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Analysis

Give and take: An analysis of the distributional consequences of emission tax-and-rebate schemes with an application to greenhouse gas emissions from European agriculture

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ABSTRACT

The potential regressivity of an emission tax is a major obstacle to the implementation of this otherwise cost-effective instrument. Rebates may help overcome this difficulty. Their distributional consequences depend on their design and the distribution of agents' initial emissions and abatement costs. We develop a stylized analytical framework to derive general conditions under which a tax-and-rebate scheme increases income inequality and compare the performances of various rebate designs. This framework is applied to the regulation of greenhouse gas emissions from European agriculture. An emission tax with no rebate is found to substantially reduce agricultural emissions (by approximately −15% for a 100 €/tCO_2eq tax), but also strongly affect the total sector income (approximately −20% with the same tax rate) as well as increase income inequality. A flat rebate considerably reduces income inequality relative to pre-policy levels. For the same impacts on aggregate income and budget, a rebate proportional to initial emissions leaves pre-existing inequality virtually unchanged. A well-designed rebate can thus be critical for the acceptability of climate policy instruments.

1. Introduction

Emission taxes have been proposed for decades as a cost-effective instrument to incentivize greenhouse gas (GHG) mitigation (Goulder and Parry, 2008; Stiglitz et al., 2017). However, their potentially regressive impacts (Metcalf, 2009; Ohlendorf et al., 2020) have raised increasing concerns, as they may undercut the political support to such instruments and jeopardize the implementation of ambitious climate policies (Tiezzi, 2005; Parry, 2015).

One obvious way to lessen the regressive impacts of an emission tax is to transfer back to agents all or part of the tax revenue through lump sum payments or, equivalently, to set a rebate whereby a fixed amount of emissions is deducted from each agent's tax bill (Bento et al., 2009). Abatement subsidies–which are extensively used in climate policies–can also be interpreted as a tax-and-rebate scheme, but one whereby the rebate is proportional to each agent's initial emissions. Given the heterogeneity in individual initial emissions, mitigation costs, and behavioral responses to the tax, the design (flat or proportional) and level of the rebate raise issues with regard to the distribution of post-policy income and implications on the regulator's budget.

The overall objective of this article is to examine how emission tax-and-rebate schemes affect income inequality, to compare the impacts of various rebate designs on aggregate income, regulator's budget, and inequality, and to study how a change in the tax rate affects income inequality. These issues are first addressed from an analytical perspective. The general insights gained from this approach are then complemented by an empirical assessment of the distributional implications of tax-and-rebate schemes aimed at mitigating agricultural GHG emissions in the European Union (EU).

This study contributes to a growing body of literature on the distributional effects of emission taxes. The focus of this literature is mainly on carbon taxes that target households. Carbon taxes have been found to increase income inequality in many contexts (Mathur and Morris, 2014; Araar et al., 2011; Grainger and Kolstad, 2010; Ravigné et al., 2022). See e.g., Ohlendorf et al. (2020) and Köppl and Schratzenstaller (2023) for a review. Several authors have investigated the possibility of mitigating the regressive nature of such taxes (or even making them progressive) through a simple flat-recycling rebate (Bento et al., 2009; Klenert and Mattauch, 2016; Goulder et al., 2019;

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Douenne, 2020; Cronin et al., 2019) or a broader modification of the tax system (Chiroleu-Assouline and Fodha, 2006, 2014). As poor households often devote a greater share of their budget to carbon-intensive energy than rich households, pre-policy emissions increase less than linearly with pre-policy income and carbon taxes tend to be regressive (Chancel, 2022). However, this alone is not sufficient to assess the distributional impacts of a carbon tax, as the distributional impacts also depend on the extent to which agents can adjust their behavior and the associated costs and on how income sources (e.g., wages, transfers, and capital income) are affected by the tax system (Metcalf, 2021). The heterogeneity in agents' response to the tax makes *ex ante* assessments of the distributional impacts challenging.

The EU agricultural sector provides an interesting application case for several reasons. First, although agriculture is a substantial contributor to GHG emissions (about 10% of total EU GHG emissions, mostly due to direct emissions of methane and nitrous oxide, European Environment Agency, 2020), it is still largely absent from the scope of the main climate policy instruments currently in place at both the member states and EU levels (Grosjean et al., 2016). The contribution of this sector is critical to the fulfillment of the EU's objectives of reducing GHG emissions by 40% by 2030 relative to 2005 in the sectors covered by the Effort Sharing Regulation (European Parliament, 2018; European Commission, 2021b). Second, *"ensuring a fair standard of living for the agricultural community"* was historically one of the founding objectives of the Common Agricultural Policy (CAP) and *"generating fairer economic returns"* has remained an important goal in the subsequent CAP reforms (European Commission, 2020). Third, the European agricultural sector is characterized by large income inequality (European Commission, 2021a) and large heterogeneities both between and within countries in terms of importance of agriculture, and level of agricultural policy instruments, as well as GHG emissions and marginal abatement costs (De Cara et al., 2018; Fellmann et al., 2021). This motivates the studying of rebates that are not necessarily constant across agents.

The regulation of agricultural GHG emissions has attracted increasing attention in environmental economics, with contributions quantifying the mitigation potential and costs in the agricultural sector at various spatial scales and resolutions (Havlík et al., 2013; Baker et al., 2013; Frank et al., 2018; Lötjönen et al., 2020; Fellmann et al., 2021), or simulating the consequences of various second-best policy designs (Garnache et al., 2017; De Cara et al., 2018). This literature focuses on cost-effectiveness and to a large extent, is disconnected from the distributional consequences of the policies. In parallel, the issue of income inequality within the agricultural sector has given rise to a substantial body of literature, mostly in low- and middle-income countries, but also in more developed regions (Finger and El Benni, 2014). In Europe, this issue has been often examined in relation to the role of the CAP (Hanson, 2021; Piet and Desjeux, 2021).

Our contribution is twofold. First, we analytically investigate and compare various tax-and-rebate schemes and derive general conditions under which they increase income inequality. This analysis builds on the abundant literature on Lorenz-dominance and the measurement of inequality (Atkinson, 1970; Jakobsson, 1976; Fellman, 1976). See for instance Aaberge (2001) for an axiomatic approach. We compare flat rebates (i.e., constant per unpaid individuals working on the farm) and rebates proportional to initial emissions. The former are based on a constant emission threshold and the latter on a constant relative abatement threshold. Regardless of the design of the rebate, the chosen level of the threshold determines the impacts on the regulator's budget. Combining these two dimensions, we can compare the performances of schemes that are based on a similar design but have contrasting impacts on the regulator's budget, and schemes that have the same consequences on the regulator's budget but differ in their design. Our findings confirm the key role played by the elasticity of initial emissions with respect to initial income, a feature often at the center of attention in analyses of income inequality and the environment (Chancel, 2022). They also reveal the importance of how individual mitigation costs and potential vary with respect to initial income, a feature that has drawn less attention in the literature. The analytical framework sheds new light on how various rebate designs compare in terms of income inequality, and how their distributional impacts vary with respect to the emission tax rate.

Our second contribution is empirical. To the best of our knowledge, this study is the first to examine the distributional impacts of climate-policy instruments in the agricultural sector. We quantify the distributional impacts of an emission tax on GHG emissions from European agriculture, and explore various rebate scheme designs with contrasting impacts on the regulator's budget and aggregate income. In the absence of GHG emission regulation, the distributional consequences of the policy cannot be estimated ex post. The analysis builds on a micro-economic, supply-side model of EU agriculture that operates at the farm level and covers a wide diversity of contexts across the EU (De Cara et al., 2018; Lungarska and Jayet, 2018; Bamière et al., 2021). As the model accounts for heterogeneities across farms in terms of GHG emissions, supply response to an emission tax, and marginal abatement costs, the simulations enable to discuss the implications of various tax-and-rebate schemes on income at both the farm and aggregate levels. In order to recover information about individual income (rather than farm profit), the original simulation results are complemented with individual data regarding wages paid and numbers of unpaid farmers per farm. Our findings indicate that an emission tax with no rebate tends to increase income inequality among European farmers. They also show that a rebate based on a well-chosen emission threshold may offset these regressive impacts and even substantially reduce pre-existing income inequality, while preserving cost-effectiveness.

The remainder of this paper is organized as follows. Section 2 presents the analytical framework developed in the study. The conditions under which an emission tax-and-rebate scheme is inequality-reducing are examined in Section 3, along with an analysis of how these conditions vary with the design of the rebate and tax rate. Section 4 presents the simulations used, the model they are based on, and the adjustments made for the analysis of income inequality. The impacts on aggregate income and the regulator's budget, and the distributional implications of an emission tax combined with various designs of the rebate scheme are analyzed in Section 5. Section 6 concludes.

2. Analytical framework

Consider a continuum of heterogeneous agents whose population is normalized to 1. Agents are characterized by their (positive) initial income y. The distribution of initial income is denoted by $\mathcal{Y}$, and is defined by the cumulative distribution function $F(y)$.

The activity of each agent causes emissions. We assume that initial emissions can be mapped with initial income, so that agent with initial income y initially emits $e_0(y) > 0$, with $e_0(y)$ differentiable for all y.[1] Agents may reduce their emissions at a cost $c(\alpha, y)$, where α denotes the rate of reduction in emissions relative to initial emissions. $c(\alpha, y)$ is defined for all y and for all α such that $0 \leq \alpha \leq 1$, and is assumed to be twice differentiable with respect to both arguments. The following standard assumptions are made for all y (subscripts indicate partial derivatives): $c(0, y) = 0$, $c_\alpha(0, y) = 0$, and $c_\alpha(\alpha, y) > 0$, $c_{\alpha\alpha}(\alpha, y) > 0$ for all α such that $0 < \alpha \leq 1$.

The regulator considers a policy scheme S that combines an emission tax and a rebate. Each unit of emission is taxed at a constant rate

[1] Pre-policy income y is assumed to be a pre-determined characteristic of the agent. The notation $e_0(y)$ should thus be interpreted as the initial emissions of agent with initial income y, rather than as a structural relationship between emissions and income. Note that this implies that two agents with exactly the same income have the same emissions. The same remarks apply to mitigation costs $c(\alpha, y)$.

t. The rebate is defined by a (pre-determined) non-negative quantity of emissions $\tilde{e}^{S}(t,y)$ that is deducted from the tax bill. Note that $\tilde{e}^{S}(t,y)$ depends on y to accommodate the fact that the regulator may opt for an individualized rebate. It also takes t as an argument as the rebate may be determined by the total tax revenues collected by the regulator, as will be seen later. Under scheme S, the net amount paid by an agent with income y who reduces emissions by α is:

$$g^{S}(t,y) = t.\left((1-\alpha)e_0(y) - \tilde{e}^{S}(t,y)\right) = te_0(y)\left(\tilde{\alpha}^{S}(t,y) - \alpha\right),\quad \text{where } \tilde{\alpha}^{S}(t,y) = 1 - \frac{\tilde{e}^{S}(t,y)}{e_0(y)}. \tag{1}$$

All agents emitting more than $\tilde{e}^{S}(t,y)$ (i.e., reducing their emissions by less than $\tilde{\alpha}^{S}(t,y)$) are liable for a positive net payment ($g^{S}(t,y) > 0$). All agents emitting less than $\tilde{e}^{S}(t,y)$ (i.e., reducing their emissions by more than $\tilde{\alpha}^{S}(t,y)$) receive a positive net transfer ($g^{S}(t,y) < 0$).

The case where $\tilde{\alpha}^{S}(t,y) = 1$ for all y corresponds to a standard emission tax without any rebate (no rebate, or NR). The case where $\tilde{\alpha}^{S}(t,y) = 0$ for all y corresponds to a subsidy to each unit of abatement at constant rate t (abatement subsidy, or AS).

The post-policy income of an agent with initial income y who reduces emissions by α is:

$$x^{S}(t,y) = y - c(\alpha,y) - g^{S}(t,y). \tag{2}$$

The relative net loss in individual income associated with policy scheme S is:

$$\Delta^{S}(t,y) = \frac{y - x^{S}(t,y)}{y}. \tag{3}$$

As long as individual agents cannot influence $\tilde{e}(t,y)$, the rebate does not interfere with their abatement decisions. It is easy to see that the abatement maximizing $x^{S}(t,y)$ is such that:

$$\frac{c_\alpha(\alpha,y)}{e_0(y)} = t \text{ for all } y. \tag{4}$$

Eq. (4) implicitly defines the optimal individual abatement supply $\alpha(t,y)$. As a direct consequence of the assumptions regarding abatement costs, the abatement supply for any agent is equal to zero if the emission tax is zero, and is positive and monotone increasing with respect to t for all positive emission tax rates. Thus, for all y, we have that $\alpha(0,y) = 0$. In addition, for all y and all $t > 0$, we have that $0 < \alpha(t,y) \le 1$ and $\alpha_t(t,y) > 0$.

It will be useful to normalize the impact of the policy on agents' income. Using Eqs. (1), (2), and (4), the net loss in income per unit of initial emissions can be expressed as

$$\ell^{S}(t,y) = \frac{y - x^{S}(t,y)}{e_0(y)} = t\tilde{\alpha}^{S}(t,y) - \int_0^t \alpha(u,y)\mathrm{d}u. \tag{5}$$

Fig. 1 depicts the situation for an agent with initial income y, facing an emission tax t and a rebate defined by a relative abatement threshold $\tilde{\alpha}^{S}(t,y)$. If $\tilde{\alpha}^{S}(t,y) = 1$ for all y (NR), then $\ell^{NR}(t,y)$ is unambiguously non-negative ($0 \le \ell^{NR}(t,y) \le t$). Conversely, if $\tilde{\alpha}^{S}(t,y) = 0$ for all y (AS), then $-t \le \ell^{AS}(t,y) \le 0$. More generally, if the rebate scheme leads to a net positive payment from the agent to the regulator (i.e., if $\alpha(t,y) \le \tilde{\alpha}^{S}(t,y)$), then the corresponding agent's income is negatively affected by the policy, that is $\ell^{S}(t,y) \le 0$. If, as is the case in the situation illustrated in Fig. 1, $\alpha(t,y) > \tilde{\alpha}^{S}(t,y)$, then $\ell^{S}(t,y)$ can be either positive (net loss for the agent) or negative (net gain).

As the focus is on the distributional effects of environmental policy rather than on its optimality at the aggregate level, its impacts will be examined for any emission tax rate, regardless of the actual value of the marginal damage caused by emissions. Nevertheless, it is useful to consider the aggregate impact of the policy on the regulator's budget. Integrating $g^{S}(t,y)$ over the entire population yields the total net amount of tax collected by the regulator:

$$G^{S}(t) = t\int_y e_0(y)\left(\tilde{\alpha}^{S}(t,y) - \alpha(t,y)\right)\mathrm{d}F(y). \tag{6}$$

Table 1
Five rebate designs and their impacts on the regulator's budget and total post-policy income. Note: Variables in uppercase are the aggregate counterparts of the individual variables (in lowercase) defined in the text, and can be interpreted indifferently as total or population average. NR: No rebate; AS: Abatement subsidy; BN: Budget-neutral; BC: Budget-costly; CAET: Constant absolute emission threshold; CRAT: Constant relative abatement threshold.

Rebate S	Absolute emission threshold $\tilde{e}^{S}(t,y)$	Relative abatement threshold $\tilde{\alpha}^{S}(t,y)$	Net tax revenue $G^{S}(t)$	Post-policy income $X^{S}(t)$
NR	0	1	$t(E_0 - A(t))$	$Y - C(t) - t(E_0 - A(t))$
BN-CAET	$E_0 - A(t)$	$1 - \frac{E_0 - A(t)}{e_0(y)}$	0	$Y - C(t)$
BN-CRAT	$e_0(y)\left(1 - \frac{A(t)}{E_0}\right)$	$\frac{A(t)}{E_0}$	0	$Y - C(t)$
BC-CAET	E_0	$1 - \frac{E_0}{e_0(y)}$	$-tA(t)$	$Y - C(t) + tA(t)$
AS	$e_0(y)$	0	$-tA(t)$	$Y - C(t) + tA(t)$

The net tax revenue for the regulator under an emission tax with no rebate amounts to $G^{NR}(t) = t(E_0 - A(t))$, where E_0 and $A(t)$ are the aggregate initial emissions and abatement, respectively. An abatement subsidy entails a net budget cost for the regulator ($G^{AS}(t) = -tA(t)$).

Budget-neutral (BN) schemes–such that $G^{S}(t) = 0$–are of particular interest. If based on a constant absolute emission threshold (CAET), one such scheme is defined by:

$$\tilde{e}^{BN\text{-}CAET}(t,y) = E_0 - A(t) \text{ for all } y. \tag{7}$$

If the rebate is based on Eq. (7), agents with higher-than-average[2] post-policy emissions are liable for a positive net payment to the regulator, whereas agents with lower-than-average post-policy emissions receive a net transfer from the regulator.

A budget-neutral scheme may also be based on a constant relative abatement threshold (CRAT):

$$\tilde{\alpha}^{BN\text{-}CRAT}(t,y) = \frac{A(t)}{E_0} \text{ for all } y. \tag{8}$$

In this case, any agent who reduces emissions by a greater (lower) rate than the average abatement rate receives (pays) a net positive amount from (to) the regulator.

Specifications (7) and (8) assume that the regulator can predict the overall abatement $A(t)$ when setting the rebate. If this information is not available, one can imagine a rebate based on a constant absolute emission threshold equal to the average initial emissions:

$$\tilde{e}^{BC\text{-}CAET}(t,y) = E_0 \text{ for all } y. \tag{9}$$

Specification (9) imposes the same net budget cost (BC) to the regulator as in the case of an abatement subsidy ($G^{BC\text{-}CAET}(t) = -tA(t)$), but involves a different distribution of post-policy income.

The five rebate designs discussed above are presented in Table 1. By construction, for a given tax rate, they are all equivalent in terms of total emissions and abatement costs. The sum of the total post-policy income and net tax revenue is also constant across schemes ($X^{S}(t) + G^{S}(t) = Y - C(t)$). Note that the total post-policy income $X^{S}(t)$ is smaller than the pre-policy income Y under the first three schemes (NR, BN-CAET, BN-CRAT), and larger than Y under BC-CAET and AS (as $tA(t) > C(t)$).

The rebate design impacts not only post-policy income, but also how it varies with respect to the tax rate. Differentiating the net loss in income per unit of initial emissions with respect to t yields (see Eq. (5)):

$$\ell^{S}_t(t,y) = \tilde{\alpha}^{S}(t,y) + t\tilde{\alpha}^{S}_t(t,y) - \alpha(t,y) \tag{10}$$

The term $t\tilde{\alpha}^{S}_t(t,y)$ in Eq. (10) is relevant only for budget-neutral schemes (BN-CAET, BN-CRAT), and is equal to zero under the three other rebate

[2] Remember that, as the population mass is normalized to 1, aggregate emissions are equal to average emissions.

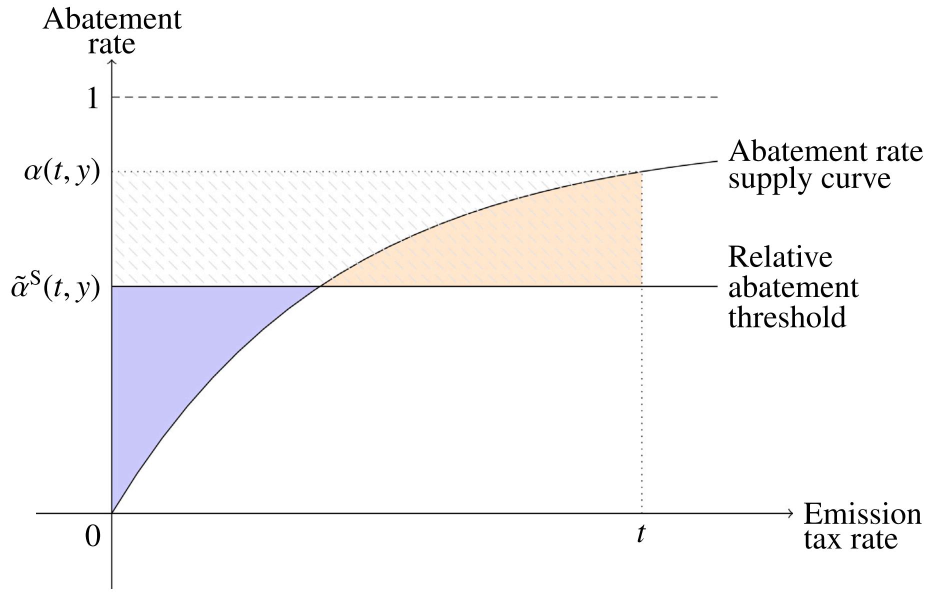

Fig. 1. Situation of an individual agent with pre-policy income y under a tax-and-rebate scheme defined by a tax rate t and a relative abatement threshold $\tilde{\alpha}^S(t,y)$. Note: The net loss in income per unit of initial emissions, $\ell^S(t,y)$, is given by the difference between the blue area and the orange area; the gray hatched area represents the net payment per unit of initial emissions ($g^S(t,y)/e_0(y)$), which is negative in this case (net transfer to the agent). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

designs (NR, BC-CAET, and AS, see Table 1). This term captures the fact that, as total abatement rises in response to the tax increase, the threshold needs to be adjusted accordingly to ensure budget-neutrality.

A marginal increase in t decreases the income for all agents under the no-rebate scheme (NR), and increases it under an abatement subsidy (AS). For the other three schemes, the change in income is negative (positive) for agents reducing their emissions by a rate smaller (larger) than $\tilde{\alpha}^S(t,y) + t\tilde{\alpha}^S_t(t,y)$.

To describe how the various components of the model vary with respect to y, we introduce the following notations:

$$\varepsilon(y) = \frac{ye'_0(y)}{e_0(y)}, \xi^S(t,y) = \frac{yx^S_y(t,y)}{x^S(t,y)}, \lambda^S(t,y) = \frac{y\ell^S_y(t,y)}{\ell^S(t,y)}, \nu^S(t,y) = \frac{y\ell^S_{ty}(t,y)}{\ell^S_t(t,y)}, \tag{11}$$

which represent the (local) elasticity with respect to initial income y of initial emissions, post-policy income, net loss in income per unit of initial emissions, and change in net loss in income per unit of initial emissions due to a marginal change in t, respectively.

3. Impacts of tax-and-rebate schemes on income inequality

We now examine how the design of an emission tax-and-rebate scheme affects income inequality. Intuitively, the distributional impacts of an emission tax-and-rebate scheme hinges on whether the net loss in income due to the tax varies more or less than proportionally with income. It partly depends on how initial emissions vary with respect to income. If lower-income agents have proportionally larger emissions than higher-income agents, this tends to make them proportionally more affected by the emission tax. This regressive effect can be compensated (reinforced) if lower-income agents are able to reduce their emissions relatively more (less) than higher-income agents for the same emission price.

The comparison of income distributions is based on the Lorenz-dominance criterion. In particular, we use that the post-policy income distribution $\mathcal{X}^S$ is Lorenz-dominated by the pre-policy income distribution $\mathcal{Y}$–that is, $\mathcal{Y} \preceq_L \mathcal{X}^S$, and the policy is inequality-increasing–if and only if the policy is regressive everywhere (i.e. $x^S(t,y)/y$ is non-decreasing with respect to y for all y in $\mathcal{Y}$) or (ii) non-rank-preserving everywhere (i.e. $x^S(t,y)$ is non-increasing with respect to y for all y in $\mathcal{Y}$) (Eichhorn et al., 1984).

For any given value of t, and assuming that $y > 0$, $x^S(t,y) > 0$ and $x^S_y(t,y) > 0$ for all y, these conditions can be summarized as follows:

$$\xi^S(t,y) \geq 1 \text{ for all } y, \tag{12}$$

where $\xi^S(t,y)$ is the elasticity of post-policy income with respect to y as defined in (11).

Conditions (12) can be rearranged and expressed in terms of the net loss in income ($e_0(y)\ell^S(t,y)$, see Eq. (5)) and how it varies with respect to initial income.

Proposition 1. *Consider a rank-preserving tax-and-rebate scheme S with an emission tax rate $t > 0$ such that post-policy income is positive for all y. S is inequality-increasing ($\mathcal{X}^S \preceq_L \mathcal{Y}$) if and only if (the arguments t and y are omitted):*

$$\varepsilon \leq 1 - \lambda^S \text{ for all } y \text{ such that } \Delta^S > 0 \tag{13}$$

$$\text{and } \varepsilon \geq 1 - \lambda^S \text{ for all } y \text{ such that } \Delta^S < 0 \tag{14}$$

Proof. See Appendix A.1.

The tax-and-rebate scheme is regressive if the net loss in income varies less than linearly with respect to initial income for agents who loose from the policy, and more than linearly with respect to y for those who gain from the policy. These conditions permit to distinguish the respective roles of the distribution of initial emissions with respect to pre-policy income (through $\varepsilon(y)$) from that of the loss in income per unit of initial emissions (through $\lambda^S(t,y)$). Additionally, they underscore the importance of how the chosen threshold partitions the population into agents who incur a net loss due to the policy (13) and those who benefit from it (14).

To clarify the interpretation of Proposition 1, first consider a policy involving a positive emission tax but no rebate (NR). In this case, it is clear that all agents face a net loss and, hence, that conditions (13) apply for all y. In such a situation, if $\varepsilon(y)$ is smaller than 1 for all y, lower-income agents tend to have proportionally larger emissions than higher-income agents, which tends to make them proportionally more affected by the emission tax. However, the ability of agents to reduce their emissions in response to the tax may lessen this potentially regressive impact. This effect depends on how abatement and the associated costs vary with respect to initial income y and is encapsulated in $\lambda^{S}(t,y)$, which is the elasticity of the net loss in income per unit of initial emissions with respect to y ($\ell^{S}(t,y)$, see Eq. (5)). In the case of no rebate (NR), conditions (13) indicate that, even if $\varepsilon(y) < 1$ for some values of y, the policy can still be progressive provided that $\lambda^{NR}(t,y)$ is sufficiently large for the respective agents.

Now, consider the polar case of an abatement subsidy (AS). In this case ($\tilde{\alpha}^{AS}(t,y) = 0$ for all y), all agents unambiguously gain from the policy and conditions (14) apply. A comparison of the conditions for NR and AS shows that the effect of the distribution of initial emissions on inequality depends on the rebate design. Other things held constant, an increase in $\varepsilon(y)$ makes the no-rebate scheme more progressive, whereas it makes the abatement subsidy more regressive.

The three other rebate designs (BN-CAET, BN-CRAT, and BC-CAET) split the population into two categories: those who face a net loss and those who enjoy a net gain from the policy. Whether each scheme reduces or increases income inequality partly depends on whether the agents in the former category are also those with higher or lower initial income.

As seen above, the various rebate designs differ only in the total level and distribution of post-policy income, as well as in their impacts on the regulator's budget. For a given value of t, it is always possible to reduce income inequality relative to that under an emission tax by introducing a rebate based on a constant absolute emission threshold (CAET), which is equivalent to a lump-sum transfer. Moreover, the larger the emission threshold, the lower the inequality (but also the larger the net budget cost for the regulator). We thus have (see Appendix A.2):

$$\mathcal{X}^{NR} \preceq_L \mathcal{X}^{BN\text{-}CAET} \preceq_L \mathcal{X}^{BC\text{-}CAET} \tag{15}$$

The following proposition further compares various rebate designs in terms of income inequality. We assume in this proposition that initial emissions are monotone increasing with respect to initial income ($\varepsilon(y) > 0$). This assumption is essentially meant to simplify the exposition of the results.[3]

Proposition 2. *Assume that emissions are monotone increasing with initial income and that, for any given emission tax rate $t > 0$, the no-rebate policy leaves a positive post-policy income for all agents and is rank-preserving, that is, $\varepsilon(y) > 0$, $x^{NR}(t,y) > 0$ and $x_y^{NR}(t,y) > 0$ for all y. Under these assumptions, the following results hold (the arguments t and y are omitted):*

(i) If $\varepsilon \leq 1 - \Delta^{NR}\lambda^{NR}$ for all y, then $\mathcal{X}^{NR} \preceq_L \mathcal{X}^{BN\text{-}CRAT} \preceq_L \mathcal{X}^{AS}$;
(ii) If $\varepsilon \geq 1 - \Delta^{NR}\lambda^{NR}$ for all y, then $\mathcal{X}^{AS} \preceq_L \mathcal{X}^{BN\text{-}CRAT} \preceq_L \mathcal{X}^{NR}$;
(iii) If $\varepsilon \geq \frac{e_0 - E_0}{e_0 - E_0\Delta^{BC\text{-}CAET}}\left(1 - \Delta^{BC\text{-}CAET}\lambda^{BC\text{-}CAET}\right)$ for all y such that $e_0 \geq E_0$, then $\mathcal{X}^{AS} \preceq_L \mathcal{X}^{BC\text{-}CAET}$.
(iv) If $\varepsilon \geq \frac{e_0 - E_0}{e_0 - E_0\Delta^{BN\text{-}CAET}}\left(1 - \Delta^{BN\text{-}CAET}\lambda^{BN\text{-}CAET}\right)$ for all y such that $e_0 \geq E_0$, then $\mathcal{X}^{BN\text{-}CRAT} \preceq_L \mathcal{X}^{BN\text{-}CAET}$.
(v) If $\varepsilon \geq \frac{e_0 - (E_0 - A)}{e_0 - (E_0 - A)\Delta^{BN\text{-}CAET}}\left(1 - \Delta^{BN\text{-}CAET}\lambda^{BN\text{-}CAET}\right)$ for all y such that $e_0 \geq E_0 - A$, then $\mathcal{X}^{AS} \preceq_L \mathcal{X}^{BN\text{-}CAET}$.

Proof. See Appendix A.2.

Part (i) of the proposition indicates that inequality can be reduced through a rebate proportional to initial emissions (BN-CRAT and AS), and all the more so as the total transfer is large. However, this requires that $\varepsilon(y)$ not be too large. In particular, this result holds true if $0 < \varepsilon(y) < 1$ for all y and the no-rebate scheme is regressive (i.e., $\varepsilon(y) + \lambda^{NR}(t,y) < 1$, see (13)). If, by contrast, $\varepsilon(y)$ is too large, such schemes may perform worse than an emission tax with no rebate in terms of income inequality (part (ii)). Interestingly in that case, the greater the total transfer to agents (and hence the budget cost), the greater the post-policy income inequality.

Parts (iii) and (iv) provide pairwise comparisons of tax-and-rebate schemes with the same impact on the regulator's budget. Smaller-than-average emitters are better off if the rebate is based on a constant absolute emission threshold (CAET) than on a constant relative abatement threshold (CRAT). This implies that, for the same impact on the regulator's budget, CRAT-based rebates cannot Lorenz-dominate CAET-based rebates as soon as initial emissions are monotone increasing with initial income. For agents with greater-than-average emissions, $\varepsilon(y)$ must be large enough for a CAET-based rebate to reduce income inequality compared with a CRAT-based rebate. Part (v) indicates that if $\varepsilon(y)$ is large enough, a budget-neutral policy (BN-CAET) Lorenz-dominates a budget-costly policy (AS). This confirms that the form of the rebate matters more for income inequality than the total amount of transfers.

Under some additional conditions, the results presented in Proposition 2 lead to a complete ranking of the rebate schemes in terms of income inequality.

Corollary 1. *Under the assumptions of Proposition 2, if conditions (i) and (v) are satisfied then*

$$\mathcal{X}^{NR} \preceq_L \mathcal{X}^{BN\text{-}CRAT} \preceq_L \mathcal{X}^{AS} \preceq_L \mathcal{X}^{BN\text{-}CAET} \preceq_L \mathcal{X}^{BC\text{-}CAET}.$$

Proof. See Appendix A.3.

The last question examined in this section is how a change in the emission tax rate affects inequality for a given rebate scheme.

Proposition 3. *Consider a tax-and-rebate scheme S defined by a tax rate t and a relative abatement threshold $\tilde{\alpha}^{S}(t,y)$ such that post-policy income is positive and rank-preserving for all agents ($x^{S}(t,y) > 0$ and $x_y^{S}(t,y) > 0$ for all y). A marginal increase in the tax rate t increases income inequality if and only if (the arguments t and y are omitted):*

$$\varepsilon \leq 1 - \Delta^{S}\lambda^{S} - \left(1 - \Delta^{S}\right)\nu^{S} \text{ for all } y \text{ such that } \alpha < \tilde{\alpha}^{S} + t\tilde{\alpha}_t^{S}, \tag{16}$$

$$\text{and } \varepsilon \geq 1 - \Delta^{S}\lambda^{S} - \left(1 - \Delta^{S}\right)\nu^{S} \text{ for all } y \text{ such that } \alpha > \tilde{\alpha}^{S} + t\tilde{\alpha}_t^{S}. \tag{17}$$

Proof. See Appendix A.4.

To interpret the conditions given in Proposition 3, consider the case of an emission tax with no rebate (NR). In this situation, condition (16) applies for all y, and reduces to:

$$\varepsilon(y) \leq 1 - \Delta^{NR}(t,y)\lambda^{NR}(t,y) + \left(1 - \Delta^{NR}(t,y)\right)\left(\frac{y\alpha_y(t,y)}{1 - \alpha(t,y)}\right) \quad \text{for all } y. \tag{18}$$

Notice that, $\Delta^{S}(0,y) = 0$ for all y regardless of the choice of the policy scheme design. Moreover, as $\alpha(0,y) = 0$ for all y, we have that $\alpha_y(0,y) = 0$ for all y. Therefore, starting from $t = 0$, a marginal increase in the emission tax rate increases income inequality under a no-rebate scheme if and only if $\varepsilon(y) \leq 1$ for all y. The intuition is similar to that behind Proposition 1. In the neighborhood of $t = 0$, the direction of the change in income inequality due to a marginal increase in t is predominantly determined by the distribution of initial emissions. If $\varepsilon(y) < 1$, the emission tax with no rebate tends to be regressive, and a marginal increase in t reinforces its regressivity. That is only when starting from a sufficiently large tax rate that the distribution of $\alpha_y(t,y)$ might counteract this tendency at the condition that lower-income agents are able to cut their emissions by a larger rate than higher-income agents (i.e. $\alpha_y(t,y) < 0$).

Under an abatement subsidy (AS) with $t > 0$, condition (17) applies as $\alpha(t,y) > 0$ for all y. Therefore, in this context, a marginal increase in t increases inequality if and only if:

$$\varepsilon(y) \geq 1 - \Delta^{AS}(t,y)\lambda^{AS}(t,y) - \left(1 - \Delta^{AS}(t,y)\right)\left(\frac{y\alpha_y(t,y)}{\alpha(t,y)}\right) \quad \text{for all } y. \tag{19}$$

[3] This assumption corresponds to the empirical findings, which indicate a positive relationship between initial emissions and initial income (see Fig. 4).

A comparison of conditions (18) and (19) highlights the contrasting roles played by $\varepsilon(y)$ and $\alpha_y(t, y)$ under NR and AS.

The results presented above confirm the importance of the elasticity of initial emissions with respect to y when assessing the distributional consequences of any tax-and-rebate scheme. However, whether initial emissions vary less or more than linearly with initial income is not sufficient on its own to compare various candidate schemes with contrasting consequences on the regulator's budget and/or income distribution. This should be examined jointly with the distribution of agents' ability to reduce emissions. In other words, the ranking of various rebate schemes also depends on the heterogeneity of agents in terms of abatement potential and costs. This is, to a large extent, an empirical question.

The analytical results presented above rely on three assumptions that must hold true for all agents: (i) post-policy income remains positive, (ii) initial emissions are increasing with respect to initial income, (iii) the policy is rank-preserving. Although these assumptions seem reasonable, they may not be satisfied locally. The remainder of the paper examines whether the insights gained from the analytical framework are still valid in an empirical context in which these assumptions do not hold true for all agents.

4. Simulation data: Abatement costs of GHG emissions from EU agriculture

We now turn to the empirical application to the mitigation of GHG emissions from EU agriculture. In addition to a comprehensive sectoral coverage, the framework presented above requires a representation of individual heterogeneity not only in terms of initial income and emissions, but also in terms of abatement potential and costs. AROPAj, a micro-economic model of the EU agricultural supply, is one of the rare empirical models able to provide such information both at the farm and EU levels. See e.g., De Cara et al. (2005) for a general and synthetic presentation of the model and Jayet et al. (2023) for a full technical description of the current version. The model has been used extensively to assess the economic and environmental impacts (GHG emissions, nitrogen compounds, water use and quality) of policies affecting the EU agricultural sector (De Cara and Jayet, 2011; Lungarska and Jayet, 2018; De Cara et al., 2018; Bamière et al., 2021; Gérard and Jayet, 2023). The empirical application builds on a set of simulations based on this model and produced by Isbasoiu (2019) to examine the impacts of the implementation of an emission tax on EU agricultural GHG emissions. These simulations cover the period 2007–12. For ease of presentation, only the results for the most recent year (2012) are used in the analysis.

The model describes the optimal annual economic behavior of a set of representative farmers in terms of farmland allocation (food and feed crops, temporary and permanent pastures, and grasslands) and livestock management (animal numbers, animal feeding). It integrates the relevant CAP provisions and a rich technical content in terms of crop and livestock production. The behavior of each representative farmer is modeled using a static, mixed integer linear-programming model. Farmers are assumed to be price-takers and act independently of one another. In a given economic and policy context (input and output prices, taxes and subsidies, CAP provisions), each farmer chooses crop area allocation, animal feeding, and animal numbers to maximize the farm's gross margin, subject to technical (e.g., crop rotations, animal-specific feeding requirement), resource availability (e.g., available farmland area, herd size), and CAP-related constraints.

Most parameters and initial values of the model variables are taken from or estimated based on the EU Farm Accountancy Data Network (EU-FADN), which provides accounting and structural data (revenues, variable costs, prices, yields, crop area, animal numbers, support received, and type of farming) for more than 70,000 surveyed professional farms across the EU. The surveyed farms are representative of the diversity of farming production contexts at the regional level. The EU-FADN provides a weight attached to each surveyed farm that enables the aggregation of farm results at regional, country, or EU scales. The model represents a total population of 3.766 million farms for 2012.

The model covers the 24 main annual crops currently grown in Europe as well as temporary and permanent pastures and grasslands. Perennial crops (orchards and vineyards) and specialty crops are excluded. Animal categories represented in the model are sheep, goats, swine, poultry, dairy, and non-dairy cattle. Cattle are further disaggregated into age and sex categories. The possible interactions between vegetal and animal production activities occurring at the farm level are explicitly modeled, notably through the on-farm consumption of feed crops. This is particularly important for mixed-farming systems that represent a substantial share of European agriculture.

Representative farms are constructed as clusters of the farms surveyed by the EU-FADN. This classification groups farms that operate in the same region and are similar in terms of main type of farming (14 modalities, see Table B.5; a representative farm may combine several types of farming), economic size, and altitude (0–300 m, 300–600 m, and over 600 m). This typology resulted in 1993 representative farms across 133 regions in 2012.

The main agricultural sources of GHG emissions are endogenously determined at the representative farm level: nitrous oxide (N_2O) emissions due to agricultural soils and manure management and methane (CH_4) emissions due to enteric fermentation, manure management, and rice cultivation. Smaller sources (such as CO_2 emissions due to the use of fossil fuels and carbon-containing fertilizers in the sector) are not covered by the model. Note that carbon sinks/sources in soils and biomass, which would require a dynamic approach, are not included. The calculation of emissions relies on country-specific emission factors taken from member states' GHG inventory reports to the UNFCCC. These factors link the level of the relevant activity for any representative farm to that of the corresponding sources of emissions. N_2O and CH_4 emissions are converted into CO_2eq based on the respective 100-year global warming potential: $GWP_{N_2O} = 298$ and $GWP_{CH_4} = 25$.

Over the full set of farms represented in the simulations, initial emissions average about 97 tCO_2eq per farm (see Table 2), with a wide range of variation in per-farm emissions from 0.2 to more than 8500 tCO_2eq. The resulting distribution of initial emissions is right-skewed, with a median almost four times lower than the mean and a coefficient of variation slightly above 2.

The main purpose of these simulations was to evaluate the response of each representative farm to an emission tax. We focus on tax rates ranging from 0 to 100 €/tCO_2eq (by steps of 1 € up to 60 €/tCO_2eq, and of 2.5 € from 60 to 100 €/tCO_2eq). The highest value of this range is slightly below the maximum price observed on the EU Emissions Trading System to date and also larger than the carbon tax rates currently implemented in most European countries (World Bank, 2022). Farmers respond to the tax by adjusting their input use and output through changes in their crop area allocation, animal numbers, and/or animal feeding (e.g., on-farm produced vs. marketed feed, forage vs. concentrates) within the feasible set defined by the model constraints. For each simulated tax rate t, one obtains a point evaluation of the abatement supply (difference between initial emissions and emissions at price t) and abatement costs (initial gross margin minus gross margin at price t excluding the total amount of tax paid).

Table 3 reports the EU-wide results for three emission tax rates. Emissions (365 $MtCO_2$eq with no tax) are reduced by approximately 6, 9, and 15% for tax rates of 30, 50, and 100 €/tCO_2eq, respectively. The total abatement costs reach up to 2.1 billion € for the highest explored tax rate.

In line with the purpose of eliciting mitigation costs at the farm level, the main variable of interest in the original set of simulations was the gross margin per representative farm. This raises three main issues. First, the gross margin may not perfectly align with farm income. In particular, the gross margin provided in the simulations (sales value

Table 2
Descriptive statistics of the main variables of interest for two normalizations and two sets of farms. Note: Income is proxied by operational surplus (see text). AWU: Annual Workforce Unit; Full set of farms: 3.766 million farms and 4.967 million unpaid AWU; Only farms with positive income at t = 100 €/tCO_2eq: 3.503 million farms and 4.611 million unpaid AWU.

	Per farm					Per unpaid AWU				
	mean	s.d.	min	med.	max	mean	s.d.	min	med.	max
	Full set of farms									
Emissions (tCO_2eq)	96.8	206	0.2	26.1	8570	73.4	162	0.1	21.9	8570
Gross margin (k€)	45.8	111	−312.4	14.6	4589	34.7	90	−242.4	11.0	4589
Income (k€)	41.0	99	−447.0	13.0	3311	31.1	79	−398.4	10.0	3531
	Only farms with positive income at t = 100 €/tCO_2eq									
Emissions (tCO_2eq)	97.2	209	0.2	26.2	8570	73.9	164	0.1	21.9	8570
Gross margin (k€)	49.7	113	0.0	16.1	4589	37.7	91	0.0	12.4	4589
Income (k€)	46.5	98	0.0	15.1	3311	35.4	77	0.0	11.7	3531

Table 3
EU-aggregated results for the full (3.766 M farms, 4.967 M unpaid AWU) and restricted (3.503 M farms, 4.611 M unpaid AWU) sets of farms.

	Emission tax (t, in €/tCO_2eq)			
	0	30	50	100
	Full set of farms			
Emissions ($E(t)$, in MtCO_2eq)	365	343	332	312
Abatement ($A(t)$, in MtCO_2eq)	.	21	33	53
Abatement costs ($C(t)$, in M€)	.	238	698	2148
	Only farms with positive income at t = 100 €/tCO_2eq			
Emissions ($E(t)$, in MtCO_2eq)	341	320	309	290
Abatement ($A(t)$, in MtCO_2eq)	.	21	32	50
Abatement costs ($C(t)$, in M€)	.	231	677	2038

minus variable costs) does not account for wages paid, depreciation of capital, land, opportunity cost of own capital, or possible off-farm income sources. Second, a farm may support more (or in some cases less) than one farmer. This raises the question of whether income inequality should be measured per individual or per farm. Third, a recurring issue with farm accounting data is that a non-negligible share of farms reports a negative value of income (Piet and Desjeux, 2021; European Commission, 2021a). Although this is not an issue *per se* for profit maximization, it is clearly problematic when applying the analytical framework presented in Sections 2 and 3, which requires that both pre- and post-policy incomes be positive. The presence of negative income values blurs the interpretation of Lorenz curves, hinders their use in comparing income distributions (Atkinson, 1970), and impedes to relate scheme progressivity and inequality-reducing properties (Le Breton et al., 1996).

These difficulties lead us to make three changes to the simulation data. First, following Piet and Desjeux (2021), we use the operating surplus as a proxy for income. For each representative farm, we retrieved from the EU-FADN the wages paid to workers external to the farm for each representative farm and subtracted them from the gross margin. Total wages amount to approximately 18.1 billion €, or an average of approximately 4800 € per farm. Annual per-farm income averages about 41,000 € and is characterized by a large coefficient of variation (approximately 2.4), and a median more than three times lower than the mean (see Table 2).

Second, we analyze the income distribution on a per-individual basis rather than on a per-farm basis. To do so, we retrieved the number of unpaid workers from the FADN database to account for the number of individuals supported by the respective farm's income. These numbers are expressed in full-time equivalent annual workforce units (AWU). The farms represented in the simulations occupy 4.967 million unpaid AWU. This corresponds to an average of 1.32 unpaid AWU per farm, with values ranging from 0.04 to 6 AWU. All variables at the farm level are normalized using the respective number of unpaid AWU (see the right part of Table 2). This normalization slightly increases the coefficient of variation and median-to-mean ratio for both emissions and income.

Third, we exclude farms with negative income, as is done for example in Piet and Desjeux (2021). Approximately 3.6% of the farms represented in the model (approximately 136,300 farms) fall in this category even in the absence of an emission tax. This share is consistent with that reported by the (European Commission, 2021a, Figure 1.20, p. 24). As post-policy income must also be positive, we further restrict the analysis to farms with a positive operating surplus for the maximum emission tax rate (100 €/tCO_2eq). This leads us to exclude an additional 3.4% of the represented farms (approximately 127,200 farms). As the initial emissions of the excluded farms are, on average, slightly lower than that of the total population, the average initial emissions among the remaining farms are slightly larger than those of the full set of farms (See Table 2). Over the retained set of farms, the total initial emissions are almost 7% (ca. 24 MtCO_2eq) lower than over the full set of farms (see Table 3). The overall relative changes in emissions remain very close to those obtained with the full set of farms for the range of emission tax rates presented in Table 3.

These modeling choices call for some discussion. First, we restrict the distributional analysis to that of annual income inequality, although inequality could manifest across several other dimensions (e.g., wealth, consumption, lifetime income). Moreover, there are alternatives to operating surplus as a measure of farm income (Finger and El Benni, 2021). Unfortunately, the simulation data set did not contain the information necessary to compute the corresponding variables. Second, as labor is not endogenously modeled, the number of unpaid AWU per farm and the amount of wages paid are assumed to not vary with the tax rate. This assumption is supported by the results of Pellerin et al. (2017) at least for the range of emission tax considered here. The authors estimate the mitigation costs and potential for French agriculture using a bottom-up approach. They find that a carbon price of at least 125 €/tCO_2eq is needed to trigger adoption of practices involving a substantial change in dedicated labor time. Third, the use of per-farm (rather than per individual) income and emissions may make sense from a policy point of view. Fourth, alternative treatments of farms with negative income might be envisaged, for example by including all farms and arbitrarily setting income to 0 for those with negative income or restricting the analysis to that of a synthetic inequality

Table 4
Aggregate farm income and impacts on the regulator's budget of the five tax-and-rebate schemes. Note: Income is proxied by operational surplus (see text). The scope is restricted to farms with positive income at $t = 100$ €/tCO_2eq (3.503 million farms and 4.611 million unpaid AWU across the EU-27). NR: No rebate; AS: Abatement subsidy; BN: Budget-neutral; BC: Budget-costly; CAET: Constant absolute emission threshold; CRAT: Constant relative abatement threshold.

	Emission tax (t, in €/tCO_2eq)			
	0	30	50	100
Income ($X^S(t)$, in M€)				
NR	163,034	153,205	146,914	131,982
BN-CAET/BN-CRAT	163,034	162,803	162,357	160,996
BC-CAET/AS	163,034	163,421	163,941	166,035
Net tax revenue ($G^S(t)$, in M€)				
NR	.	9,598	15,442	29,014
BN-CAET/BN-CRAT	.	.	.	.
BC-CAET/AS	.	−618	−1,584	−5,039

index that can accommodate negative values such as the generalized Gini index (Raffinetti et al., 2014). Fifth, farms with extreme income values might be considered too influential and excluded as outliers, as is done for example in Piet and Desjeux (2021). Various combinations of normalizations and alternative treatments for farms with negative and/or extreme income values are explored as robustness checks in Appendix C. In addition, we provide a detailed focus on farms with income below the first decile (including negative incomes).

5. Distributional impacts of a tax-and-rebate scheme applied to GHG emissions from EU agriculture

We now examine the consequences of the schemes introduced in Section 2 and applied to the simulation data presented in Section 4, starting with their effects at the aggregate level.

The results reported in Table 4 underscore the contrasting impacts of the various rebate schemes on total farm income and the regulator's budget. When no rebate accompanies the emission tax (NR), the aggregate farm income is substantially affected. It decreases by 6, 10, and 19% for emission tax rates of 30, 50, and 100 €/tCO_2eq, respectively. The abatement costs represent only a small fraction of this decrease. The loss in income is predominantly due to the tax paid on unabated emissions, which represents more than 93% of the aggregate loss of income across the range of tax rates. By construction, the tax paid is fully redistributed to farmers under budget-neutral schemes (BN-CAET and BN-CRAT). As a result, the decrease in aggregate farm income relative to initial income remains limited in that case, reaching at most 1.3% of initial income for a 100 €/tCO_2eq emission tax. Under the two remaining rebate schemes (BC-CAET and AS), farmers see their income increase by up to 3 billion € (1.8% of the total initial income) for a 100 €/tCO_2eq emission tax. The corresponding cost for the regulator's budget reaches more than 5 billion €.

The Gini index provides a synthetic overview of the consequences in terms of income inequality. This index is computed for the five rebate schemes and the full range of emission tax rates. The results are shown in Fig. 2. The initial situation is characterized by substantial income inequality, with a Gini index value of 0.673. This value is very close to that reported by the (European Commission, 2021a, Tab. 1.1, p. 24) for the year 2012 (0.67). Fig. 2 suggests that the design of the rebate has a larger impact on the value of the Gini index than its overall level.

Under an emission tax with no rebate (NR), the Gini index increases with the emission tax rate, and reaches a maximum value of 0.690 for a tax rate of 100 €/tCO_2eq. This finding suggests an increase in income inequality relative to the initial situation. Applying an Atkinson–Plotnick–Kakwani decomposition, we show that 25.7% of this increase in income inequality is due to a reranking effect, whereas 74.3% is due to a vertical equity effect. The decomposition for all rebate schemes is presented in C.6.

If the rebate is based on a constant relative abatement threshold (BN-CRAT and AS), the Gini index remains very close to its initial value, increasing by at most 0.15% under BN-CRAT and decreasing by at most 0.08% under AS. By contrast, if the rebate is based on a constant absolute emission threshold (CAET), the Gini index decreases markedly with the emission tax rate. At its minimum (for $t = 100$ €/tCO_2eq), it reaches 0.566 and 0.549 under BN-CAET and BC-CAET, respectively, that is, more than 10 percentage points below its initial value, and almost 15 percentage points below that with the same tax rate but no rebate. This suggests a strong decrease in income inequality.

As a synthetic measure, the Gini index does not provide clear conclusions about the ordering of income distributions (Lorenz curves may intersect), nor does it fully describe the policy impact on income distribution across all income quantiles. To refine the analysis of the distributional impacts of the tax, we examine these impacts along the full distribution of initial income, focusing first on the case of an emission tax with no rebate (NR).

The Lorenz curves of individual income under the pre-policy situation and three emission tax rates (30, 50, and 100 €/tCO_2eq) are depicted in Fig. 3 (left), along with the associated delta Lorenz curves relative to the pre-policy situation (right). The latter correspond to the respective changes in cumulative income share for all quantiles (Ferreira et al., 2018). Although the resulting Lorenz curves are very close to one another, the delta Lorenz curves show that the emission tax is unambiguously inequality-increasing for the three considered tax rates. These findings also indicate that the emission tax reduces (increases) the income share of the population below (above) the 9th income decile. The larger the tax rate, the larger the loss in income share for low-income agents.

These results can be further explored along the lines suggested by Proposition 1. Fig. 4 (left) depicts the (log-transformed) distribution of individual initial emissions with respect to initial income. It shows a significantly positive association between $\log(e_0(y))$ and $\log(y)$. The estimated slope of the (weighted, log–log) regression line shown in Fig. 4 (left) is approximately 0.87 (significant at the 1% confidence level). On average, individual initial emissions increase slightly less than linearly with initial income. Thus, lower-income agents tend to bear a proportionally larger tax burden than higher-income agents. As seen in Section 3, this tends to make the emission tax regressive. By contrast, the (log of) net loss in income per unit of initial emissions is not significantly correlated with (log of) initial income (see Fig. 4, right). In this context, the regressive tendency of the emission tax cannot be compensated for by the distribution of abatement costs.

The result that an emission tax with no rebate is inequality-increasing makes it all the more interesting to further investigate rebate schemes, and compare their distributional impacts for a given tax rate. For ease of exposition, we focus only on the results corresponding to $t = 100$ €/tCO_2eq.

Fig. 5 depicts the Lorenz curves of individual income for a 100 €/tCO_2eq emission tax and the five rebate schemes (left), along with the corresponding delta Lorenz curves relative to the pre-policy situation (right). The results confirm that rebate designs based on a constant relative abatement threshold (BN-CRAT and AS), despite their marked impacts on the level of aggregate income, have minimal effects on income distribution relative to the pre-policy situation. By contrast, income inequality is substantially reduced (in the Lorenz sense) when the rebate is based on a constant absolute emission threshold (BN-CAET and BC-CAET). In this case, agents with income below the seventh decile see their share in the total income increase.

The ranking of the income distributions shown in Fig. 5 is related partly to the distribution of initial emissions (Fig. 4, left) and partly to the distribution of abatement costs and potential, which jointly determine the individual net loss or gain in income under each rebate design. Fig. 6 depicts the log of individual net loss or gain in income per unit of initial emissions with respect to the log of initial income for all rebate designs except NR and a 100 €/tCO_2eq emission tax.

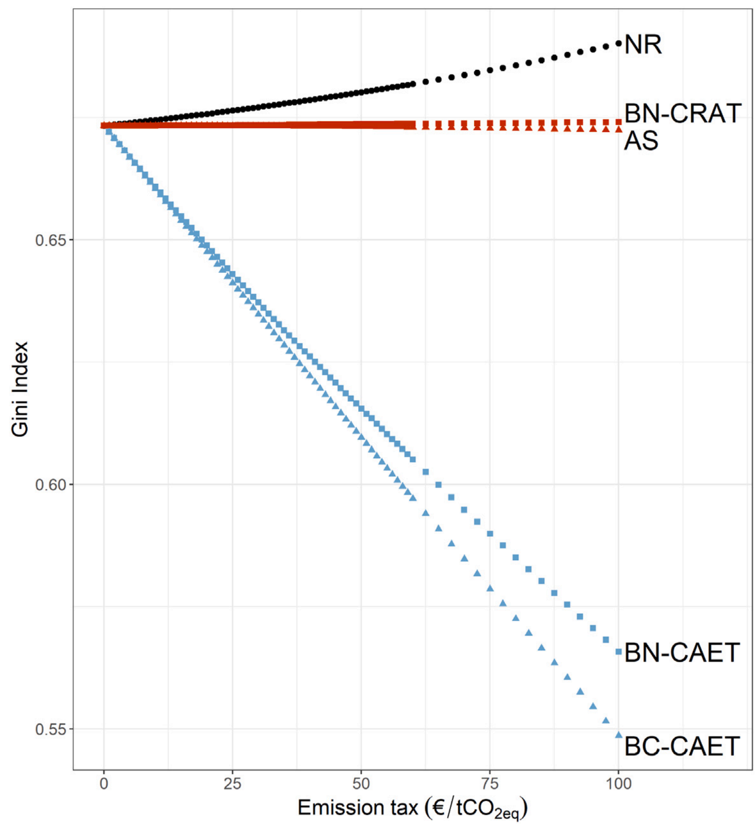

Fig. 2. Gini index of the distribution of income (per unpaid AWU) under an emission tax from 0 to 100 €/tCO_2eq and five rebate schemes. NR: No rebate; AS: Abatement subsidy; BN: Budget-neutral; BC: Budget-costly; CAET: Constant absolute emission threshold; CRAT: Constant relative abatement threshold.

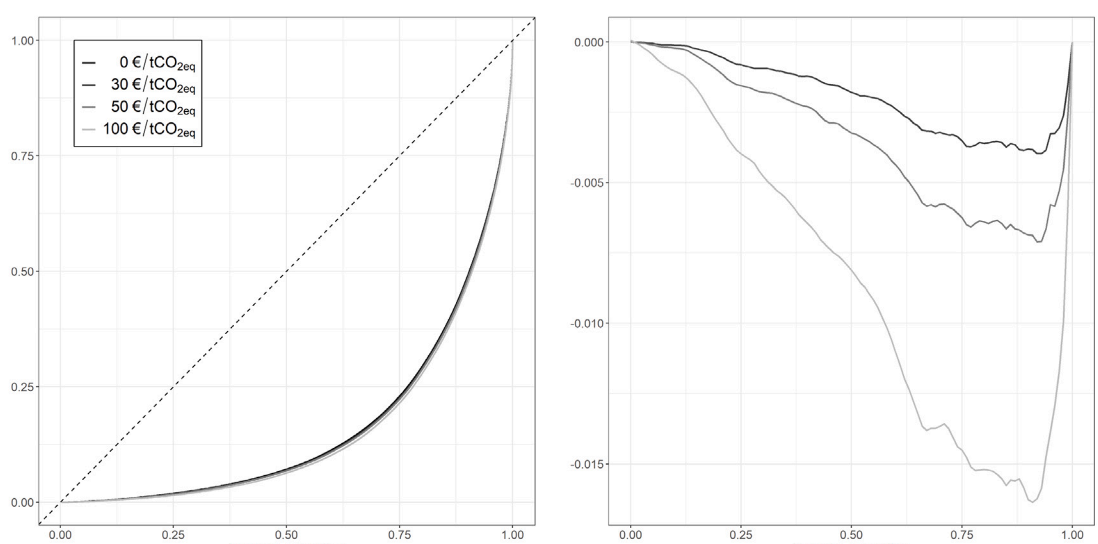

Fig. 3. Lorenz curves of post-policy income (left) and delta Lorenz curves relative to the pre-policy situation (right) of income under the no rebate (NR) scheme and for various emission tax rates.

Under an abatement subsidy (AS), all agents enjoy a net gain. The larger the abatement rate that the individual can attain for a given value of t, the larger the gain per unit of initial emissions. The weighted log–log regression line shown in Fig. 6 (AS, bottom left panel) is slightly downward sloping (estimated slope −0.11, significant at the 1% level). Together with initial emissions increasing slightly less than linearly with initial income, this implies that the abatement subsidy has a very limited impact on post-policy income inequality. A similar situation prevails for BN-CRAT (bottom right panel of Fig. 6). In that case, some agents face a net loss and others enjoy a net gain, but these two categories of agents are spread over the entire spectrum of initial income, with no clear pattern indicating that agents in any of these two categories are characterized by lower or higher initial income.

The picture is very different for rebate schemes based on a constant absolute emission threshold (top panels in Fig. 6). As initial emissions are, on average, increasing with respect to initial income, farmers with low (high) initial emissions tend to be also those with low (high) income. Consequently, farmers emitting initially less than the absolute

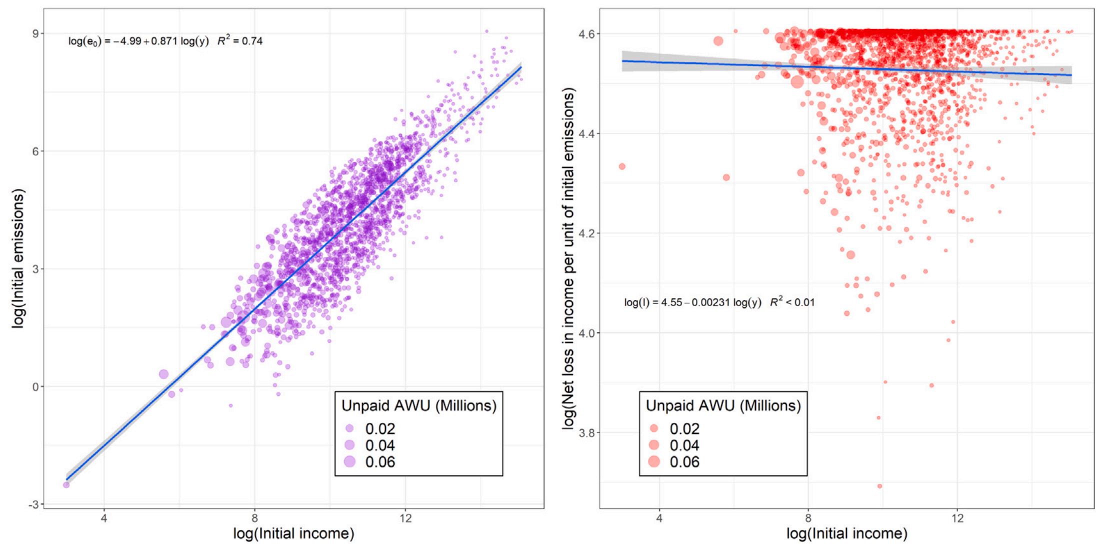

Fig. 4. Individual initial emissions (left, in tCO_2eq per unpaid AWU) and net loss in income per unit of initial emissions (right, in €/tCO_2eq per unpaid AWU) with respect to initial income (in € per unpaid AWU) for an emission tax rate of 100 €/tCO_2eq with no rebate (NR). Note: All variables are log-transformed. The regressions are weighted by the number of unpaid AWU.

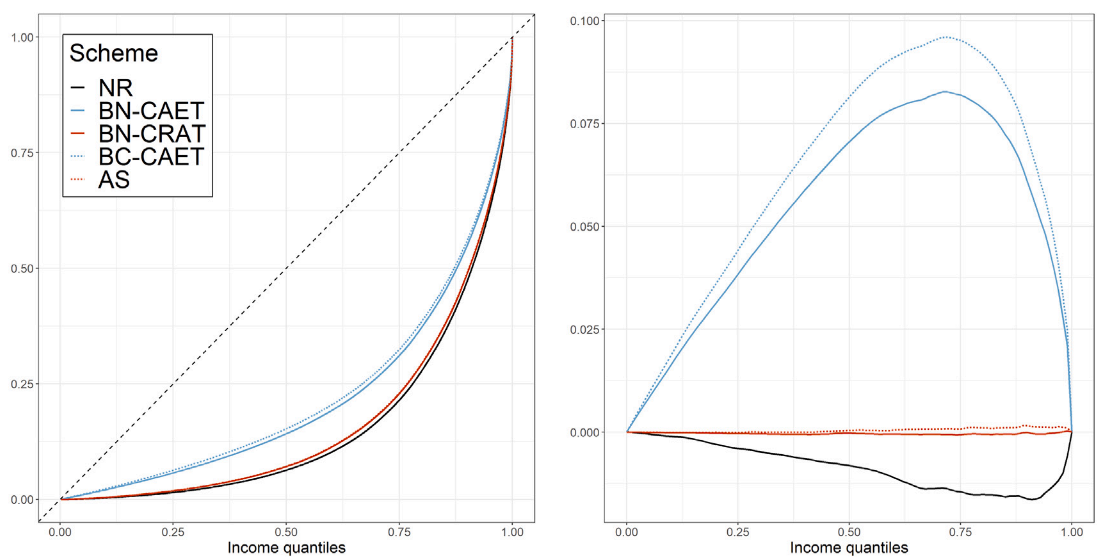

Fig. 5. Lorenz curves of post-policy income (left) and delta Lorenz curves relative to the pre-policy situation (right) of income under the five rebate designs and for an emission tax rate of 100 €/tCO_2eq. NR: No rebate; AS: Abatement subsidy; BN: Budget-neutral; BC: Budget-costly; CAET: Constant absolute emission threshold; CRAT: Constant relative abatement threshold.

emission threshold gain from the policy and are also more likely to have lower initial income, whereas farmers with initial emissions larger than the absolute emission threshold are more likely to have a large initial income and incur a net loss. The regression lines summarizing the relationship between the net loss or gain per unit of initial emissions and initial income are resultingly much steeper under BN-CAET and BC-CAET than under BN-CRAT and AS. The findings presented in this section are robust to various alternative combinations of assumptions regarding the measure of income (per farm or per unpaid AWU), treatment of farms with negative income, and exclusion of potential outliers with extreme income values (see Figs. C.7–C.10 in Appendix C). We also provide a focus on incomes below the first decile (see Figs. C.11 and C.12 in Appendix C).

The quantitative results presented above substantiate and complement the analytical findings discussed in Section 3. The results show that agriculture can deliver substantial mitigation for tax rates in the range of current carbon prices. However, if not accompanied by transfers, an emission tax would strongly affect the total farm income, mainly through the tax paid on unabated emissions. An important finding is that the average elasticity of initial emissions with respect to initial income is slightly lower than one. This has a regressive impact, which is not compensated for by the distribution of abatement costs in the absence of a rebate. Therefore, the conditions of Propositions 1 and 3 are met, and the emission tax is inequality-increasing, all the more so as the tax rate is high. Hence, a rebate may be appealing to the regulator. If based on a sufficiently large constant absolute emission threshold, income inequality would be reduced not only relative to NR (15), but also relative to the initial situation (conditions of Proposition 1 are met in that case). If, for the same impact on total income, the threshold is set proportional to farmers' initial emissions, the rebate would still reduce income inequality compared to NR (part (i) of Proposition 2), but would do very little, if at all, with regard to pre-existing inequality, and thus be Lorenz-dominated by a rebate based on a constant absolute emission threshold (parts (iii) and (iv) of Proposition 2 and Corollary 1).

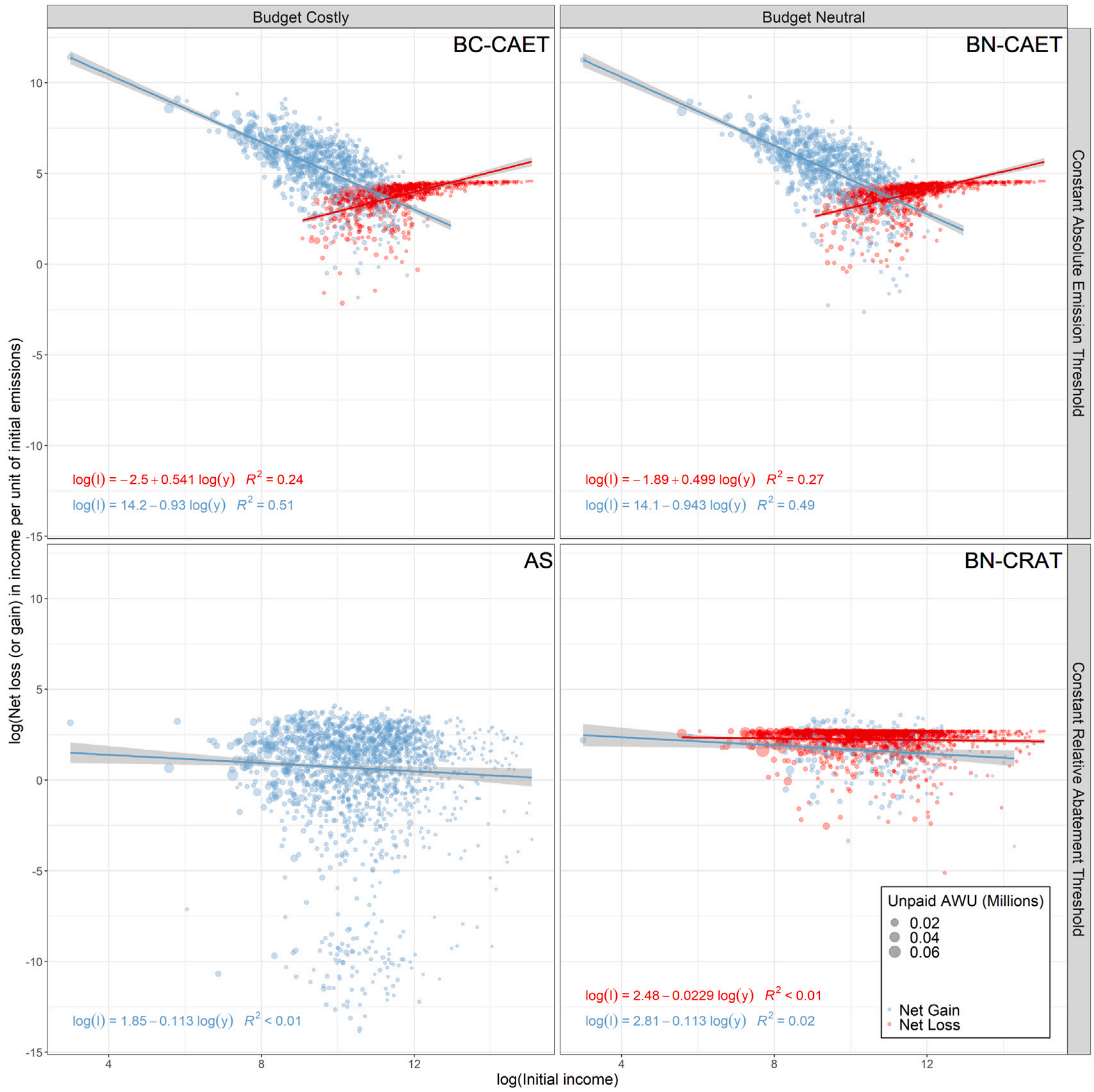

Fig. 6. Net loss or gain in income per unit of initial emissions for an emission tax rate of 100 €/tCO_2eq (in €/tCO_2eq per unpaid AWU), with respect to initial income (in € per unpaid AWU). Note: All variables are log-transformed. The regressions are weighted by the number of unpaid AWU. AS: Abatement subsidy; BN: Budget-neutral; BC: Budget-costly; CAET: Constant absolute emission threshold; CRAT: Constant relative abatement threshold.

6. Concluding remarks

In this study, the distributional consequences of various emission tax-and-rebate schemes have been investigated from both analytical and empirical perspectives.

The design of these schemes differs in the form of the rebate (based on an absolute emission or relative abatement threshold), total transfer to agents, and emission tax rate. For the same emission tax rate, all considered designs yield the same environmental benefit, but have contrasting impacts on the level and distribution of post-policy income, as well as on the regulator's budget. Our analytical framework helps to unravel the respective role played by the distributions of initial emissions and abatement costs with regard to income inequality and on how the distributional impacts vary with the tax rate.

As is the case for GHG sources from other sectors (Chancel, 2022), individual GHG emissions from EU agriculture are found to increase slightly less than linearly with initial income. This tends to make the taxation of these emissions regressive. Our empirical findings indicate that this regressive impact is not compensated for by the distribution of individual marginal abatement costs.

To illustrate the policy implications of these findings, consider a policy aimed at reducing EU agricultural GHG emissions based on a social cost of carbon of 100 €/tCO_2eq. Total emissions would decrease by approximately 15%. This suggests a substantial contribution of agriculture to the EU mitigation targets. However, without transfers, this would decrease average farm income by almost 20% and increase income inequality (the Gini index increases by almost 2 percentage points). Clearly, this is likely to undermine the political acceptability of such a policy.

For the same environmental benefit, the regulator may find it easier to subsidize each abatement unit. This would be equivalent to accompany the emission tax by a transfer to each individual farmer of 100 €/tCO_2eq per unit of initial emissions. In this case, farm income would increase by almost 2% on average, income inequality would remain almost constant relative to the initial situation, and the total social value of abatement would be fully supported by the regulator's budget. For the same net budget cost (ca. 5 bn€), income inequality could be further decreased (Gini index more than 12 percentage points below its initial level) if the regulator chooses to tax emissions with a constant rebate based on average initial emissions. As initial emissions average almost 74 tCO_2eq per full-time equivalent farmer, this would be equivalent to a lump-sum transfer of approximately 7400 € to each farmer. The policy could be made budget-neutral by setting the emission threshold to 63 tCO_2eq for all individual farmers (equivalent to a 6300 € lump-sum transfer). This would still keep the Gini index 10 percentage points below its initial level. An individualized threshold set at 85% (63/74) of each farmer's initial emissions would also ensure budget neutrality but have a negligible impact on pre-existing income inequality.

Rebate schemes can thus be pivotal in overcoming some of the barriers to the implementation of an emission tax that would otherwise have a strongly negative and regressive impact on farm income. This is all the more important in agriculture as this sector is still largely left aside from the scope of climate policy instruments and is characterized by lower income levels than in the overall population and large income inequality. Moreover, the design of such a scheme leaves room for maneuver to the regulator. For a given value of the marginal environmental damage, the regulator can choose from a variety of designs, depending on social preferences regarding total farm income, income inequality, and considerations regarding potential budget constraints.

The set of simulations used in this study is unique as it informs about the response to an emission tax at the individual farm level with comprehensive coverage of the sector. However, these simulations do not account for possible changes in prices in response to changes in input and output quantities.

Accounting for the impacts of the changes in equilibrium prices may have three types of implications. First, it may impact the aggregate level of income. A recent study by Fujimori et al. (2022) provides some quantitative indications in this regard. The authors examine the market impacts of mitigation of agricultural emissions using six global agroeconomic models under a 2 °C climate-stabilization scenarios. Under a middle-of-the-road scenario (Shared Socio-economic Pathway, SSP 2) and a median emission tax of 89 USD/tCO_2eq (range 75–204 USD/tCO_2eq, corresponding to the non-CO_2 GHG mitigation target in 2050), they find a moderate increase in European agricultural producer prices relative to the baseline (median: +6%, ranging from +1% to +11%), with only small impacts on total agricultural EU production (median: −0.3%, ranging from −2.4% to +3%). These findings suggest that some of the decrease in income found in the present paper (almost 20% for an emission tax of 100 €/tCO_2) could be partially offset by the increase in equilibrium prices.

Second, this may arguably affect the distribution of abatement costs and potential in equilibrium. Nevertheless, unless the impacts of the resulting changes in equilibrium prices affect disproportionally more higher-income farms, an emission tax with no rebate would remain regressive and rebates based on a constant emission threshold would still reduce income inequality.

Third, it may also affect consumers. However, including this aspect would require an entirely different approach able to explicitly model food demand, as well as the competition structure within the downstream agrifood sector (international trade, transformation, retail) to determine the share of the emission tax that is eventually passed on to consumers.

This research can be extended in several directions. We only mention two possible directions for future research. First, the implementation costs of these schemes can be investigated further. Whatever the chosen design, emissions from a large number of agents must be monitored and reported. To reduce the associated costs in the case of an emission tax, De Cara et al. (2018) propose exempting the smallest emitters. Such an exemption can be easily combined with a tax-and-rebate scheme based on a constant emission threshold. Second, the sources of inequalities in terms of initial emissions and abatement costs can be further decomposed according to the characteristics of the farms, for instance with regard to their region and/or type of farming. This could serve as a basis for designing rebate schemes based on type-of-farming- or region-specific thresholds, which may more accurately reflect differences in terms of initial emissions and abatement costs.

CRediT authorship contribution statement

Maxime Ollier: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing, Data curation. **Stéphane De Cara:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

We disclose the data used in this article. We declare that we have no known competing financial interests or personal relationships that could have influenced this article. No party had the right to review the paper prior to its circulation.

Data availability

Data and code will be attached to a supplementary material.

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Appendix A. Proofs

A.1. Proof of Proposition 1

Using Eqs. (5) and (11), $\xi^{S}(t,y)$ can be expressed as:

$$\xi^{S}(t,y) = \frac{y}{x^{S}(t,y)} - \frac{e_0(y)\ell^{S}(t,y)}{x^{S}(t,y)}\left[\varepsilon(y) + \lambda^{S}(t,y)\right] \tag{A.1}$$

Plugging Eq. (A.1) into (12), and rearranging gives the conditions of the proposition. □

A.2. Proof of Proposition 2

Consider three continuous and non-negative income distributions x in $\mathcal{X}$, x_i in $\mathcal{X}_i$, and x_j in $\mathcal{X}_j$, with $x_i = h_i(x)$ and $x_j = h_j(x)$ both positive and monotone increasing for all x in $\mathcal{X}$. We know that $\mathcal{X}_j \preceq_L \mathcal{X}_i$ if and only if $h_i(x)/h_j(x)$ is monotone decreasing (Fellman, 1976, 2016).

If the emission tax with no rebate (NR) is (strictly) rank-preserving, i.e. if $x_y^{NR}(t,y) > 0$ for all y and any given $t > 0$, we can define $\phi(x)$ as the inverse function of $x^{NR}(t,y)$ with respect to y such that $\phi(x^{NR}(t,y)) = y$ for all $x^{NR}(t,y)$ in $\mathcal{X}^{NR}$, with $\phi'(x^{NR}(t,y)) = 1/x_y^{NR}(t,y)$.

For any given $t > 0$, consider the following functions:

$$h_1(x) = x + t(E_0 - A(t)) \qquad h_2(x) = x + tE_0 \tag{A.2}$$

$$h_3(x) = x + \left(1 - \frac{A(t)}{E_0}\right) te_0(\phi(x)) \qquad h_4(x) = x + te_0(\phi(x)) \tag{A.3}$$

We have that $x^{BN\text{-}CAET}(t,y) = h_1(x^{NR}(t,y))$, $x^{BC\text{-}CAET}(t,y) = h_2(x^{NR}(t,y))$, $x^{BN\text{-}CRAT}(t,y) = h_3(x^{NR}(t,y))$, and $x^{AS}(t,y) = h_4(x^{NR}(t,y))$, which are all positive as soon as $x^{NR}(t,y) > 0$ and $A(t) < E_0$.

It is straightforward to verify that $h_1'(x) > 0$ and $h_2'(x) > 0$. It is also easily seen that, for any given $t > 0$, $h_1(x)/x$ is monotone decreasing ($\mathcal{X}^{NR} \preceq_L \mathcal{X}^{BN\text{-}CAET}$), and so is $h_2(x)/h_1(x)$ ($\mathcal{X}^{BN\text{-}CAET} \preceq_L \mathcal{X}^{BC\text{-}CAET}$).

If $\varepsilon(y) > 0$ (i.e., $e_0'(y) > 0$) and $x_y^{NR}(t,y) > 0$, then $h_3(x)$ and $h_4(x)$ are also both monotone increasing.

(i) $(h_3(x)/x)'$ and $(h_4(x)/h_3(x))'$ are of the same sign as that of:

$$x h_3'(x) - h_3(x) = \left[\frac{x\phi'(x)e_0'(\phi(x))}{e_0(\phi(x))} - 1\right] te_0 \times (\phi(x))\left(1 - \frac{A(t)}{E_0}\right) \quad (A.4)$$

$$\text{and } h_3(x)h_4'(x) - h_3'(x)h_4(x) = \left[\frac{x\phi'(x)e_0'(\phi(x))}{e_0(\phi(x))} - 1\right] \times te_0(\phi(x))\left(\frac{A(t)}{E_0}\right), \quad (A.5)$$

respectively. The sign of Eqs. (A.4) and (A.5) is given by that of the term in square brackets. Using the properties of $\phi(.)$, we have that:

$$\frac{x^{NR}(t,y)\phi'(x^{NR}(t,y))e_0'(\phi(x^{NR}(t,y)))}{e_0(\phi(x^{NR}(t,y)))} = \frac{x^{NR}(t,y)}{yx_y^{NR}(t,y)}.\frac{ye_0'(y)}{e_0(y)} = \frac{\varepsilon(y)}{\xi^{NR}(t,y)} \quad (A.6)$$

$h_3(x^{NR}(t,y))/x^{NR}(t,y) = x^{BN\text{-}CRAT}(t,y)/x^{NR}(t,y)$ and $h_4(x^{NR}(t,y))/h_3(x^{NR}(t,y)) = x^{AS}(t,y)/x^{BN\text{-}CRAT}(t,y)$ are therefore both monotone decreasing if and only if $\varepsilon(y) \le \xi^{NR}(t,y)$ for all y. Using Eq. (A.1) and re-arranging leads to the condition in (i).

(ii) The proof follows directly from Eqs. (A.4) and (A.5).

(iii) $(h_2(x)/h_4(x))'$ is of the same sign as that of:

$$h_2'(x)h_4(x) - h_2(x)h_4'(x) = \left[\left(1 - \frac{E_0}{e_0(\phi(x))}\right) - \frac{x\phi'(x)e_0'(\phi(x))}{e_0(\phi(x))}.\frac{x + tE_0}{x}\right] te_0(\phi(x)). \quad (A.7)$$

Using (A.6), we thus have that $h_2(x^{NR}(t,y))/h_4(x^{NR}(t,y)) = x^{BC\text{-}CAET}(t,y)/x^{AS}(t,y)$ is therefore monotone decreasing if and only if $\varepsilon(y) \ge \left(1 - \frac{E_0}{e_0(y)}\right)\xi^{BC\text{-}CAET}(t,y)$ for all y.
Note that, if $\varepsilon(y) \ge 0$ for all y, this condition is readily verified when $e_0(y) \le E_0$. Using Eq. (A.1) and re-arranging leads to the condition in (iii).

(iv) The proof proceeds exactly as in (iii) with $(h_1(x)/h_3(x))'$ being of the same sign as that of:

$$h_1'(x)h_3(x) - h_1(x)h_3'(x) = \left[\left(1 - \frac{E_0}{e_0(\phi(x))}\right) - \frac{x\phi'(x)e_0'(\phi(x))}{e_0(\phi(x))}.\frac{x + t(E_0 - A(t))}{x}\right] \times te_0(\phi(x))\left(1 - \frac{A(t)}{E_0}\right) \quad (A.8)$$

(v) The proof proceeds exactly as in (iii) with $(h_1(x)/h_4(x))'$ being of the same sign as that of:

$$h_1'(x)h_4(x) - h_1(x)h_4'(x) = \left[\left(1 - \frac{E_0 - A(t)}{e_0(\phi(x))}\right) - \frac{x\phi'(x)e_0'(\phi(x))}{e_0(\phi(x))}.\frac{x + t(E_0 - A(t))}{x}\right] te_0(\phi(x)). \quad \square \quad (A.9)$$

A.3. Proof of Corollary 1

It is sufficient to see that $\xi^{BN\text{-}CAET}(t,y) \ge \xi^{BC\text{-}CAET}(t,y)$ for all y (see (15)). This implies that if the condition in (iv) is satisfied then the condition in (iii) is also satisfied. In addition, as $A(t) \ge 0$, if the condition in (v) is satisfied, then the condition in (iv) is also satisfied. Combining (i), (iii), (iv), and (v) leads to the ranking given in Corollary 1.

A.4. Proof of Proposition 3

Differentiating $\xi^S(t,y)$ with respect to t yields:

$$\xi_t^S(t,y) = \frac{x_t^S(t,y)}{x^S(t,y)}\left(\frac{yx_{ty}^S(t,y)}{x_t^S(t,y)} - \xi^S(t,y)\right). \quad (A.10)$$

Whenever $\xi_t^S(t,y)$ is positive (negative), an increase in the tax rate leads to an increase (decrease) in income inequality. The sign of (A.10) depends on that of the marginal change in income $x_t^S(t,y)$ and on whether the marginal change in income is less or more equally distributed than $x^S(t,y)$.

The distribution of the marginal change in income among the total population can be summarized by:

$$\frac{yx_{ty}^S(t,y)}{x_t^S(t,y)} = \frac{-ye_0'(y)\ell_t^S(t,y) - ye_0(y)\ell_{ty}^S(t,y)}{-e_0(y)\ell_t^S(t,y)} = \varepsilon(y) + v^S(t,y) \quad (A.11)$$

Plugging Eq. (A.11) into (A.10) and rearranging with Eq. (3) leads to the conditions given in the proposition. □

Appendix B. EU-FADN types of farming covered by the model

Table B.5
Classification of main types of farming from the EU-FADN.

Covered by the model
Specialist cereals, oilseeds, protein crops
General field cropping
Specialist dairying
Specialist cattle - rearing and fattening
Cattle - dairying, rearing and fattening combined
Sheep, goats and other grazing livestock
Specialist pigs
Specialist poultry
Various granivore combined
Mixed cropping
Mixed livestock, mainly grazing livestock
Mixed livestock, mainly granivores
Field crops - grazing livestock combined
Various crops and livestock combined
Excluded from the model
Specialist horticulture
Specialist wine
Specialist orchards - fruits
Specialist olives
Permanent crops combined

Appendix C. Robustness checks

Table C.6
Gini index and the Atkinson–Plotnick–Kakwani decomposition associated for an emission tax of t = 100 €/tCO_2eq and for five rebate designs. Note: NR: No rebate; AS: Abatement subsidy; BN: Budget-neutral; BC: Budget-costly; CAET: Constant absolute emission threshold; CRAT: Constant relative abatement threshold.

Rebate	G_{pre}	G_{post}	G_{pre} - G_{post}	Vertical effect	Reranking effect
NR	0.673	0.690	−0.0168	−0.0125	0.00433
BN-CAET	0.673	0.566	0.108	0.111	0.00355
BN-CRAT	0.673	0.674	−0.000694	−0.000599	0.0000954
BC-CAET	0.673	0.549	0.125	0.128	0.00344
AS	0.673	0.672	0.000894	0.00104	0.000150

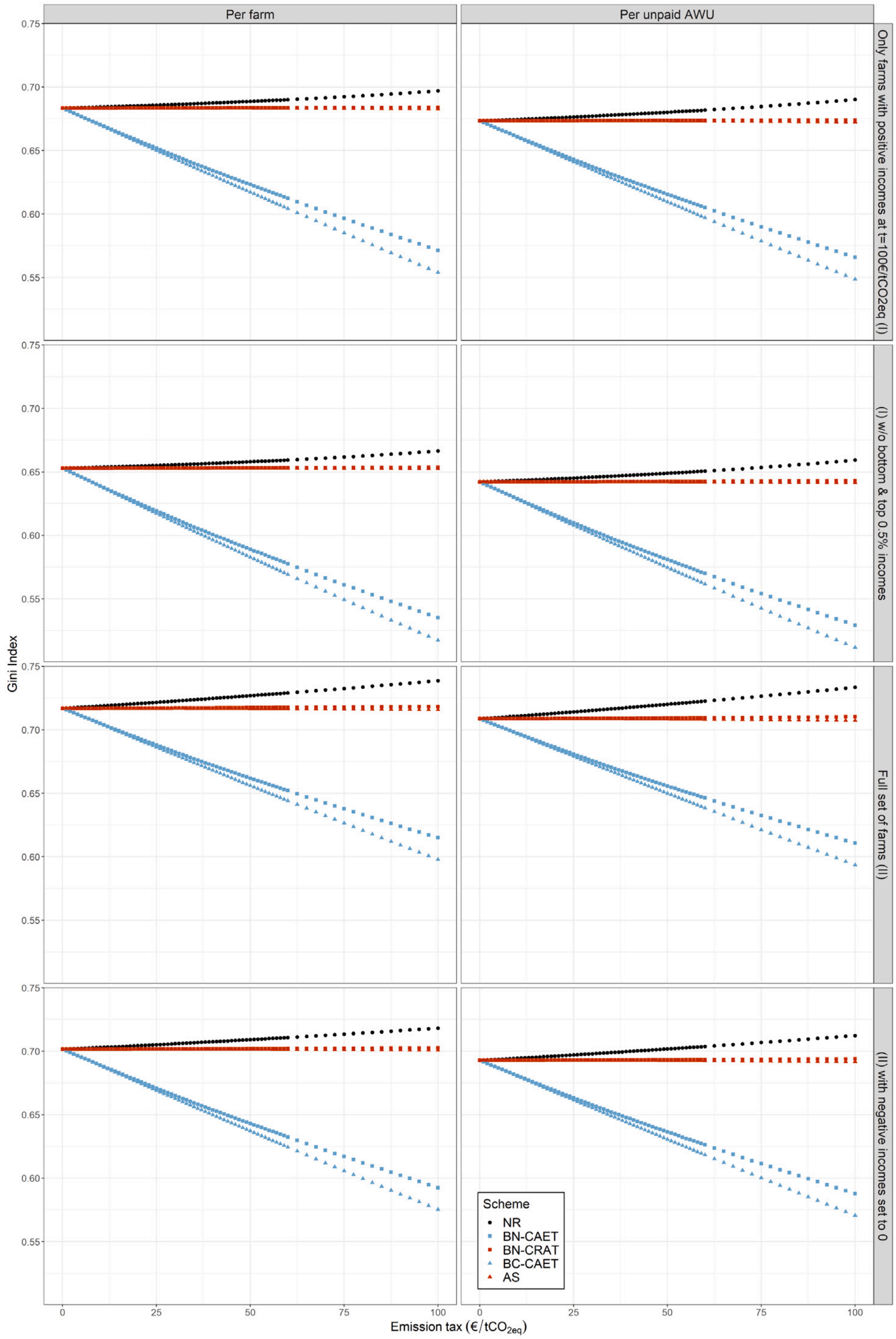

Fig. C.7. Gini index under an emission tax from 0 to 100 €/tCO$_2$eq and five rebate schemes for two normalizations (per farm or per unpaid AWU) and four sets of farms: Only farms with positive income at $t = 100$ €/tCO$_2$eq, only farms with positive income at $t = 100$ €/tCO$_2$eq and excluding the top and bottom 0.5% of income, full set of farms (Generalized Gini Index, Raffinetti et al. (2014)), full set of farms with negative income set to 0. Note: AS: Abatement subsidy; BN: Budget-neutral; BC: Budget-costly; CAET: Constant absolute emission threshold; CRAT: Constant relative abatement threshold.

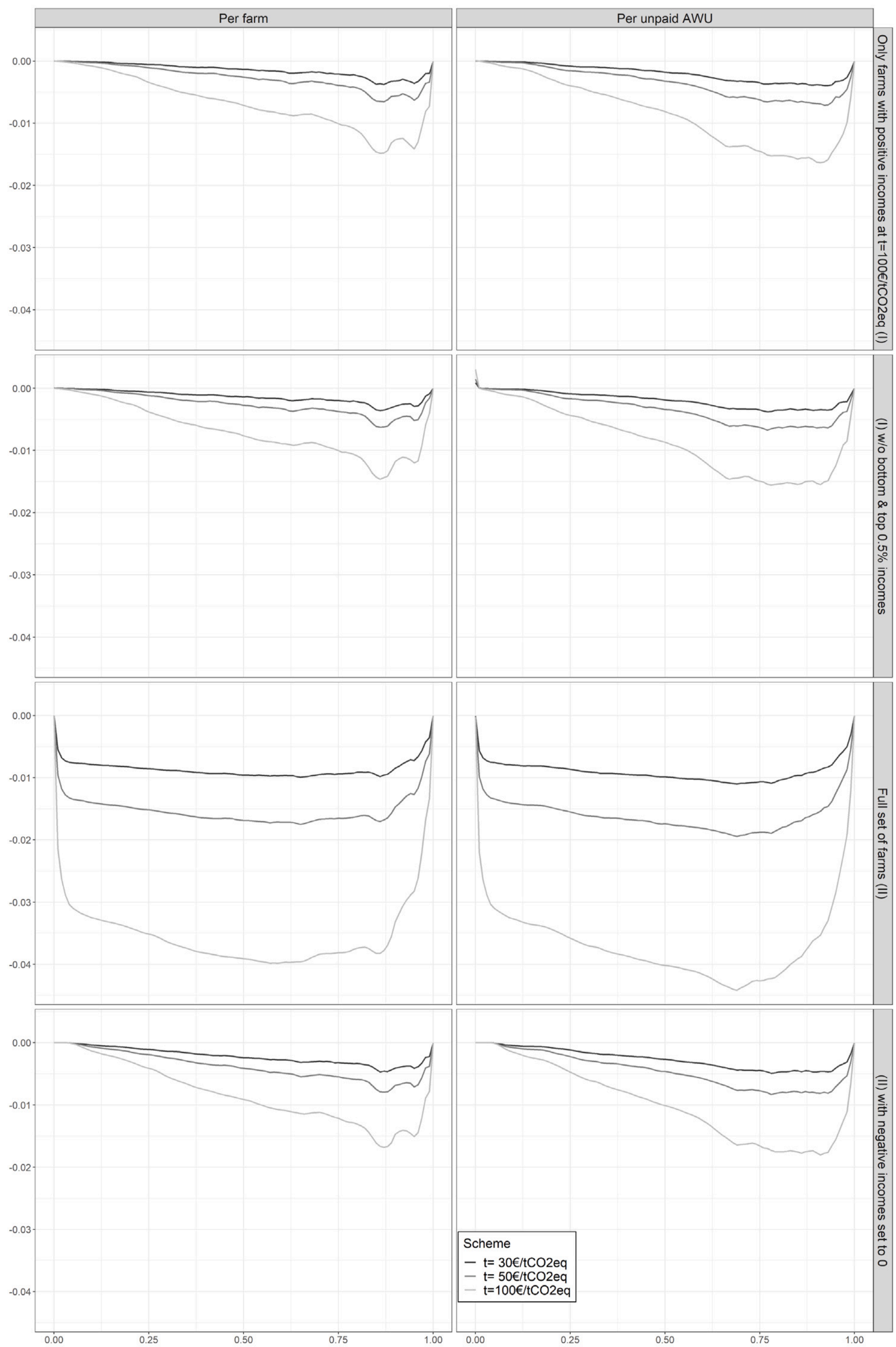

Fig. C.8. Delta Lorenz curves relative to the pre-policy situation of income under the no-rebate scheme and for various emission tax rates for two normalizations (per farm or per unpaid AWU) and four sets of farms: Only farms with positive income at t = 100 €/tCO_2eq, only farms with positive income at t = 100 €/tCO_2eq and excluding the top and bottom 0.5% of income, full set of farms, full set of farms with negative income set to 0.

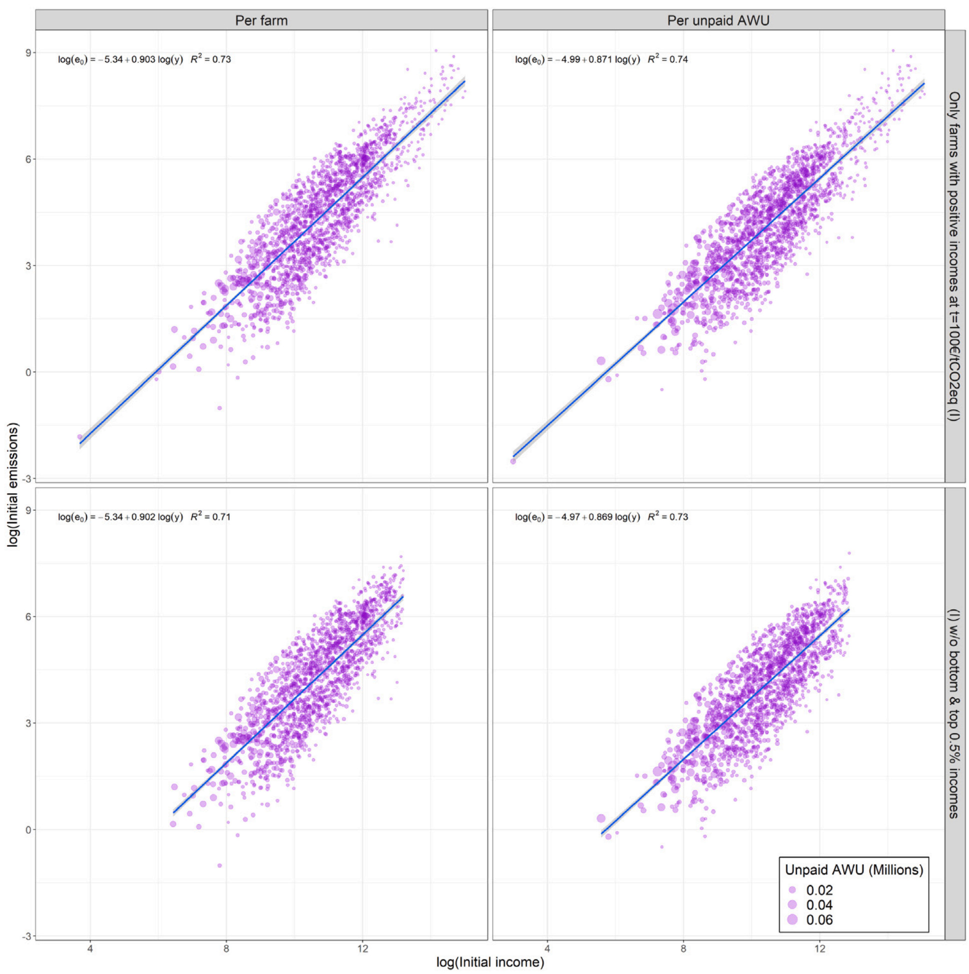

Fig. C.9. Individual initial emissions (in tCO_2eq per farm or per unpaid AWU) for two sets of farms: Only farms with positive income at $t = 100$ €/tCO_2eq, only farms with positive income at $t = 100$ €/tCO_2eq and excluding the top and bottom 0.5% of income. Note: All variables are log-transformed. The regressions are weighted by the number of farms or unpaid AWU.

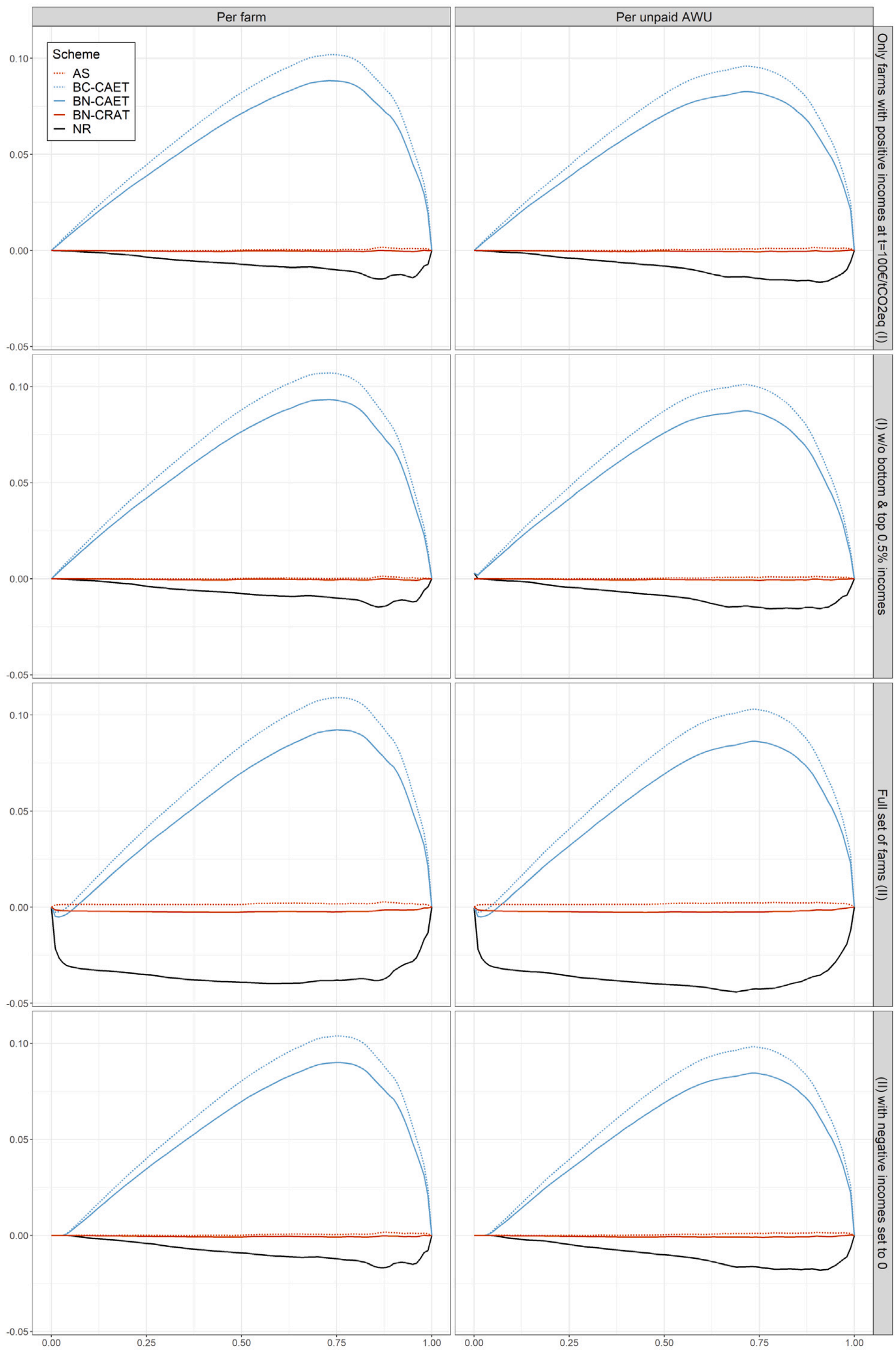

Fig. C.10. Delta Lorenz curves relative to the pre-policy situation of income under the five rebate schemes and for an emission tax rate of 100 €/tCO_2eq for two normalizations (per farm or per unpaid AWU) and four sets of farms: Only farms with positive income at $t = 100$ €/tCO_2eq, only farms with positive income at $t = 100$ €/tCO_2eq and excluding the top and bottom 0.5% of income, full set of farms, full set of farms with negative income set to 0.

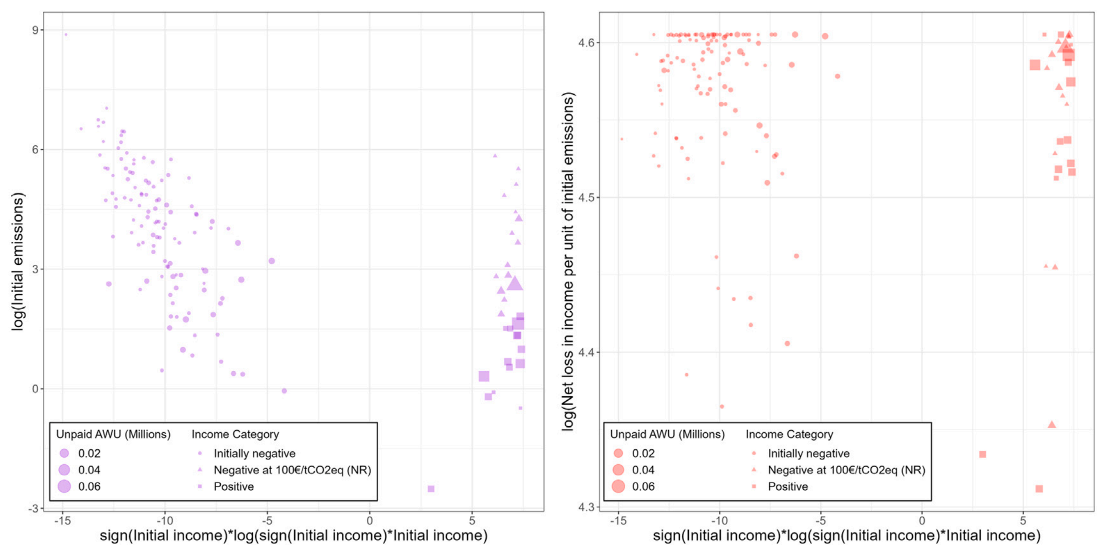

Fig. C.11. Individual initial emissions (left, in tCO_2eq per unpaid AWU) and net loss in income per unit of initial emissions (right, in €/tCO_2eq per unpaid AWU) with respect to initial income (in € per unpaid AWU) for initial incomes below the first decile and for an emission tax rate of 100 €/tCO_2eq with no rebate (NR). Note: All variables are log-transformed.

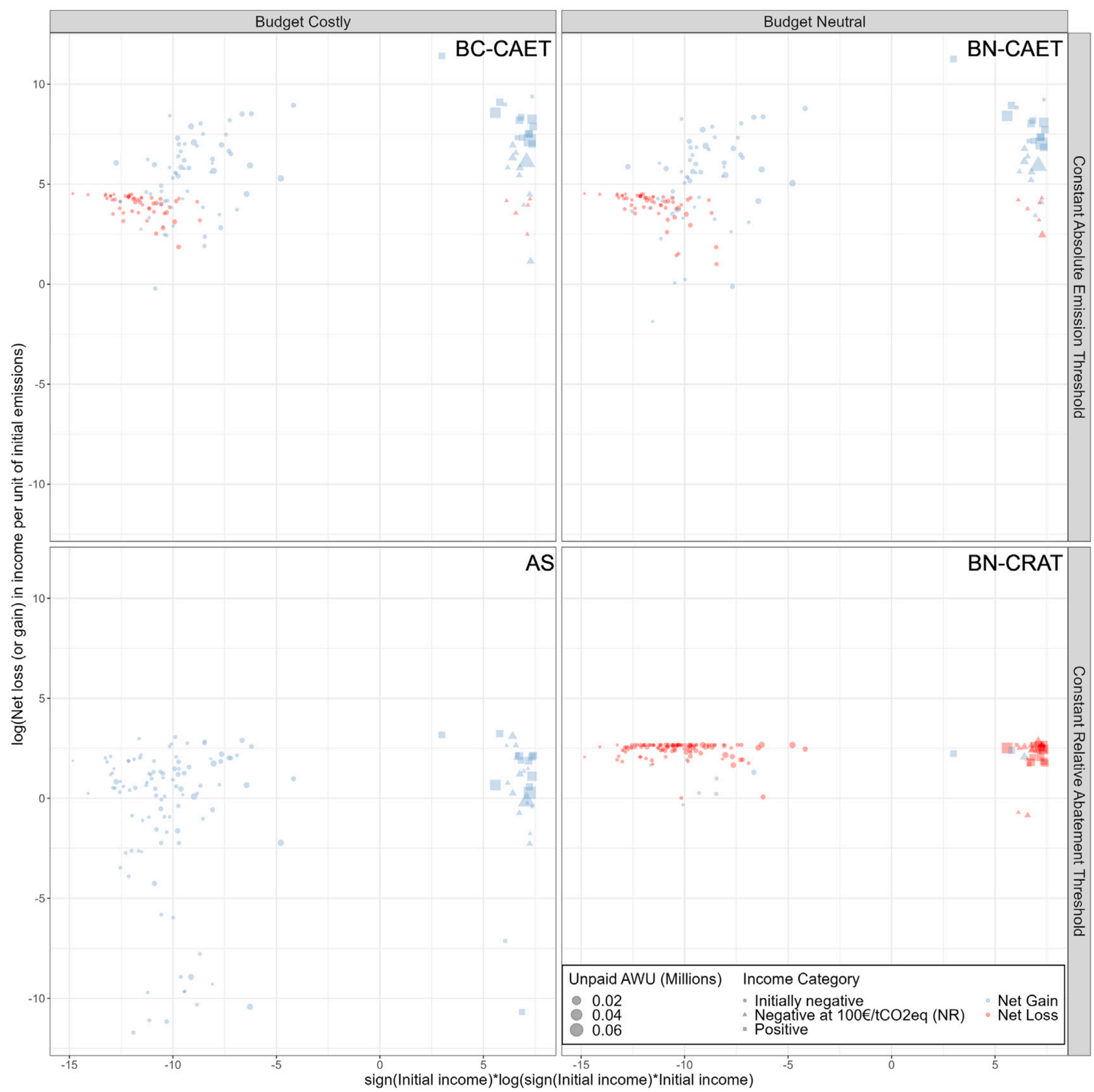

Fig. C.12. Net loss or gain in income per unit of initial emissions for an emission tax rate of 100 €/tCO_2eq (in €/tCO_2eq per unpaid AWU), with respect to initial income (in € per unpaid AWU) for initial incomes below the first decile. Note: All variables are log-transformed. AS: Abatement subsidy; BN: Budget-neutral; BC: Budget-costly; CAET: Constant absolute emission threshold; CRAT: Constant relative abatement threshold.

Appendix D. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108154.

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