial emissions (e_{0k}), area (s_{0k}), or livestock numbers (ℓ_{0k}). Equation (B.2) (weighted by f_k) is estimated using a Generalized Additive Model (GAM) model as implemented in the package `mgcv` (version 1.8) under R 3.2.

	Initial emissions $\theta \equiv e_0$ [tCO_2eq/farm]	Initial area $\theta \equiv s_0$ [ha/farm]	Initial livestock numbers $\theta \equiv \ell_0$ [LU/farm]
Parametric coefficient (α_2)			
$\log(\theta)$	1.11^{***}	1.39^{***}	1.48^{***}
	(0.00)	(0.00)	(0.00)
Approximate significance of smooth term ($\log(\alpha_1(\delta))$)			
EDF:	8.99^{***}	8.99^{***}	8.99^{***}
	(9.00)	(9.00)	(9.00)
Predicted value of smooth term for specific values of δ			
$\alpha_1(5)$	$5.44.10^{-4}$	$5.73.10^{-4}$	$4.84.10^{-4}$
$\alpha_1(30)$	0.09	0.09	0.09
$\alpha_1(50)$	0.29	0.30	0.29
$\alpha_1(100)$	1.73	1.72	1.77
Log Likelihood	-971486.50	-996536.91	-968460.82
Deviance	6233.51	7233.25	7700.32
Deviance explained	0.73	0.69	0.65
Adj. R^2	0.52	0.44	0.35
Num. obs.	336816	336816	320697

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$

Table B.4: Net social value of abatement as a function of farm size: Estimation results.

Appendix B.4. Results under various assumptions

Table B.5: First-best results

MRV costs specicification and magnitude	Emission tax δ [€/tCO_2eq]	Share of exempted Farms [1]	Share of exempted Emissions [1]	Abatement $A^*(\delta)$ [10^6 tCO_2eq]	MRV costs $M^*(\delta)$ [10^6€]	Social benefit $B^*(\delta)$ [10^6€]
(A) Constant per-farm MRV costs						
Low	5	0.989	0.928	3.6	5.3	5.4
	30	0.819	0.480	27.3	84.6	420.7
	50	0.716	0.317	43.1	133.0	1124.6
	100	0.501	0.146	79.6	234.1	4237.1
Medium	5	0.996	0.965	2.2	4.1	2.4
	30	0.886	0.588	23.9	115.7	342.8
	50	0.787	0.394	40.9	216.3	992.7
	100	0.618	0.205	77.9	389.0	4002.7
High	5	1.000	0.998	0.1	0.2	0.2
	30	0.978	0.860	11.2	122.5	105.3
	50	0.937	0.688	26.6	356.5	482.5
	100	0.815	0.385	68.1	1043.3	2855.8
(B) Increasing, concave per-farm MRV costs						
Low	5	0.997	0.973	1.8	3.8	1.8
	30	0.841	0.556	25.9	120.7	369.7
	50	0.712	0.357	42.8	197.5	1057.8
	100	0.478	0.164	79.6	307.9	4168.7
Medium	5	1.000	0.994	0.3	1.0	0.4
	30	0.915	0.692	21.2	157.0	260.3
	50	0.811	0.477	38.9	310.8	863.3
	100	0.591	0.224	78.0	567.6	3839.2
High	5	1.000	1.000	-	-	-
	30	0.995	0.952	4.5	70.7	25.2
	50	0.975	0.855	14.9	302.5	209.9
	100	0.851	0.489	62.3	1495.9	2123.7
(C) Increasing, linear per-farm MRV costs						
Low	5	0.999	0.999	0.1	0.4	0.1
	30	0.790	0.638	24.6	169.6	303.4
	50	0.565	0.401	42.2	280.7	975.6
	100	0.263	0.155	80.2	396.2	4107.4
Medium	5	1.000	1.000	0.0	0.0	0.0
	30	0.893	0.798	17.8	205.6	148.1
	50	0.721	0.562	37.1	445.4	698.0
	100	0.353	0.210	79.1	803.2	3659.6
High	5	1.000	1.000	-	-	-
	30	1.000	1.000	0.1	1.4	0.1
	50	0.984	0.977	4.6	127.9	28.9
	100	0.798	0.654	49.8	1948.3	1141.9

Table B.6: Optimal emission threshold

MRV costs specification and magnitude	Emission tax δ [€/tCO_2eq]	Threshold $\tilde{e}_0$ [tCO_2eq]	Share of exempted: Farms $F(\tilde{e}_0)$ [1]	Share of exempted: Emissions $L(F(\tilde{e}_0))$ [1]	Abatement $A^s(\delta, \tilde{e}_0)$ [10^6tCO_2eq]	MRV costs $M^s(\delta, \tilde{e}_0)$ [10^6€]	Social benefit $B^s(\delta, \tilde{e}_0)$ [10^6€]
(A) Constant per-farm MRV costs							
Low	5	1675	0.998	0.944	0.5	1.0	0.8
	30	128	0.774	0.222	25.2	106.2	354.8
	50	50	0.607	0.096	43.0	184.3	1052.8
	100	17	0.386	0.035	79.6	287.9	4169.6
Medium	5	5250	1.000	0.992	0.1	0.1	0.3
	30	212	0.847	0.333	21.8	155.2	248.6
	50	93	0.714	0.163	39.9	290.6	866.8
	100	39	0.570	0.081	76.8	437.7	3872.6
High	5	7686	1.000	1.000	-	-	-
	30	952	0.992	0.880	3.9	46.5	33.4
	50	409	0.927	0.550	22.3	410.0	256.4
	100	138	0.785	0.236	66.1	1213.9	2475.4
(B) Increasing, concave per-farm MRV costs							
Low	5	5250	1.000	0.992	0.1	0.3	0.1
	30	138	0.785	0.236	24.9	187.8	267.4
	50	42	0.579	0.084	43.5	297.0	952.8
	100	16	0.350	0.030	79.8	379.9	4091.8
Medium	5	7686	1.000	1.000	-	-	-
	30	370	0.915	0.507	16.7	194.1	123.6
	50	138	0.785	0.236	36.9	407.4	670.7
	100	19	0.415	0.040	79.3	779.2	3662.0
High	5	7686	1.000	1.000	-	-	-
	30	5250	1.000	0.992	0.3	3.9	1.8
	50	1295	0.996	0.924	3.8	72.9	41.0
	100	211	0.847	0.332	59.3	1744.4	1523.8
(C) Increasing, linear per-farm MRV costs							
Low	5	7686	1.000	1.000	-	-	-
	30	138	0.785	0.236	24.9	358.3	96.9
	50	9	0.128	0.007	45.7	465.7	842.7
	100	5	0.047	0.002	80.8	468.2	4055.5
Medium	5	7686	1.000	1.000	-	-	-
	30	7686	1.000	1.000	-	-	-
	50	42	0.579	0.084	43.5	931.6	318.1
	100	6	0.052	0.002	80.8	1015.1	3508.4
High	5	7686	1.000	1.000	-	-	-
	30	7686	1.000	1.000	-	-	-
	50	7686	1.000	1.000	-	-	-
	100	7686	1.000	1.000	-	-	-

Table B.7: Approximated emission threshold (Eq. (13))

MRV costs specification and magnitude	Emission tax δ [€/tCO_2eq]	Threshold $\hat{e}_0$ [tCO_2eq]	Share of exempted: Farms $F(\hat{e}_0)$ [1]	Share of exempted: Emissions $L(F(\hat{e}_0))$ [1]	Abatement $A^s(\delta, \hat{e}_0)$ [10^6tCO_2eq]	MRV costs $M^s(\delta, \hat{e}_0)$ [10^6€]	Social benefit $B^s(\delta, \hat{e}_0)$ [10^6€]
(A) Constant per-farm MRV costs							
Low	5	1928	0.998	0.952	0.3	0.8	0.3
	30	106	0.738	0.184	26.1	122.8	351.5
	50	48	0.599	0.092	43.2	188.0	1050.5
	100	16	0.352	0.030	79.8	304.0	4165.9
Medium	5	3881	1.000	0.979	0.1	0.5	0.0
	30	214	0.851	0.340	20.9	151.8	232.2
	50	97	0.725	0.172	39.1	279.8	859.4
	100	32	0.522	0.065	77.6	486.4	3861.1
High	5	7686	1.000	1.000	-	-	-
	30	1006	0.993	0.890	3.5	40.0	27.7
	50	454	0.940	0.599	19.7	338.8	250.5
	100	148	0.798	0.253	64.8	1139.3	2458.7
(B) Increasing, concave per-farm MRV costs							
Low	5	7686	1.000	1.000	-	-	-
	30	143	0.790	0.243	24.5	184.3	262.1
	50	45	0.591	0.089	43.3	291.8	950.1
	100	9	0.163	0.010	80.5	432.0	4077.2
Medium	5	7686	1.000	1.000	-	-	-
	30	391	0.923	0.535	15.7	177.8	116.8
	50	124	0.767	0.215	37.4	432.0	664.4
	100	25	0.460	0.049	78.7	745.6	3657.7
High	5	7686	1.000	1.000	-	-	-
	30	3638	1.000	0.979	0.5	12.0	-2.2
	50	1157	0.995	0.911	4.4	92.1	35.2
	100	231	0.858	0.353	56.2	1647.0	1440.7
(C) Increasing, linear per-farm MRV costs							
Low	5	7686	1.000	1.000	-	-	-
	30	78	0.680	0.137	27.7	404.7	93.6
	50	0	-	-	45.8	469.0	841.3
	100	0	-	-	80.8	469.0	4055.0
Medium	5	7686	1.000	1.000	-	-	-
	30	7686	1.000	1.000	-	-	-
	50	29	0.498	0.058	44.2	957.7	310.5
	100	0	-	-	80.8	1017.0	3506.9
High	5	7686	1.000	1.000	-	-	-
	30	7686	1.000	1.000	-	-	-
	50	7686	1.000	1.000	-	-	-
	100	2470	0.999	0.972	2.1	160.0	-40.4

Table B.8: Approximated emission threshold (Eq. (15))

MRV costs specification and magnitude	Emission tax δ [€/tCO_2eq]	Threshold $\hat{e}_0$ [tCO_2eq]	Share of exempted Farms $F(\hat{e}_0)$ [1]	Share of exempted Emissions $L(F(\hat{e}_0))$ [1]	Abatement $A^s(\delta, \hat{e}_0)$ [$10^6 tCO_2$eq]	MRV costs $M^s(\delta, \hat{e}_0)$ [10^6€]	Social benefit $B^s(\delta, \hat{e}_0)$ [10^6€]
(A) Constant per-farm MRV costs							
Low	5	2340	0.999	0.971	0.2	0.3	0.4
	30	95	0.722	0.170	26.5	130.4	350.2
	50	39	0.570	0.081	43.6	201.5	1050.4
	100	11	0.252	0.018	80.3	350.8	4146.7
Medium	5	5075	1.000	0.989	0.1	0.2	0.2
	30	205	0.844	0.327	21.9	158.4	246.6
	50	85	0.701	0.152	40.3	303.8	863.9
	100	25	0.460	0.049	78.7	549.5	3853.7
High	5	7686	1.000	1.000	-	-	-
	30	1139	0.995	0.909	2.9	29.0	27.3
	50	473	0.945	0.620	18.8	310.4	255.5
	100	137	0.784	0.235	66.1	1219.1	2470.8
(B) Increasing, concave per-farm MRV costs							
Low	5	2340	0.999	0.971	0.2	1.5	-0.8
	30	95	0.722	0.170	26.5	225.9	254.7
	50	39	0.570	0.081	43.6	300.7	951.3
	100	11	0.252	0.018	80.3	408.5	4089.0
Medium	5	5075	1.000	0.989	0.1	1.0	-0.6
	30	205	0.844	0.327	21.9	318.7	86.3
	50	85	0.701	0.152	40.3	514.9	652.8
	100	25	0.460	0.049	78.7	745.6	3657.7
High	5	7686	1.000	1.000	-	-	-
	30	1139	0.995	0.909	2.9	94.8	-38.5
	50	473	0.945	0.620	18.8	738.3	-172.4
	100	137	0.784	0.235	66.1	2265.8	1424.1
(C) Increasing, linear per-farm MRV costs							
Low	5	2340	0.999	0.971	0.2	13.4	-12.7
	30	95	0.722	0.170	26.5	389.4	91.1
	50	39	0.570	0.081	43.6	431.1	820.9
	100	11	0.252	0.018	80.3	460.6	4036.9
Medium	5	5075	1.000	0.989	0.1	11.3	-10.9
	30	205	0.844	0.327	21.9	684.3	-279.3
	50	85	0.701	0.152	40.3	862.0	305.7
	100	25	0.460	0.049	78.7	967.2	3436.0
High	5	7686	1.000	1.000	-	-	-
	30	1139	0.995	0.909	2.9	511.8	-455.6
	50	473	0.945	0.620	18.8	2139.9	-1574.0
	100	137	0.784	0.235	66.1	4315.0	-625.2